INERTIAL NAVIGATION SYSTEM IMPROVEMENT USING GROUND STATION DATA

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ABSTRACT

INERTIAL NAVIGATION SYSTEM IMPROVEMENT USING GROUND STATION DATA

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Missile navigation systems rely on hybrid INS/GPS systems to employ lower grade inertial sensors for the sake of cost and availability. Current inertial navigation systems on missiles can perform accurately for a limited time without GPS aiding. However, GPS is the most likely system that is going to be jammed in a crisis or war by low cost jammers by any opposing force. Missiles do not have adequate equipment to maintain accuracy when GPS is jammed completely in the battle area.

In this thesis, a new method is proposed to improve performance of INS systems onboard missiles and autonomous aerial vehicles with EO sensors in a GPS denied environment. Previously laid ground based beacons are used by the missile EO/IIR seeker for bearing-only measurements and position updates are performed by the use of modified artillery survey algorithms based on triangulation techniques which involve angle measurements.

For mission planning, two main problems are identified as deployment problem and path planning problem and a tool for the optimal laying of beacons for a given desired trajectory and optimal path planning for a given network of beacons is developed by using evolutionary algorithms and results for test scenarios are discussed.

Keywords: inertial navigation system, GNSS denied environment, surveying algorithms, beacon navigation system.

ÖZ

YER İSTASYONU VERİSİ KULLANILARAK ATALETSEL NAVİGASYON SİSTEMLERİNİN BAŞARIMININ ARTTIRILMASI

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Füze seyrüsefer sistemleri maliyet-etkinlik ve temin edilebilirlik gibi nedenlerle küresel konumlama sistemi (KKS-GPS) destekli taktik seviye ataletsel navigasyon sistemlerine (ANS) sahiptir. Füzelerde günümüzde kullanılmakta olan ataletsel navigasyon sistemleri, KKS desteği olmaksızın kısa bir sure hassasiyetlerini devam ettirebilmektedir. Küresel konumlama sistemleri savaş ya da kriz durumunda düşman tarafından kolaylıkla karıştırılacak ilk sistem olarak öne çıkmaktadır. Füze sistemleri, insansız hava araçları gibi otonom hava araçlarının çoğunluğu KKS sisteminin savaş alanının büyük bölümünde karıştırıldığı durumda hassas olarak görev yapabilme yeteneğini kaybetmektedir.

Bu çalışmada KKS'nin karıştırıldığı durumda füze sistemleri ve insansız hava araçlarındaki ataletsel navigasyon sistemlerinin başarımının korunması/iyileştirilmesine yönelik yeni bir yöntem önerilmektedir. Füzenin elektrooptik/kızılötesi görüntüleyici arayıcı başlığı tarafından daha önceden döşenmiş sinyal yayıcılara nişan alınarak, topçu yer ölçme faaliyetlerinde kullanılan kestirme yöntemlerinin hava aracına uyarlanması sonucu elde edilen algoritmalar sayesinde sadece açı ölçümlerine dayalı konum güncelleme yapılmaktadır.

Görev planlama amacıyla, verilen görev profili için sinyal yayıcıların yerleştirilmesi ve verilen sinyal yayıcı ağı için yörünge planlama olmak üzere iki temel eniyileme problemi tanımlanmış, belirlenen test senaryoları doğrultusunda sinyal yayıcıların en verimli şekilde yerleştirilmesini sağlayacak evrimsel algoritma tabanlı bir yapı tasarlanmış ve belirlenen test senaryoları için elde edilen sonuçlar gösterilmiştir.

Anahtar Kelimeler: Ataletsel navigasyon sistemi, KKS'nin karıştırılması, kestirme algoritmaları, sinyal yayıcı tabanlı navigasyon sistemi.

To my mother, Saadet Güner...

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Symbols

C_n^b	transformation matrix from navigation to body frame
C_i	rotation matrix about ith axis
$\vec{F}$	Force vector
g	gravity vector magnitude
$\vec{H}$	angular momentum vector
I	Radiant intensity
m	mass
$\bar{M}$	moment vector
P	power
$\vec{p}$	Linear momentum vector
q	Size distribution of scattering particles
r	radius
R	range
T	transmission
V	visibility
$x\|_I$	x vector with respect to inertial frame
$x\|_F$	x vector with respect to fixed frame
y_c	distance from the rolling body axis to the area center of fin panel

Greek letters

γ	reflectivity
θ	divergence angle
θ	incidence angle

λ	wavelength
φ	yaw angle
θ	pitch angle
ϕ	roll angle
σ	atmospheric attenuation coefficient

Abbreviations

2PR	two point resection
3PR	three point resection
AGM	U.S. designation for air to ground missile class
BGM	U.S. designation for multiple environment to ground missile class
CCW	counter clockwise
CEP	circular error probable
CM	center of mass
CW	clockwise
DOP	dilution of precision
DSP	digital signal processing
ECCM	electronic counter counter measure
EA	Evolutionary algorithm
EA	Electronic attack
EO	electro-optic
FO	forward observer
FOV	field of view
FOR	field of regard
GA	Genetic algorithm
GLONASS	GLObal'naya NAvigatsiyonnaya Sputnikovaya Sistema
GNSS	Global navigation satellite system
GPS	Global positioning system
HARM	high speed anti-radiation missile
Hz	hertz

(I)IR	(imaging) infrared
IMU	inertial measurement unit
INS/GPS	inertial navigation system / global positioning system
JASSM	joint air to surface standoff missile
JDAM	joint direct attack munition
JSOW	joint standoff weapon
LOAL	lock on after launch
LOCAAS	low cost autonomous attack system
LOBL	lock on before launch
LOS	line of sight
NED	north east down
NTS	night targeting system
NVG	night vision goggle
PRF	pulse repetition frequency
RF	radio frequency (radar guided)
RGM	U.S. designation for surface ship launched anti-surface missile class
RI	Reverse intersection
RPG	rocket propelled grenade (i.e. RPG-7)
SLAM	standoff land attack missile
TAN	Terrain aided navigation
TERCOM	terrain contour matching
UAV	unmanned aerial vehicle
UV	ultraviolet
VLC	variable length chromosome
WCMD	wind corrected munition dispenser

CHAPTER I

INTRODUCTION

1.1 Overview

The purpose of this chapter is to define the aim and scope of this study, constitute a general understanding of various navigation methodologies, introduce the primary characteristics of inertial navigation and GNSS systems, comment about their drawbacks, and decide an approach for an alternative navigation scheme for air assets such as smart munitions, missiles or UAV's, by the use of a ground based beacon network and angle measurement based position fixing algorithms, in case of a theater or country-wide GNSS jamming scenario.

Navigation methods are classified, information about inertial navigation systems and space based global radio navigation systems is given. The primary problem involved with the GNSS systems, "jamming" and its effects of navigation performance of unmanned air vehicles and missiles are described.

Possible alternatives to complement GNSS systems are mentioned along with their advantages, disadvantages and, feasibilities.

The proposed solution, namely "ground based beacon navigation concept" is introduced, reasoning behind beacon navigation, benefits of beacon network, beacon type selection, operation doctrine and possible extensions of the method to various mediums are given.

This chapter is concluded with the expected original contributions to the subject and an outline of the thesis describing the contents of following chapters.

1.2 The Art of Navigation and the Quest of Position

The origin of word “navigation” comes from the words “navi” meaning “ship”, and ago which means “showing the way” in Latin language. The primary aim of the navigation is to find the position and route of the ship.

Navigation is an ancient art which is being employed since the first ship went to the sea. The time when the first ship started sailing is unclear but it is known that some early forms of small boats made from papyrus wood were sailing on the Nile delta around BC2700. When the Phoenicians discovered the use of long strong cedar woods on building the keel of the ship, stronger ships that can withstand the waves of Mediterranean had been built.

The first captains were employing “shore navigation”, in which they were trying not to miss the sight of the shore. By the use of new shipbuilding techniques, ships that can be used in off-shore sailing had been built, but to navigate in the open seas was a formidable and very dangerous task. The “art” of navigation was consisting of several secret taught that were passed from generation to generation. The navigation capability was one of the main talents that saved the lives of the sailors as well as the captain, diminishing the possibility of the crew to revolt against the captain.

Ptolemy was the first who proposed a way to find position on earth. He offered the parallel and meridian concept and selected equator as the 0^{th} parallel.

Several instruments and methods have been devised in the centuries. Octant, astrolabe, and sextant (1730) have been discovered, to observe the stars. Sextant is a tool that can measure the altitude of the celestial body from the horizon without being much effected from the ships heave motion. By this way, the latitude of the ship could be found. However finding the longitude was harder which required the time in Greenwich meridian and the time at local meridian. To maintain the Greenwich meridian time required the advent of accurate clocks. John Harrison solved the longitude problem by his H-4 clock in 1759 and won the longitude prize of the royal astronomers in England (Dovel [1]).

Further developments in the field of navigation led to the invention of many methods and systems. The first gyrocompass system that Sperry had developed was installed on USS Delaware in 1911. The gyrocompass was first designed to replace the magnetic compass but inertial navigation technology evolved and became the main navigation system of the ships. USS Nautilus (SSN-571) used the General Autonetics N6A-1 inertial navigation system in her voyage under the North Pole all the way submerged in 1958.

Inertial navigation technology has been evolved thanks to the World Wars and the successful implementation of inertial navigation onboard German V2 missiles (designated as missile due to inertial guidance system). Some early forms of inertial guidance systems are seen in WWII. Post war led to a new era of exploration, and an amazing progress in navigation technology has been achieved. The impetus for this significant progress came during the ballistic missile programs of the 1960s, in which the need for high accuracy at ranges of thousands of kilometers using autonomous navigation systems was apparent. By "autonomous" it is meant that no man-made signals from outside the vehicle are required to perform navigation. If no external man-made signals are required, then an enemy cannot jam them.

One of the early leaders in inertial navigation was the Massachusetts Institute of Technology (MIT) Instrumentation Laboratory (now Draper Laboratory), which was asked by the U.S. Air Force to develop inertial systems for the Thor and Titan air defense missiles and by the Navy to develop an inertial system for the Polaris submarine launched nuclear ballistic missile. This request was made after the Laboratory had demonstrated in 1953 the feasibility of autonomous all-inertial navigation for aircraft in a series of flight tests with a system called SPIRE (Space Inertial Reference). The notable success of those early programs led to further application in aircraft, ships, missiles, and spacecraft such that inertial systems are now almost standard equipment in military and civilian navigation applications (Schimdt [2]).

Another form of navigation is the radio navigation which relies on transmission of radio signals and measuring angles and distances by special means.

LORAN, OMEGA, ALPHA systems has been developed in 20^{th} century and provided accuracies around 400 meters to 3 nautical miles. Some of these ground based radio navigation systems had global coverage thanks to the use of VLF radio waves.

Today GNSS (global navigation satellite system) systems provide global coverage with an accuracy of 10 to 1 meters. GPS (Global Positioning System) GLONASS (GLONASS: GLObal'naya NAvigatsiyonnaya Sputnikovaya Sistema), GALILEO (from Galileo Galilei), and Chinese COMPASS system are the four GNSS systems in current or near term full operational status.

As the history of navigation is analyzed, it can be said that the improvements achieved in navigation science is primarily on the basis of equipment and high technology components. Other than that, the primary geometrical principles and position fixing methods consisting of measuring distances and angles are the same for a captain of an ancient dhow or a nuclear aircraft carrier.

1.3 A Classification of Navigation Methods

With the wide usage of hybrid navigation systems, classification of navigation systems has become complicated. Several classifications of navigation methods can be made based on different parameters. One classification is given below which is based on NATO booklet "Basic Guide to Advanced Navigation" [3].

The navigation methods can be classified according to being externally dependent or self contained. Dead reckoning is a self-contained method of navigation that does not rely on any external infrastructure. Sensors that measure quantities to be used in navigation by themselves fall into this category such as inertial sensors, barometric sensors, speed sensors etc. Externally dependent systems are using measurements by a pre-formed network of signal sources.

Externally dependent systems use angle or distance measurements. Distance measurement techniques used in radio navigation can be divided into time of arrival (TOA), time difference of arrival (TDOA) and received signal strength intensity (RSSI) systems. Angle measurement systems use triangulation. Some systems like VOR/DME (Very High Frequency Omni-directional Range/Distance Measuring Equipment) and TACAN (Tactical Air Navigation) use both distance and angle information to obtain a position fix.

Externally dependent systems mostly in radio navigation are classified according to their measurement type. These systems are rho-rho, theta-rho, theta-theta systems where "rho" stands for distance measurement and "theta" for angle measurement. A position fix that is obtained by using 2 VOR stations is a theta-theta position fix while a VOR/DME system is a theta-rho radio navigation aid.

1. Dead Reckoning Techniques
    - Inertial Navigation Sensors and Systems
    - Velocity and Distance Travelled Sensors
        - Speed Sensors
        - Doppler Velocity Sensor
        - Zero Velocity Update
        - Visual Odometry
    - Heading Sensors
        - Magnetic Compass
        - Gyrocompass
    - Altitude / Depth Sensors
        - Barometric Altimeter
        - Radar Altimeter
        - Water Depth Sensor

2. Externally Dependent Systems
    - Time of Arrival / Time Difference of Arrival (Range determination)
        - Global Navigation Satellite System (GNSS) (TOA)

        - LORAN-C, DECCA, OMEGA, ALFA (hyperbolic,TDOA)
        - Distance Measuring Equipment (DME) (rho-rho)
        - Pseudolites
        - Ultra Wideband
    - Angle (Bearing determination)
        - VHF Omni Directional Radio-Range (VOR) system
        - ILS

      (TACAN (rho-theta) and VOR/DME systems are combinations of angle and distance measurement devices.)
    - Signals of Opportunity
        - Radio / TV Broadcast Signals
        - Mobile Telephone Positioning
        - Received Signal Strength

3. Database Matching

    - Map Matching
    - Image Matching
    - Laser Imaging
    - Terrain Referenced Navigation
    - Celestial Navigation
    - Gravimetry

Hybrid systems employing multiple navigation methods are widely in use today such as INS/GPS systems combined with other sensors.

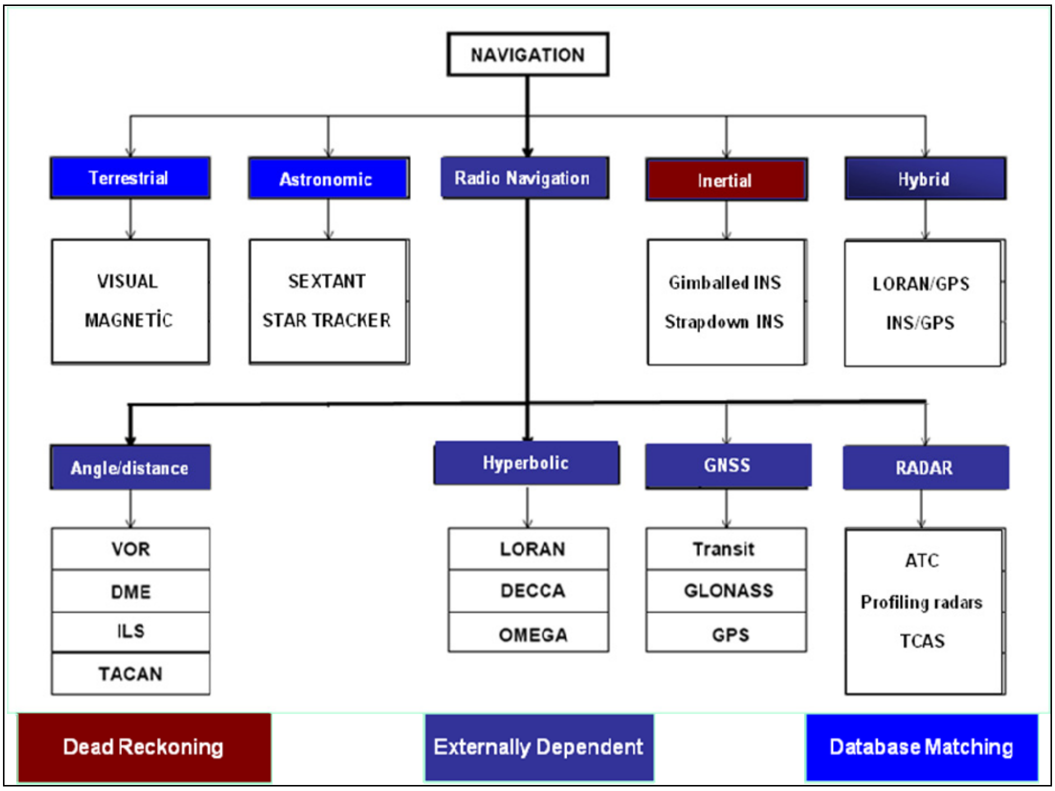


Figure 1-1 Navigation systems

1.4 Inertial Navigation Systems

Inertial navigation system (INS) is a kind of dead reckoning navigation system which has means to measure linear accelerations and rotation rates in 3 orthogonal axes.

An inertial navigation system (INS) is a three-dimensional dead-reckoning navigation system. It comprises a set of inertial sensors, known as an inertial measurement unit (IMU), a navigation processor, power and sensor electronic cards, a clock, and a mechanical interface to be accurately mounted on the host vehicle.

An IMU has 3 accelerometers and 3 gyroscopes which are mounted orthogonally to measure accelerations and rotation rates in 3 orthogonal axes. By this way it provides acceleration, angular rates and position information in all axes (Figure 1-2).

The navigation processor card has the navigation algorithms and Kalman filter when used with aiding sensors. Navigation algorithm integrates acceleration and angular rates to obtain linear and angular velocities and then these quantities are integrated to obtain position and attitude. Navigation quantities are projected in time on the basis of initial position which is given from the user as a known coordinate or by the aiding system such as GNSS.

Inertial navigation systems require initial position to be entered by the user or taken from an external source. Some lower grade inertial navigation systems also require initial heading or employ a “2 point alignment” which is performed on 2 known points to achieve an accurate heading.

Inertial navigation systems employ initial alignment algorithms to find their initial angular orientation. The initial alignment process uses gravity to level itself either electronically or mechanically, and earth rate at the given initial position to find the direction of north. This process is called gyrocompass alignment. When backed with GPS, an inertial navigation system can employ an on-the-move alignment.

A gravity model is used to extract the acceleration from the specific force measurements by using a known position. The errors grow with time as inertial sensor errors are integrated. Positive feedback in the vertical channel destabilizes the height solution.

There are two types of INS based on their mechanical design and classified as strapdown and gimbaled systems.

- In a strapdown INS, the accelerometers and gyros’ sensitive axes are aligned with the chassis of the INS which is mechanically or electronically aligned with the host platform.
- In a gimballed system, the system is physically maintained in level position by the use of torquers and motors. Gimballed systems' maintenance is harder and failure rates are higher when compared to strapdown systems.

Inertial sensors are classified according to their sensing quality as control, tactical, navigation and strategic grade sensors, whose cost and volume increases drastically from control to strategic grade. Submarines, ICBM's (intercontinental ballistic missile) and space vehicles are instrumented with strategic grade inertial navigation systems. High performance electrostatically suspended gyros are used in ICBM's (Figure 1-3).

Military aircraft and modern artillery howitzers which can fire to a range of 40/70 km with 1 mil accuracy use navigation grade INS's that has 1 nm/hr position drift performance. INS's used in high performance missiles are tactical grade systems with best accuracies between 1deg/hr to 100 deg/hr. As an example, GBU-29/31 JDAM uses HG-1700 ring laser IMU. RGM-84 Harpoon Block II also utilizes the IMU/GPS system featuring HG-1700 Ring laser IMU (1 deg/hr, 1mg). The smallest and lower cost inertial systems are used in stabilization and control systems such as a gyro in a seeker head of a missile.

The advantages of inertial navigation systems can be summarized as follows;

- Independent operation. No external information is required for navigation except initial position for initial alignment process.
- Can not be jammed by external sources using electronic attack methods, its operation can not be interrupted.
- Since inertial navigation systems are passive sensors which do not emit signals, their operation is completely self contained and covert, making an ideal navigation system for submarines.
- Inertial navigation systems can operate in every tactical situation, in ECM environment, airborne, on land and under water.
- Provides navigation information in high rates in high dynamic environments.
- Provides attitude, angular rates, acceleration, position, velocity information in high rates (i.e. 100 Hz) with time of validity information which is very critical in stabilization of weapon systems.

The disadvantages of inertial navigation systems are the error growth with time which is due the integration of errors and the necessity to enter initial coordinates. (and heading for initial alignment for lower quality systems.)

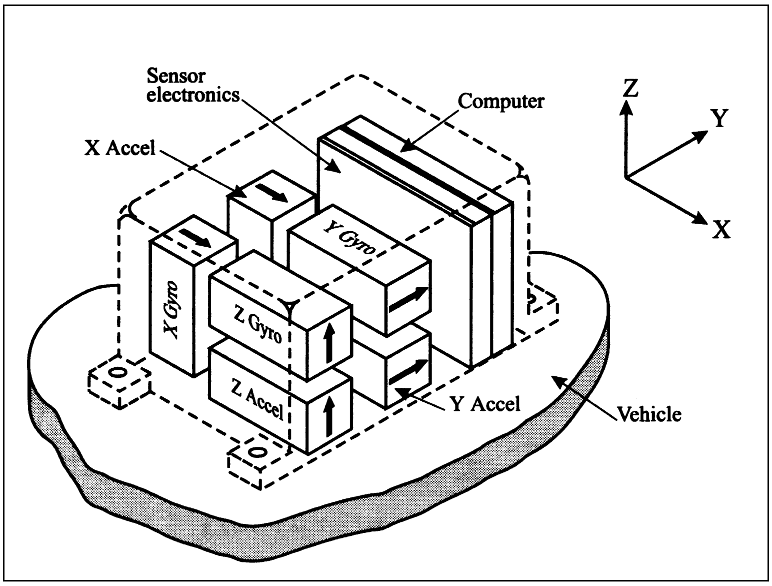


Figure 1-2 A schematic of a strapdown INS.

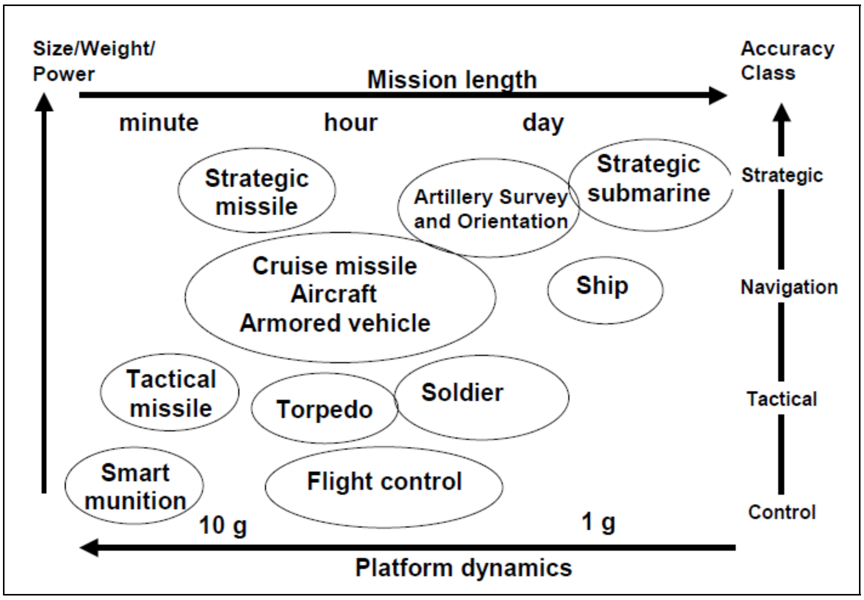


Figure 1-3 Classification and usage areas of inertial navigation systems (NATO [3]).

1.5 GNSS and Vulnerabilities

GNSS is the acronym for Global Navigation Satellite System and used to designate global coverage satellite navigation systems such as GPS, GLONASS, GALILEO and, COMPASS.

GNSS systems are designed to give three-dimensional position, velocity and time data almost anywhere in the world with an accuracy of a few meters. This specialty makes them unique when compared to other forms of navigation systems. A GNSS receiver uses timing signals from a constellation of orbiting satellites to determine its geographic location using range measurements from four or more satellites with precisely known coordinates. Position is derived by computing the distance from the receiver to each satellite, by measuring the time taken for a signal transmitted from the satellite to travel to the receiver. In order to make precise distance measurements, the accurate time tagging of the satellite signal is essential. This is achieved with the aid of multiple, but expensive, atomic clocks on each satellite. The clock used in the receiver can therefore be of much lower cost. Measurements of range to at least four satellites are required to determine four unknowns: three spatial co-ordinates (latitude, longitude, altitude), and time. By using the Doppler shift of the satellite signal, the range rate to each satellite can also be computed in the receiver. This can be used to determine the vehicle's velocity (NATO [3])

The advantages of GNSS can be summarized as follows

- Global coverage.
- All weather-all time availability.
- Very accurate position information in the order of meters.
- Error sources are independent of time.
- Investment in user side is minimal. A low cost receiver is the only investment.

The disadvantages of GNSS is the establishment of a huge infrastructure comprised of ground control stations, satellites, launching facilities to replace old satellites, namely continuous and high cost of maintenance of the overall systems infrastructure. This makes such systems to be established by only a few countries such as USA, Russian Federation, China and the whole European Union. Due to the working principle of the GNSS, signal power levels are extremely weak so intentional or unintentional radio interference can block the use of GNSS signals. GNSS signals also can not be used in confined environments.

1.5.1 General Information and Positioning Accuracies

GNSS systems are radio navigation systems that employ distance-distance navigation scheme based on signal time of arrivals. . The first system is the GPS, whose theory has been discovered in 1957 by U.S. scientists who are trying to figure out the orbital trajectory of Russian Sputnik I satellite.

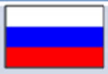
USSR has developed GLONASS which did not achieve global coverage due to breaking of Soviet Union. After 2008 GLONASS has undergone a major regeneration program and as of 2012 reached almost global coverage with 23 satellites. Russian Federation is promoting GLONASS for civilian usage to increase its usage and familiarity throughout the world. Galileo is the European initiative of a GNSS system which will be controlled by European Union and will provide more flexible military and civilian services when it reaches full operation capability (Figure 1-4).

As all joint European programs, GALILEO program is experiencing delays. The system still has 2 satellites, namely GIOVE-A and B. IOC (initial operation capability) is planned to be achieved with the launch of two additional satellites by the end of 2012. Full operational capability is expected to be beyond 2020. Chinese COMPASS system is currently in test and evaluation phase with 13 satellites in orbit as of 2012. Table 1-1 shows key specialties of GNSS systems.

GNSS systems provide high accuracy positioning information. General GNSS horizontal position accuracies will give an insight about the accuracy obtained by the users. GPS has a positioning accuracy of <20 meters (95%) use in P(Y) - PPS mode and 100 meters if selective availability is applied. GLONASS standard mode positioning accuracy is 55 meters (95%) horizontal 60/70 meters vertical. The services that will be offered by the European GALILEO satellite navigation system can be divided into three different service groups, with the highest accuracy of Public-Utility Services of 4 to 6 meters (99%).

Figure 1-4 GNSS infrastructure (GALILEO)

Table 1-1 Overview of GNSS systems

Name	GPS	GALILEO	GLONASS	COMPASS
Origin				
Space Segment	• 24 op. Satellites • 3 spare sat.. • 20187 km orbit height • 12h orbit duration • 6 planes • 55° plane inclination	•27 op. Satellites, •3 spare sat. • 23616 km orbit height • 14h orbit duration • 3 planes • 56° plane inclination	•24 op. Satellites*, • 19130 km orbit height • 11h orbit duration • 3 planes • 64,8° plane inclination	•30 MEO Satellites • 5 GEO Satellites •21500 km orbit height
Ground Segment	1 Master Control Station (MCS) 1 Backup MCS 4 Ground Antennas 6 Monitor Stations	2 Galileo Control Center 5 Telemetry & Tracking Stations 9 Uplink Stations 29 Galileo Sensor Stations	1 System Control Center (Moscow) 4 Command Tracking Stations Quantum Optical Stations	1 System Control Center 1 Upload Station Tracking stations
Comment	• Developed as US military system • In full operation (FOC) since 1995 (IOC 1993) • Upgrades planned (Block IIR-M, IIF, III, GMSP) • US monopoly position in SatNav • 2 signal types: Commercial and Military • Controlled by US Department of Defense (DoD)	• Developed as an European civil system • Go ahead for Galileo given by European Council at 26 march 2002 • Was planned to be in full operation by 2008. • Still 2 satellites operational. • IOC expected in 2012. • Full operational capability delayed to 2020 • Designed for GPS interoperability • 5 signal types: Commercial, Military, + 3 • Controlled by European Union	• Developed as a USSR military system • First satellite launch in 1982 • Has experienced setbacks due to financial distress, Restored global coverage in 2011 • 2 signal types: Commercial and Military • Controlled by the Russian Space Forces for the Russian Federation Government	• Being developed by PRC • First satellite launch in 2007 • 13 Satellites launched by April 2012. • Regional operation started. • FOC expected by 2020 • 4 signal frequencies • Controlled by the CSNPC
Status	Fully operational globally	Testing	Almost fully operational globally	Testing Regionally operational

1.5.2 Jamming GNSS

GNSS systems are one of the first systems to be jammed in a conflict. The structure and the power of the signal let the enemy to jam GPS signals easily. GPS signals can be obscured by terrain and vegetation, and signals can be overwhelmed by several electronic equipments even unintentionally. There are several occasions of unintentional jamming in literature. A new bought preamp TV antenna in a pleasure craft moored in Moss Harbor denied the use of GPS within a radius of 1 km, and the harbor authority had to employ radar aided harbour entry system in 2001. Another incident in 2007 led to the shutdown of San Diego DGPS station and cell towers (NATO [3] and Benshoof [4]).

The signal power is,

- 10 Watts at the satellite 20.000 km's away,
- $10^{-16.3}$ Watts at the receiver.
- $10^{-12.8}$ Watts required to jam signal at first start of receiver.
- $10^{-10.3}$ Watts required to jam signal with hot receiver.

Jammer eqipment are easy to produce and acquire. A 4 Watt jammer can knock down civilian code GPS signals from 150 km's. GNSS systems can be deceived by two types of electronic attack. One is the jamming and the other is the spoofing. Jamming is performed by noise inducing and preventing the receiver from locking on the GNSS signal or breaking lock and can be performed by anybody by using low cost jammers. Spoofing is more complicated and mainly done by employing stronger and same signals than original GNSS code, lock on wrong code and pulling off slowly from the original signal to the deceiver signal, from true position to a wrong intended position. Another spoofing technique is to take the GNSS signal, wait for a while and rebroadcast it. (meaconing). Spoofing requires much higher technology, planning and more sophisticated equipment when compared with jamming. The probability of being attacked by spoofing is much lower than the jamming threat.

Jamming can be made in two forms, broadband jamming and narrowband jamming. There are multiple countermeasures against jamming but due to the weakness of GNSS signals it is still very easy to jam GNSS signals. Civilian GPS code is more vulnerable to jamming

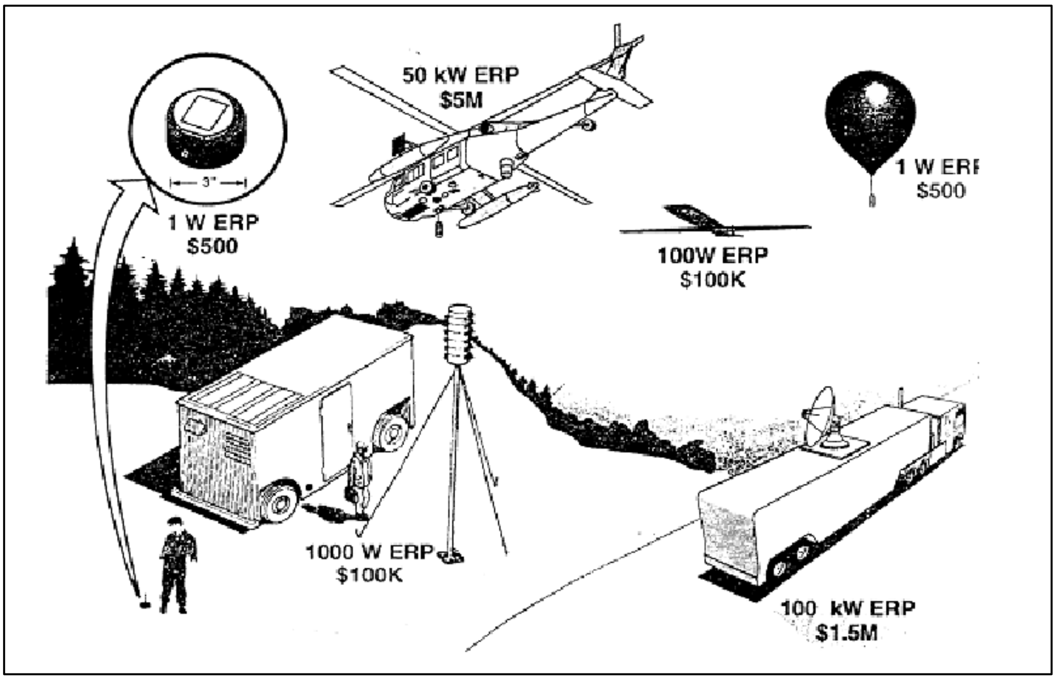


Figure 1-5 GNSS jammers and estimated costs [3].

1.6 The Problem

1.6.1 Missile and UAV Operations in GNSS Denied Battle Area

In a GPS jamming scenario two mainstays of target engagement sequence are severely affected.

- Target localization capability
- Target engagement capability

Tactical level target localization is performed by UAV's and reconnaissance aircraft in surveillance missions. Both surveillance and target position determination is one of the key issues of UAV tactical use. Currently UAV's are used for target detection and positioning. MALE UAV's can operate on surveillance areas for prolonged periods in the order of at least 8-10 hours and less capable tactical UAV's are also being used for target detection and positioning from shorter ranges.

The typical use of an UAV is that it provides target coordinates by observing the target by its FLIR, by measuring the distance to target and combining with UAV's position to obtain target coordinates. These coordinates are then transmitted to the C3I center where the most suitable weapon system is assigned to destroy the target. Generally the most responsive system of choice is an artillery battery. With a range of almost 40 km's and a rapid firing capability, modern S/P artillery pieces can respond fire order within seconds. Modern howitzers are also equipped with navigation grade INS/GPS systems

A MALE UAV such as a HERON or ANKA is usually equipped with a navigation grade inertial navigation system with GPS and a FLIR capable of observing long distances in night and day.

On the other side of the family, a tactical UAV is much smaller with limited endurance but it is also equipped with a smaller FLIR system capable of surveillance of man size targets up to 2000 meters or more. This kind of UAV's are equipped with lower grade inertial sensors, generally a MEMS IMU coupled with GPS.

For both sides of the UAV family whether they are using a navigation grade INS/GPS or a tactical grade MEMS IMU with GPS, the position accuracy of the UAV mainly stands on GPS. In case of GPS jamming, a navigation grade INS will have a positioning error of 1 nm/hr free inertial performance and, a MEMS IMU will utterly lose its functions. Even in the case of navigation grade INS, the positioning accuracy of a UAV will deteriorate shortly and the primary function of finding accurate target location will be severely affected.

For artillery engagement the targets positions must be found with high accuracy in the order of 100 meters at most.

In a GPS jamming scenario, where the area of operation of UAV and nearby artillery battery is jammed by a balloon mounted GPS jammer of enemy, the functions of UAV and howitzers are affected as follows. Even if the howitzers are not deployed to a previously surveyed position, their INS will operate by using ZUPT and/or odometer aiding, by intervals of short stops, INS systems onboard self propelled howitzers can maintain their accuracy level of order 10's of meters and they are not severely affected from Jamming.

However UAV's, whether they are tactical or long endurance type, will use their self positioning accuracy rapidly and the error growth will reach to almost 1 nautical mile within one hour in free inertial mode, In such a situation, target coordinates that are found by the UAV will be erroneous and the artillery fire upon the target will have no effect on the target. Fire correction techniques may be employed but the effect of surprise is already lost.

On the target engagement side, weapon releasing platforms such as fighters perform transfer alignment operations to the missiles under their pylons. However the navigation grade 1 nm/hr high accuracy INS onboard the fighter aircraft will have an error of nearly 1 km's before getting into position to release its ordnance. The transfer alignment operation will cause wrong position and angle information to be used in transfer alignment process to the lesser quality IMU. Starting with erroneous initial conditions, inertial-only operation of the air to ground strike missile will lead an unsuccessful engagement. Even launching a SSM with better initial conditions (since the launcher is land based), the inertial navigation system of a missile will not be able to achieve the required error budget for the seeker to lock on the target or the effective range will be much less.

1.6.2 The Requirement

Since there are several types of missiles with different missions and ranges, it is necessary to limit the discussion to air to ground, (AGM) or surface to surface (SSM) missiles, unmanned aerial vehicles and guided projectiles with tactical ranges. Today most missiles use inertial navigation systems (INS) or inertial measurement units (IMU) for determining at least the missile's/seeker's attitude, position and heading. By using transfer alignment techniques the initial position of the missile and its attitude is transferred to the missile before launch by the host platform. Regarding tactical missiles, the inertial navigation systems onboard these missiles are low, medium tactical grade inertial sensors. As an example, GBU-29/31 JDAM uses HG-1700 ring laser IMU. RGM-84 Harpoon Block II also utilizes the IMU/GPS system featuring HG-1700 Ring laser IMU. (1 deg/hr, 1mg) The driving factors are cost and availability. Most gyros used in missiles are Ring Laser (longer range, better accuracy) or MEMS (low cost) systems (Honeywell [5][6]). Due to the fact that, a missile's primary aim is to hit its target accurately, missiles success depends on inertial navigation system and any external aids.

Inertial navigation systems have a major drawback. Their error grows up with time and the error growth becomes exponential as time goes by, if no external aiding is provided. GPS is the most common aid used in almost all military systems. Ships employ EM logs (measures speed of ship relative to water), ground vehicles employ ZUPT (zero velocity update) technique and employ odometer (vehicle speed sensor). Aircraft employ barometer aiding to stabilize the otherwise unbounded height channel.

Since it is not possible to employ very high grade inertial sensors on missiles, they are backed with several aids. Missiles use GPS for INS aiding. Some very sophisticated cruise missiles employ TERCOM or DSMAC systems. The former system tries to match the profile of terrain with a previously loaded map and the latter tries to match a scene with the map. This solution is not widely used and can be seen in limited number of missiles such as BGM-109 Tomahawk. TERCOM techniques require careful planning of missile route, preloading of terrain maps to the weapon before launch and have problems when the terrain does not have distinctive features or a very sophisticated terrain is in concern.

Most missile systems have to rely on GPS/INS systems for midcourse guidance phase. Inertial navigation systems are selected to maintain accuracy for a short period of time when the missile is closing to its intended target. It is assumed that (for U.S.) GPS jamming may be performed by a network of small jammers which are hard to find and destroy. Other jammers with large area coverage are assumed to be detected by ESM systems and can be destroyed by air strike of HOJ capable missiles.

However this concept is not suitable for other countries that do not have their own GNSS system. The primary reasons are

- Enemy can jam GPS in both tactical field and theater battlefield.
- Destruction of large mobile jammers mounted on trucks or air vehicles may not be an easy task, regarding the problems that US forces has faced when going after mobile scud launchers (TEL) in Iraq. Air Force has to deal with enemy air force, attack military and industrial critical targets, provide air defense umbrella to land and naval forces. Among all, assigning aircraft to destroy jammers will probably will not be possible.
- Properly deployed small jammers can cover a large area and degrade accuracy of smart weapons. Destruction of these jammers is virtually impossible or very hard.
- The new techniques and the NAVWAR concept that the US is employing for the GPS system may lead to the following result in case of a crisis. Two GPS customers one having a special key and the other does not, one will be benefiting from GPS and the other could not decode signals

NATO studies [7], [8] classify possible promising antijam improvement strategies external to GPS receiver as

- Improve INS accuracy: requires time and new research.
- Increase GPS power levels: 20 dB increase in power levels. Still jammable.

- Use pseudolites: ground based constellation to provide terminal guidance.
- Use additional sensors such as terrain profile matching as used in BGM-109 Tomahawk cruise missile.

A new technique and method to improve the performance of missiles and aerial vehicles when GPS is unavailable is necessary. If the performance of the inertial navigation systems can be improved by an external aiding, which is not subject to RF jamming, the effects of GPS jamming can be softened and GPS independent operation capability can be gained.

1.7 Alternative Navigation System Candidates for GNSS Denied Environments

During the search for navigation techniques that can be used as alternative navigation methods to GNSS, it is important to note that, "There is no alternative system that can provide the unique special characteristics of GNSS systems such as accuracy and global coverage." If there was an alternative with the same capabilities, "the state of the art", would have utilized that technology. GNSS systems offer unprecedented precision independent of time, everywhere on the world (except confined environments such as under surface), with minimal cost to user with an extensive ground and space segment infrastructure.

All systems and techniques that can be offered as an alternative to GNSS shall provide navigation capability within several limitations when GNSS systems can not be used. None of the alternative systems can provide a better solution to the navigation problem unless the inertial navigation systems' accuracy reaches 1000 times better than the current state, accompanied with a significant decrease in cost and an unrestricted proliferation.

There are several navigation methods that can be offered to be used to minimize the effects of non-availability of GPS in case of jamming. Some of these suggestions are ineffective, useless or not cost-effective but shown here to emphasize their ineffectiveness. Some of the alternative navigation techniques are possible but requires effort, time and funding.

Establishing own GNSS system:

A first solution that comes into mind is to establish own GNSS system. However except from the system control point of view, all threats to GNSS systems are thoroughly valid. The system can be jammed easily. Establishing and maintaining the continuity of the infrastructure is very expensive, requires mature establishments in space technology. The current state of the global navigation satellite systems and their characteristics were given in Table 1-1.

Establishing own regional navigation satellite system. (RNSS):

Due to the tremendous cost of GNSS establishment, some countries have also developed regional navigation satellite systems for navigation in the vicinity of their homeland. One way to establish a regional satellite system is to place satellites to geostationary orbit (around 36000 km). The number of satellites can be three or four. The drawback of this system is even higher altitude of the satellites makes the signal weaker than the GNSS systems and, as a result jamming is still a possible and a significant threat.

DGPS network:

Offering DGPS as an alternative to GPS jamming is useless since DGPS requires GPS to operate. When GPS is jammed DGPS does not work. In the interference event in 2007, San Diego DGPS station became in-operational during GPS outage (Benshoof [4]).

New GNSS receivers which are compatible with various GNSS systems:

These GPS/GALILEO/GLONASS receivers may provide better performance in areas where satellite reception is poor, by using more satellites and decreasing the possibility of GNSS reception loss. However using these receivers is not a viable solution candidate since all GNSS systems are subject to jamming.

Ground based navigation systems:

Ground based navigation systems can also be utilized for an alternative to GNSS. There are existing structures and establishing new infrastructures is possible.

DME/TACAN systems:

DME systems operation principle dictates that the DME station should be interrogated from the air vehicle. This causes the air vehicle to send transmissions which can be intercepted by opposing force EW assets. Also DME/TACAN interrogation requires equipment in the air vehicle, which most UAV's and missiles do not already have this equipment. DME/TACAN interrogation requires high power transmission which may be a problem for smart weapons and missiles.

VOR system:

A system similar to VOR may provide an angle only position fixing aid.

Hyperbolic Navigation Systems:

Hyperbolic navigation systems such as LORAN can be considered as a backup navigation aid. However, in Turkey there is no active LORAN station. LORAN stations are being shut down in many countries. The time to first fix of a LORAN system is around two to four minutes and achievable accuracies are around 400 meters to 2 nautical miles which may cause problems in some employment scenarios. The number of LORAN base stations (with high antennas of ~200 meters) will be limited and may be regarded as a target by opposing forces.

Terrain Aided Navigation:

Terrain aided navigation techniques such as TERCOM and SITAN are used mainly in cruise missiles. TAN methods require radar altimeter, barometric altimeter, a map with terrain elevation data, and a flight computer that employs TAN algorithms.

Terrain contour matching is a very good method for long range cruise missiles when they are operating without GPS. Actually TERCOM was first devised in

1958 and implementation on cruise missiles was around 1970's when GPS was not available.

TERCOM is also a strong candidate for navigation when GPS is jammed but as all alternative methods to GPS, it has its own limitations. First of all TERCOM and its derivative methods require elevation and coordinate correlated maps of terrain for several locations throughout the flight. These maps should be relatively new in order not to collide with any man made surface feature in nap of earth (NOE) flight.

All the way through the target should be known and elevation data should be available. Entire route of the missile should be planned.

TERCOM efficiency in low altitude flight is high but at higher altitudes, some problems may arise. Radar altimeter accuracy decreases as height AGL (above ground level) increases. Most radar altimeters in civil aviation are limited to 2500 ft altitude. A military radar altimeter height limit is 8000 ft with an accuracy of % 2, which leads to 160 feet at maximum operating altitude. This may cause erroneous readings of altimeter may degrade TERCOM accuracy.

Another drawback of TERCOM systems is the lack of flexibility. TERCOM equipped weapons require serious planning before mission and their ability to be fired from unplanned or unexpected locations is low.

The classical TERCOM navigation method leads to very large errors when flying on smooth terrain, which leads to the loss of the weapon.

Improved methods can take into account the dynamics of the missile but this makes the method, platform specific. TERCOM is not a widely used navigation method. It is mainly employed on very long range cruise missiles, due to the complexity of the planning phase.

The performance also decreases when terrain elevation profiles are not near unique, which means that the path should be planned to allow maximum difference between several possible tracks so that the missile can distinguish between the possible tracks and obtain a good position fix. Roughness and uniqueness of the planned path is a key factor in TERCOM accuracy.

The number of correlation calculations obviously increases as the quality of the INS decreases, which leads to more computation power.

In his Ph.D. work about terrain aided navigation for cruise missiles, Ekütekin [9], analyzed the terrain effects on several TAN methods. TERCOM results lead to very large errors even with a 1 nm/hr navigation grade INS for smooth / non-unique terrain.. Other TAN methods reach better results but uniqueness and roughness of terrain is still a significant issue. Several cases of false position fixes are also encountered.

Most weapons are equipped with seekers but not all weapons have radar altimeters.

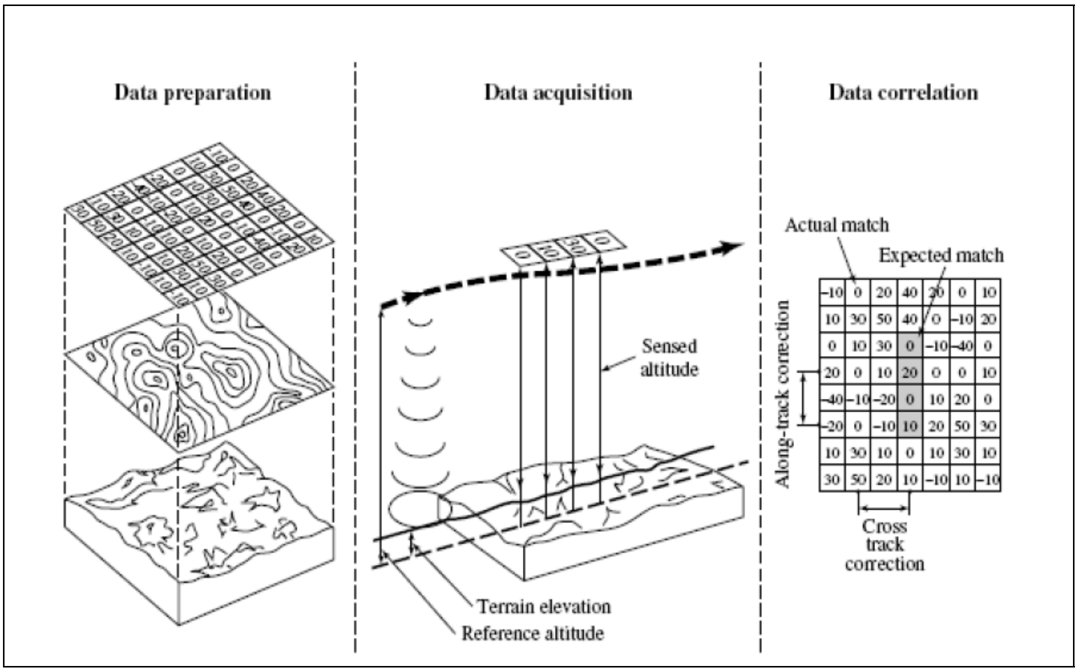


Figure 1-6 TERCOM basics (Siouris [10])

1.8 The Proposed Method

In this thesis, a method is proposed to preserve and improve the performance of inertial navigation systems onboard the smart weapons and unmanned aerial vehicles. Previously deployed ground based beacons are used to update position of the inertial navigation systems onboard missiles and autonomous air vehicles which are equipped with EO/IIR seekers, by the use of position fix algorithms based on modified artillery survey position fixing methods which involve angle measurements only. The updated positions are then used to correct the inertial navigation system to be used by the Kalman Filter of the platform during the flight. Several position fix algorithms are employed to achieve best performance.

Traditionally, beacon navigation methods has been used as navigation aids to manned aircraft and not used for weapons systems. These ground based navigation aids are currently being phased out of service with the increasing use of GNSS systems in final approach phase of manned aircraft.

For mission planning, two main problems are identified as deployment problem and path planning problem and a tool for the optimal laying of beacons for a given desired trajectory and optimal path planning for a given network of beacons is developed by using evolutionary algorithms and results for test scenarios are discussed.

Alternative methods for GNSS jamming scenario and the proposed method are given in Table 1-2.

Table 1-2 Several navigation techniques and their comparison

Navigation technique	Jamming resistance	Global /regional	Impact on covertness of platform	Weather conditions effect	Operational status when GNSS is jammed	Typical accuracy	Usability for missiles
GNSS	Poor	Global	No effect	Negligible	No	< 10 meters	Yes
Own GNSS	Poor	Global	No effect	Negligible	No	< 10 meters	Yes
Geo-stationary NSS	Very poor	Regional	No effect, if receiver transmit signals may be effective	Negligible	No	< 10 meters	Yes
DGPS network	Does not work if GPS is jammed	Regional	No effect	Negligible	No	< 1 m	Yes
Multi-GNSS receivers	Poor	Global	No effect	Negligible	No	< 10 meters	Yes
DME/ TACAN	Good	Regional	Platform is active	Negligible	Yes	~500 meter	Requires additional hardware
VOR	Medium	Regional	Platform is passive	Neglibile	Yes	1.5 -4 degrees azimuth,	Requires additional hardware
Hyperbolic Navigation	High	Regional	Platform is passive	Negligible	Yes	0.25-1 nm	Requires additional hardware Accuracy and TTFF may be problematic
Stellar navigation	High	Global	Platform is passive	Heavy, clear sky necessary, not good for flight below cloud level	Yes	0.2-1 nm typical	Requires additional hardware
TAN/ TERCOM	High	Regional	Radar altimeter active	Negligible	Yes	Dep on terrain uniquness	Radar altimeter necessary
Gruond Based Beacon navigation system	High	Regional	Platform is passive	Visibility dependent	Yes	Dep. on deployment scheme	No additional hardware requirement

1.8.1 Reasoning Behind Beacon Navigation Techniques

1.8.1.1 Benefits of Beacon Network

The network of beacons can serve a wide variety of systems independent of platform. Network of beacons can serve multiple different kinds of air vehicles in both friendly and hostile territory.

Beacon navigation concept can be applied to all systems with optical /IIR seekers. From missiles to guided munitions, tactical and MALE UAV's that are equipped with seekers/cameras/FLIR's can benefit from the beacon network.

Each beacon is composed of a battery as a power source, a solar panel to charge the battery which provides the beacon to be operated within prolonged times, a radio receiver which activates the beacon emission when triggered, and IR source (or laser source and a deflector) which generates IR emissions.

The beacon network can be constructed in a region or country wide to allow for operations inside homeland and may provide operation capability in a theater GPS jamming scenario. A typical example of this is UAV surveillance operations inside country's borders.

Once the beacon network is deployed, intercepting beacon emissions, detecting their coordinates and destroying them will require a significant effort to be sacrificed by enemy. Even if some of the beacons are detected, destruction will require artillery, air assets or land forces which is not likely to be employed easily in friendly territory without resistance. For beacons deployed in hostile territory, it is still an effort to find and destroy small sized beacons, noticing that the enemies firing accuracy will also degrade due to GPS jamming. Among all other threats, can the necessary resources be allocated to engage a group of small beacons which are hard to find and hard to destroy? The same question has arisen when dealing with a network of small GPS jammers that cover a region and the answer is the same.

1.8.1.2 Selection of Beacon Types

The proposed beacon navigation technique requires a selection of position fixing methods. As explained earlier, position fixing methods may be based on angle measurements, distance measurements or a combination of both. Either trilateration method which relies on measuring distances or triangulation methods are to be employed based on the beacon capabilities and specifications.

The choice of triangulation or trilateration techniques is also dependent upon the medium of operation. For an unmanned surface vehicle (USuV) patrolling around own naval base, distance measurements to known beacons is feasible. Obtaining position fixes just by measuring angles is also a feasible alternative. For an unmanned underwater vehicle (UUV) patrolling the same base submerged, against intruder diver assault, the position of the UUV can be found by trilateration to 3 ultrasonic signal emitting beacons. In that case, triangulation techniques based on observing optical beacons is useless since visibility is near zero in underwater operations. RF signals can not be used for trilateration since their propagation is very limited underwater. Sonar signals and trilateration remains as the only alternative.

For the primary case investigated in this thesis as the navigation of a missile and UAV in the air, it is possible to select RF emitting beacons with distance or angle measurements for position fixing or optical beacons with triangulation method (angle measurement only).

It is possible to use

- RF signal emitting beacons such as VOR beacons
- Optical beacons which radiate in IR or visible spectrum.
- Hypothetical Diffuse laser beacon in 1064 nm wavelength.

The term hypothetical stands for the laser beacon as the first two types have examples in real world for different purposes, but based on the literature survey results, that kind of a beacon is not found but theoretically possible if the power requirements does not exceed mobile operation and solar charging abilities.

Optical light emitting beacons are selected as a first candidate for beacon network. The reasoning behind this selection can be summarized as follows:

Most missiles and UAV’s have readily available cameras/seekers/FLIR systems to engage optical beacons. There is no necessity for an additional RF receiver. No additional sensor is required.

RF signal emitting beacons may be intercepted by enemy ESM systems. Most of the ESM systems deployed today are designed to intercept RF communications, RF radar emissions etc. So the probability of intercepting an RF beacon’s emissions is far higher than an optical beacon. RF intercepting ESM systems have long ranges and widely deployed when compared with optical/laser detecting systems. The chance of an optical beacon to be seen by an enemy EW asset or an enemy recon unit is possible only when it passes nearby the beacon, comes into line of sight, and is already searching for it.

When RF emitting beacons are used, the measurement method will shift from triangulation to trilateration. Receiving signals from multiple beacons requires a unique coding of each beacon transmission and the missile or UAV has to solve each code which brings complexity to the missile computer.

Another issue with the position update problem is that when optical beacons are used, it is possible to obtain a position update by using reverse intersection method by observing only one beacon. Comparison of the three beacon types are given in Table 1-3.

Table 1-3 Comparison of candidate beacon types

TYPE	Optical Beacon	RF Emitting Beacon	Diffuse Laser Beacon
Emission	IR band -optical	Radio frequency	1064 nm laser
LOS requirement	Yes	Yes	Yes
Method of position fix	Angle measurment only	Trilateration or triangulation based on emission type	Triangulation
Jamming resistance	High.	Low.	Medium.
Covertness	High.	Low.	Medium.
Detection possibility by opposing force	IR or visual search specific to the beacon is required. Low probability of intercept.	Most ESM systems operate on RF band. Widely used in operation areas. Long detection ranges possible with ESM.	IR or laser spot tracker search specific to the beacon is required. Low probability of intercept.
Counter measure	No.	RF jamming.	No.
Weather conditions	Visibility dependent.	All weather.	Visibility dependent.
Emmission	IR band.	RF.	Diffuse laser.
Additional hardware in missile/UAV	No	Yes, similar to VOR receiver	No- only for laser guided weapons.
Additional software in missile/UAV	Simple position fix algorithms.	Additional decoding algorithms necessary.	Simple position fix algorithms.

1.8.1.3 Operation Doctrine

Each platform is to be informed with a file of beacon locations, and a much more computation friendly position fix algorithm is to be implemented to the missile computer when compared with SLAM or TAN algorithms.

As an option, in order to preserve energy of beacons and in favor of covert operations, when the missile or UAV gets near a beacon, it can trigger the sleeping beacons to wake up and start emitting, by a short pulse of RF command. Beacons can then go to standby mode after some time or after a new trigger. This very short pulse of wake up signal is believed to be very hard to intercept.

A drawback of a beacon network is that the deployment may require a joint operation between multiple force branches. Missiles and UAV's are operated by Air force and Army, deployment of beacons may require special operation forces, and the planning may be involved with General Command of Mapping. However, considering the other scenario of serious degradation in operational capability, this price may be accepted, especially since successful joint operations are believed to be the key to warfighting success since WWII.

1.8.1.4 Who Can Benefit From Beacon Network

Systems and units who can benefit from the proposed approach can be summarized as follows,

1- <u>Cruise missiles that are fired from ground based launchers or air platforms from deep theater inside own country</u>.

Calibration of INS while it is flying at friendly environment may lead to improved performance in hostile environment. This approach may lead to the use of lower quality and cheaper sensors onboard these weapons. One of the main contributions of the thesis will be to demonstrate that the same mission can be accomplished by using lower grade inertial sensors and an array of beacons.

2- Smart weapons

Smart weapons with typical ranges around 40-90 km that operate EO/IIR sensors can benefit from the proposed method. Use of these weapons in tactical battle area may be vast and an array of beacons can be used to improve performance of multiple smart weapons deployed at the same time on an attack campaign performed in a predetermined battle area.

3- Unmanned vehicles

Unmanned vehicles operating in own country's border area for surveillance missions can update their navigation systems. One further capability of UAV's is that they can use laser range finders for position updates.

1.8.2 Possible Extensions of the Proposed Method

The proposed method is defined in order to provide a means to maintain operation capability of autonomous air vehicles such as UAV's cruise missiles, smart weapons etc. In this thesis, the position fix algorithms are selected as angle only measurements and RF emission of beacons is not considered regarding covertness of the beacons.

Due to the medium of the operation area and dictating requirements of several factors, trilateration techniques which are based on distance measurements and RF emitting beacons can also be considered. In that case, position fix algorithms will be different. Mission planning and optimization considerations will be different. One example may be the coverage area of the beacon since RF emitting beacons will have longer ranges when compared with optical beacons.

The beacon navigation concept is intended to be deployed on ground and to provide a navigation aid for air assets in its primary role. There may be several extensions and applications of this method for different scenarios.

Unmanned land vehicles can operate by using this method when patrolling around a base in a GPS jamming environment.

One concept may be the use of shore based beacons for position fixing of unmanned surface vehicles patrolling to provide cover at a naval base internal waters. So for short range tactical unmanned surface vehicles this technique may provide sustained operation of USV's.

For an unmanned underwater vehicle (UUV) patrolling the same base submerged, against intruder diver assault, triangulation techniques based on observing optical beacons is useless since visibility is near zero in underwater operations. In that case, the position of the UUV can be found by trilateration to 3 ultrasonic signal emitting beacons. This method's usage may be restricted for littoral waters only.

For submarine navigation and navigation of UUV's around submarines, beacon navigation method with active beacons is not suitable since emission of ultrasonic signals and their reflections from UUV's and submarine may cause the overall system to reveal their positions to enemy.

Further applications include manned air vehicles and helicopters when GPS is not available but this is a secondary task since manned air platforms have the ability to use classical radio navigation systems.

1.9 The Structure of the Thesis

The thesis consists of three main parts as shown in Figure 1-7.

For a smart weapon of an unmanned aerial platform which employs an inertial navigation system (INS) and an EO/IIR seeker,

1. Designing an algorithm to find the position and azimuth of the missile system by observations from one or multiple beacons, and obtain a position update by using triangulation algorithms based on artillery survey techniques
2. Using the obtained position updates, and erroneous INS data, correcting the position and azimuth of the missile and bound errors by the help of position updates, and provide an in-flight calibration of INS by using ground beacons. Showing that the same mission can be accomplished by a lower

cost inertial sensor which can be backed with ground stations (beacons), than a higher grade navigation system.

3. The third base of the tripod is the development of a tool for deciding how to deploy beacons in terms of distance, geometry by using the results from INS improvement amounts, and form a mission planner for different scenarios which solves

    - The deployment problem for a desired trajectory given from a higher echelon decision system, which minimizes the terminal phase error of the platform while bounding the deviations from the desired reference trajectory.
    - The path planning problem for a given network of previously deployed beacons to achieve best terminal phase errors (Figure 1-8).

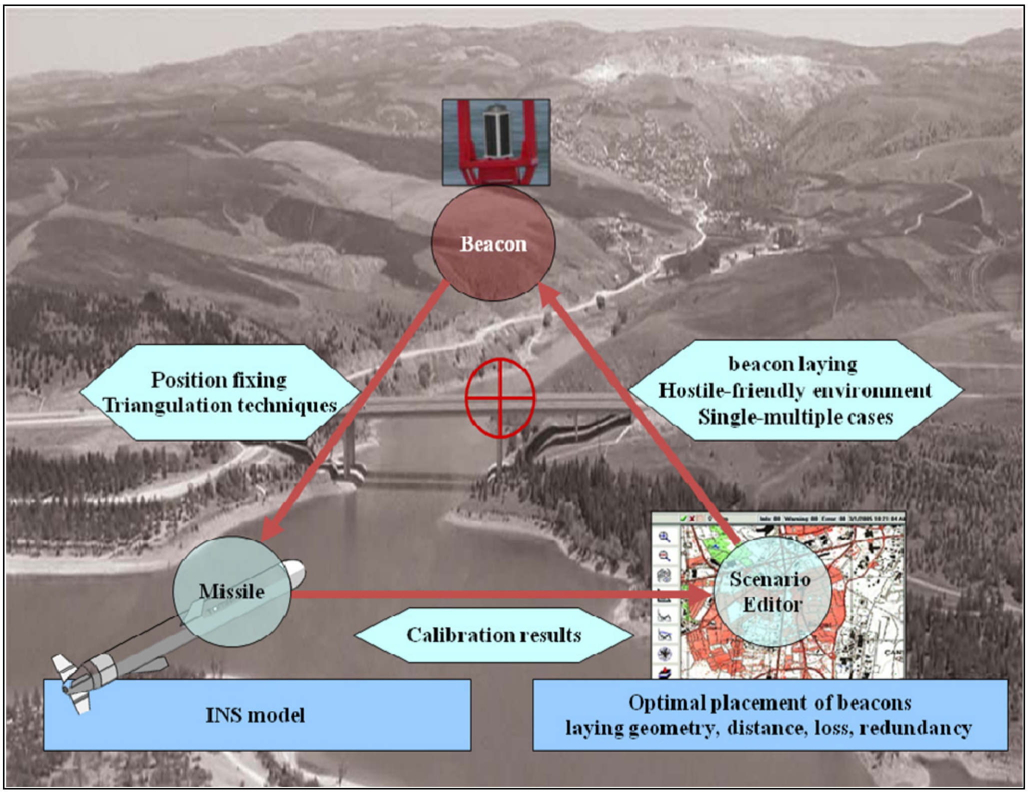


Figure 1-7 Thesis structure

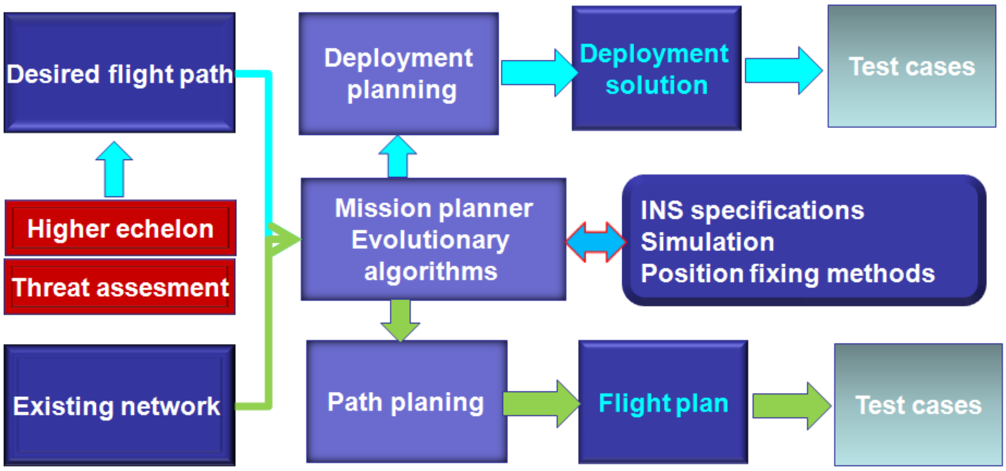


Figure 1-8 Mission planner structure.

1.10 Expected Contributions of the Thesis

This thesis will investigate the success of ground based beacon aided navigation for missiles/UAV's and guided projectiles, positioning techniques for a high speed weapon, and optimal placement of beacons for desired navigation performance.

In this thesis, position fixes obtained from ground beacons by using modified artillery survey (position and azimuth finding) methods will be used to update position of the missile and to calibrate the inertial navigation system onboard the missile. By this way performance of the missile will be preserved in case of GPS jamming. Also a tool that will be used to analyze the beacon placement geometry, placement intervals will be developed and used for scenarios based on missile launch in both hostile and friendly environments.

The contributions of the proposed thesis to the navigation and missile technology area will be summarized as follows.

1- A new method is proposed to improve performance of INS systems onboard missiles in electronic warfare environment especially in GPS jamming by use of beacon navigation.

This thesis proposes a method for missiles and guided projectiles equipped with INS/GPS systems and seekers, which gives them a chance to be able to operate in case of GPS jamming. Existing INS's onboard missiles are capable of maintaining accuracy for very limited time of flight in case of GPS jamming. Other options include TERCOM for INS aiding but this complicates the weapon and mostly seen in cruise missiles. The network of beacons and beacon navigation technique can be a candidate to continue using of multiple tactical smart weapons and missiles in battle area, in case of GPS jamming.

<u>2- Investigation and demonstration of the fact that lower cost sensors can perform equally well then a higher grade inertial sensor by the help of beacon navigation and in-flight calibration techniques.</u>

One of the main contributions of the thesis will be showing that the same mission can be accomplished by the use of lower grade inertial sensors and a network of beacons. If the results of the in-flight calibration of the missile INS prove to be acceptable, lower cost sensors can be used onboard missiles or higher performance can be achieved by the same sensor for a specified mission.

<u>3- Development of a tool for the analysis of beacon deployment patterns, intervals, induced uncertainties and for obtaining solutions based on desired performance, given specifications of missile inertial navigation system, redundancy and robustness issues.</u>

When the usage doctrine is investigated, any weapon or missile is launched at an offset distance from the front line of the battle area. Howitzers fire around 10-20 km's behind the start of friendly territory. Cruise missile launchers are not risked and they are fired at deep positions inside friendly territory, unless they are deployed from a submarine. It is obvious that most of the weapons will spend some time in friendly territory in which beacon placement is easy and positioning errors is almost negligible. Even the in-flight calibration of the missile while it is flying in friendly territory may provide better performance. When the missile passes the border zone and continues its flight at hostile territory, it will use beacons that are deployed by Special Forces or forward observers. In this case beacon numbers may decrease, positioning uncertainties may increase. The tool will provide the analysis of these situations and will answer the questions about beacon deployment patterns, namely what must be the distance and placement geometry of beacons to achieve a specified performance regarding several uncertainty sources, redundancy and robustness issues for a given specification of missile inertial navigation system. The tool for scenario planning is one of the major contributions of this thesis.

4- Application of artillery positioning methods, and triangulation methods for a high speed platform (missile or guided projectile): Applications of triangulation methods for position finding are used in robotics research and positioning at land but their applications are mostly limited with low speed, or stationary robots or land vehicles that have the ability to stop and perform static positioning by the help of these positioning methods. In this thesis positioning methods will be applied to a high speed platform.

In position finding by triangulation approach, the amounts and sources of uncertainty will be much higher than surveying, in which very accurate reference positions are available, and robotics, in which positioning is possible by using cooperative beacon-robot interaction with no constraints on robot or the beacon. Their applications are mostly limited to the areas as big as an industrial plants confined area. In this thesis the distances will be in the order of ten to hundreds of kilometers.

Effects of position updates on INS performance will be shown and In-flight inertial sensor calibration will be performed. By this way one of the major contributions of the thesis will be showing that the INS can perform better in case of GPS jamming by the help of beacons and a better inertial system can be achieved. This improved system can perform better than its original form even though the beacons are laid at a part of its trajectory.

As a summary some of the main contributions of the thesis can be classified as follows;

- To provide a technique for navigation of the missiles in order to be used under GPS jamming.
- Showing that that lower grade /lower cost sensors can be used instead of higher grade sensors by the help of proposed method.
- Development of a tool for mission planning for two main classes of optimality problems. Deployment problem for given desired trajectory and path planning problem for given network of beacons.
- Use of artillery positioning algorithms for missiles.
- High speed platform (missile) is the area of concern rather than stationary systems.

1.11 Outline of the Thesis

In chapter-1, a general classification of various navigation methodologies are given, drawbacks of INS/GNSS systems are presented and an approach for an alternative navigation scheme for air assets such as smart munitions, missiles or UAV's, by the use of ground based beacon network and angle measurement based position fixing algorithms, in case of a theater or country-wide GNSS jamming scenario is presented. The proposed solution, namely "Ground based beacon navigation concept" is introduced, reasoning behind beacon navigation, benefits of beacon network, beacon type selection, operation doctrine and possible extensions of the method to various mediums are given.

In chapter-2 information about inertial navigation system modeling, Kalman filtering and inertial sensor errors is given. Derivation of error equations in navigation frame is performed. State space equations for an indirect feedback Kalman filter is given.

In chapter-3 position fixing methods such as triangulation and trilateration methods are introduced, analysis is focused on triangulation techniques and their implementation to missile systems. A modified form of intersection for use in the thesis -reverse intersection- is introduced. Two point resection and three point resection methods and their solution techniques are given. A performance metric that relates the measurements with the states is selected as DOP and derivations of DOP for reverse intersection, two point resection and three point resection are presented.

In Chapter-4 optimal mission planning work is introduced. Two problems are defined related with the beacon navigation concept as “path planning problem” where an optimal trajectory for an air vehicle is sought for a given scheme of previously deployed beacons under FOV, FOR, range, position fix quality constraints and “deployment problem” where an optimal deployment scheme of beacons is sought for a given reference trajectory which minimizes the terminal phase error while not violating the midcourse deviation from the reference trajectory. Evolutionary algorithms class is selected for dealing with optimization problems and a variable length chromosome genetic algorithm is constructed. Details of the genetic algorithm structure are given.

Chapter-5 gives information about the modeling and simulation structure, where detection range calculations for IR and a hypothetical laser beacon is performed taking into account missile seeker parameters. A MEMS IMU’s typical error characteristics are taken into account for accelerometer and gyro data generation. A reference trajectory for the deployment problem is defined taking into account various phases of flight. The implementation and decision maker structure for the three used position fix algorithms is introduced.

Chapter-6 gives case studies and obtained results for several test cases for the deployment and path planning problems. Genetic algorithm results along with best of generation improvements, corresponding trajectories and fitness values are presented. Several case studies with different objective functions and constrains such as FOV, FOR, method specific constraints are studied. Findings about the optimization results are given. Chapter-7 summarizes the overall work done, and obtained contributions and recommendations for future work is given.

CHAPTER II

INERTIAL NAVIGATION SYSTEM MODEL

2.1 Introduction

In this chapter inertial navigation system error equations are derived. Primary inertial sensor error sources are narrated. Brief information about Kalman filtering is given and corresponding equations for a Kalman filter is derived.

2.2 Reference Frames

For navigation over the earth, it is necessary to define axis sets which allow the inertial measurements to be related to the cardinal directions of the Earth. There are a number of Cartesian coordinate reference frames which are used widely in aerospace applications. Each of them is an orthogonal right handed co-ordinate frame or axis set. Several widely used frames are as follows (Titterton [11]):

The inertial frame: (i-frame) has its origin at the center of the Earth and axes which are non-rotating with respect to some fixed stars, defined by the axes x_i, y_i, z_i with z_i coincident with the Earth's polar axis (which is assumed to be invariant in direction)(Figure 2-1).

The Earth frame: (e-frame) Earth fixed coordinate frame used for position location definition. ,has its origin at the center of the Earth and axes which are fixed with respect to the Earth, defined by the x_e, y_e, z_e with z_e along the Earth's polar axis. The axis x_e lies along the intersection of the plane of the Greenwich meridian with the Earth's equatorial plane. The Earth frame rotates, with respect to the inertial frame at a rate Ω about the axis z_i (Figure 2-1).

The navigation frame: (n-frame) is a local geographical frame which has its origin at the location of the navigation system, and axes aligned with the directions of north (N), east (E) and the local vertical (D) (Figure 2-1). The x-axis (therefore y-axis) can also be defined with a known deviation from the north direction (wander-azimuth frame).

This frame has its origin at the location of the navigation. The turn rate of the navigation frame with respect to the Earth fixed frame is governed by the motion of the navigation system. This turn rate is often referred to as the "transport rate" and denoted as $w_{n/e}$.

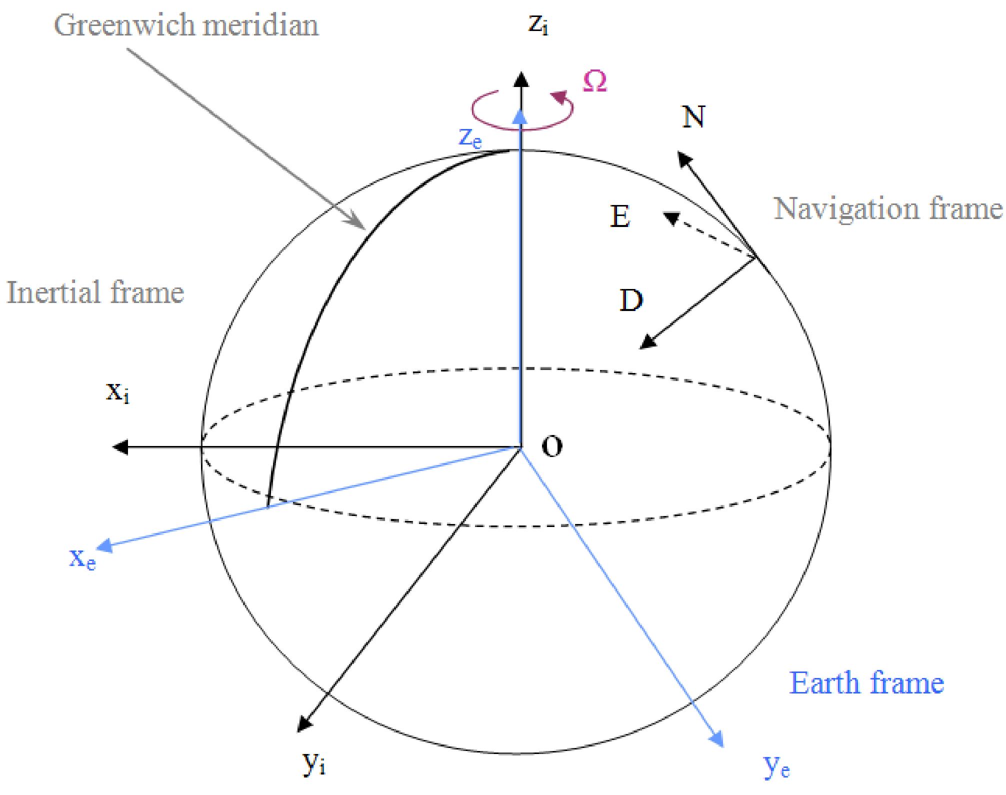


Figure 2-1 Reference frames

The body frame: (b-frame)

Strapdown inertial sensor coordinates with axes parallel to nominal right handed orthogonal sensor input axes. After the INS's boresighting to the iaircraft, it is aligned with the roll, pitch and yaw axes of a moving rigid body. The center of the axis system is, by definition, located at the center of mass (CM) of the body. The frame is fixed to the moving body and rotates with it. The axes definitions are as follows

- x-axis positive from stern to nose when looked from top of the moving object.
- y-axis from left to right when looked from the top and positive in the direction of right wing.
- z-axis downward positive when seen from starboard or port.

2.3 Navigation Equations

The navigation equations can be derived by starting from the Newton's second law. (Nalbantoğlu [12], Titterton [13], Savage [14])

$$\vec{F} + m\vec{g} = m\vec{a} \tag{2.1}$$

$$a = \left.\frac{d^2\vec{R}}{dt^2}\right|_i = \vec{f} + \vec{g} \tag{2.2}$$

Where f is the specific force which accelerometers measure, g is the gravity vector.

The velocity of the missile or any platform with respect to the rotating earth reference frame is

$$\vec{V}_e = \left.\frac{d\vec{R}}{dt}\right|_e = \left.\frac{d\vec{R}}{dt}\right|_i - w_{e/i} \times \vec{R} \tag{2.3}$$

$$\left.\frac{dV_e}{dt}\right|_i = \left.\frac{d^2\vec{R}}{dt^2}\right|_i - \left.\frac{d}{dt}[w_{e/i} \times \vec{R}]\right|_i \tag{2.4}$$

$$\left.\frac{d\vec{V}_e}{dt}\right|_i = \left.\frac{d^2\vec{R}}{dt^2}\right|_i - \left.\frac{d\vec{w}_{e/i}}{dt}\right|_i \times \vec{R} - w_{e/i} \times \left.\frac{d\vec{R}}{dt}\right|_i \tag{2.5}$$

Since the rotation of the earth can be assumed constant for navigation purposes, the second term drops. The third term can be written as $\left.\frac{d\vec{R}}{dt}\right|_i = \left.\frac{d\vec{R}}{dt}\right|_e + w_{e/i} \times \vec{R}$

$$\left.\frac{d\vec{V}_e}{dt}\right|_i = \left.\frac{d^2\vec{R}}{dt^2}\right|_i - w_{e/i} \times \left[\left.\frac{d\vec{R}}{dt}\right|_e + w_{e/i} \times \vec{R} \right] \tag{2.6}$$

Since $\left.\frac{d^2\vec{R}}{dt^2}\right|_I = \vec{f} + \vec{g}$

$$\left.\frac{d\vec{V}_e}{dt}\right|_i = \vec{f} + \vec{g} - w_{e/i} \times w_{e/i} x\vec{R} - w_{e/i} \times \vec{V}_e \tag{2.7}$$

Where the third term is the centripetal acceleration and the fourth term is the coriolis acceleration. Equation (2.7) is the <u>inertial frame mechanization</u>.

For <u>earth frame mechanization</u> it is necessary to express the rate of change of Ve with respect to earth axis.

$$\left.\frac{d\vec{V}_e}{dt}\right|_i = \left.\frac{d\vec{V}_e}{dt}\right|_e + \vec{w}_{e/i} \times \vec{V}_e \tag{2.8}$$

Substituting $\left.\frac{d\vec{V}_e}{dt}\right|_i$ from (2.7) to (2.8),

$$\left.\frac{d\vec{V}_e}{dt}\right|_e = \vec{f} + \vec{g} - w_{e/i} \times w_{e/i} x\vec{R} - 2w_{e/i} \times \vec{V}_e \tag{2.9}$$

Since in the navigation algorithm, the velocity will be obtained by integral of acceleration vector which is expressed in navigation coordinates, it is desired to obtain an expression of time derivative of velocity with respect to navigation frame. For <u>navigation frame mechanization</u> we need $\left.\frac{d\vec{V}_e}{dt}\right|_n$

$w_{n/e}$ is the angular rate between the n frame and e frame (called transport rate) Transport rate is a function of vehicle velocity and latitude.

$$\left.\frac{d\vec{V}_e}{dt}\right|_n = \left.\frac{d\vec{V}_e}{dt}\right|_e - w_{n/e} \times \vec{V}_e \tag{2.10}$$

Putting RHS of equation (2.9) into (2.10) one obtains the equation for the derivative with respect to navigation frame of velocity of vehicle relative to the earth.

$$\left.\frac{d\vec{V}_e}{dt}\right|_n = \vec{f} + \vec{g} - w_{e/i} \times w_{e/i} \times \vec{R} - 2w_{e/i} \times \vec{V}_e - w_{n/e} \times \vec{V}_e \tag{2.11}$$

Equation (2.11) is not written in any frame yet. We can express the equation in navigation frame.

The gravity is vertical to the local surface of the ellipsoid and denoted as

$$\vec{g}_l = \vec{g} - w_{e/i} \times w_{e/i} \times \vec{R} \tag{2.12}$$

So the equation becomes

$$\left.\frac{d\vec{V}_e}{dt}\right|_n = \vec{f} + \vec{g}_l - 2w_{e/i} \times \vec{V}_e - w_{n/e} \times \vec{V}_e \tag{2.13}$$

Where

$$\vec{f}^n = \begin{bmatrix} f_n \\ f_e \\ f_d \end{bmatrix} \quad \vec{g}_l^n = \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix} \quad w_{e/i}^e = \begin{bmatrix} 0 \\ 0 \\ \Omega \end{bmatrix} \quad w_{e/i}^n = \begin{bmatrix} \Omega\cos(L) \\ 0 \\ -\Omega\sin(L) \end{bmatrix} \quad \vec{V}_e^n = \begin{bmatrix} Vn \\ Ve \\ Vd \end{bmatrix} \tag{2.14}$$

In order to calculate the $\vec{f}^n$, it is necessary to find the attitude of the platform with respect to navigation frame. This can be achieved by knowing the transformation matrix $C^{(n,b)}$ which comes from the gyro measurements onboard the platform.

$C^{(n,b)}$ is the transformation matrix that transforms a vector in b frame to components of the same vector in n frame. It is also the rotation matrix which rotates the navigation frame to body frame.

In a small time increment the rotation matrix will also change

$$C^{(b(t+\Delta t),n)} = C^{(b(t+\Delta t),b(t))} C^{(b(t),n)} \tag{2.15}$$

$$C^{(b(t+\Delta t),b(t))} = I - \delta\underline{\psi} \tag{2.16}$$

Differential relation for $C^{(b,n)}$ can be obtained as follows,

$$\begin{aligned}
\dot{C}^{(b,n)} &= \lim_{\Delta t \to 0} \frac{C^{(b,n)}_{(t+\Delta t)} - C^{(b,n)}_{(t)}}{\Delta t} \\
\dot{C}^{(b,n)} &= \lim_{\Delta t \to 0} \frac{(I - \delta\underline{\psi})C^{(b,n)} - C^{(b,n)}}{\Delta t} \\
\dot{C}^{(b,n)} &= \lim_{\Delta t \to 0} \frac{-\delta\underline{\psi} C^{(b,n)}}{\Delta t}
\end{aligned} \tag{2.17}$$

$\lim_{\Delta t \to 0} \frac{\delta\underline{\psi}}{\Delta t} = \Omega$ is the skew symmetric form of the angular rate vector. $w^n_{b/n}$

Then

$$\boxed{\dot{C}^{(b,n)} = -\Omega^b_{b/n} C^{(b,n)}} \tag{2.18}$$

taking the transpose, noting that $\Omega^T = -\Omega$ for skew symmetric form.

$$\dot{C}^{(n,b)} = (-\Omega^b_{b/n} C^{(b,n)})^T = (C^{(b,n)})^T (-\Omega^b_{b/n})^T \tag{2.19}$$

$$\dot{C}^{(n,b)} = C^{(n,b)} \Omega^b_{b/n} \tag{2.20}$$

in order to express $\Omega^b_{b/n}$ it is known that,

$$\begin{aligned}
\vec{w}_{b/i} &= \vec{w}_{e/i} + \vec{w}_{n/e} + \vec{w}_{b/n} \\
\vec{w}_{b/n} &= \vec{w}_{b/i} + \vec{w}_{e/i} + \vec{w}_{n/e}
\end{aligned} \tag{2.21}$$

where

- $\vec{w}_{b/i}$ is measured by gyros,
- $\vec{w}_{e/i}$ is the earth rate (15 deg/hr)
- $\vec{w}_{n/e}$ is the transport rate which depends on north and east velocities and radius of earth.

$$w_{n/i}^{n} = w_{e/i}^{n} + w_{n/e}^{n} \tag{2.22}$$

$$w_{e/i}^{n} = \begin{bmatrix} \Omega \cos L \\ 0 \\ -\Omega \sin L \end{bmatrix} \quad \text{and} \quad w_{n/e}^{n} = \begin{bmatrix} \frac{V_e}{R_T + h} \\ -\frac{Vn}{R_M + h} \\ -\frac{V_e \tan L}{R_T + h} \end{bmatrix} \tag{2.23}$$

2.4 Earth Shape Model

For navigational purposes, the shape of the Earth is approximated as an ellipsoid. This imaginary reference ellipsoid (i.e. WGS84) is the surface from which the altitude is measured and is defined as the ellipsoid that best fits a reference geoid. The geoid is defined as the surface of the constant gravity field potential. This surface approximates the mean-sea level. Altitude is defined as the height above the reference ellipsoid measured along a line that passes through the position point.

Radii of curvature corresponding to horizontal North (Latitude-L) (r_{LS}) and east (Longitude-λ) ($r_{\lambda S}$) surface position movements are defined as the ratio of the horizontal earth surface position movement divided by the corresponding horizontal angular rotation over the earth's surface.

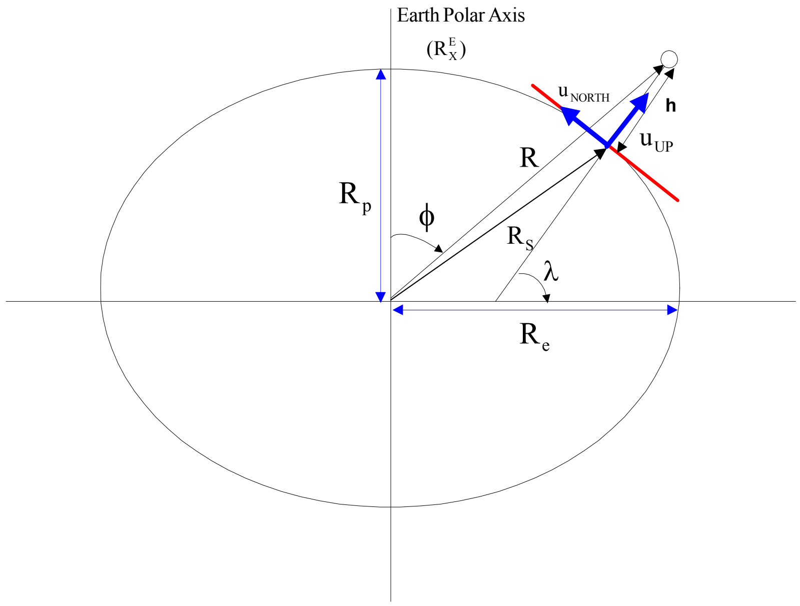


Figure 2-1 Earth shape model

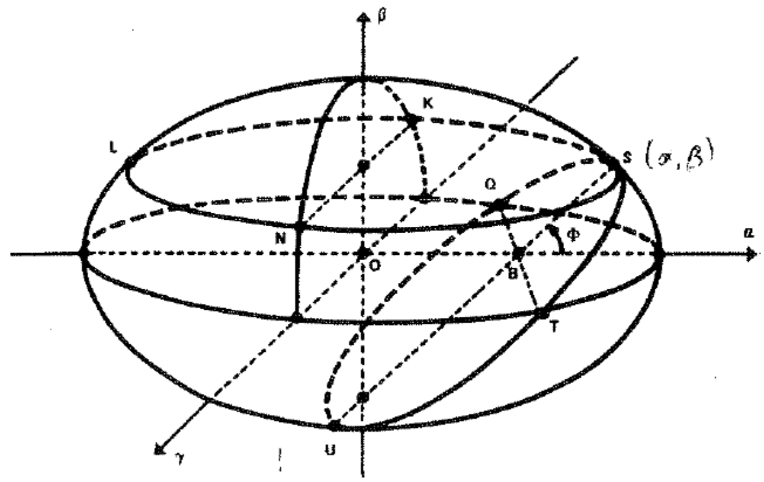


Figure 2-2 Meridian and polar Radii of Curvature

It can be shown that the radius of curvature values along longitude and latitude directions are,

$$R_{east} = \frac{dR_{E,EAST}}{d\upsilon_{EN,NORTH}} = \frac{R_0}{\sqrt{\left(1-\varepsilon^2 \sin(L)^2\right)}}$$
$$R_{north} = -\frac{dR_{E,NORTH}}{d\upsilon_{EN,EAST}} = \frac{R_0\left(1-\varepsilon^2\right)}{\left(1-\varepsilon^2 \sin(L)^2\right)^{3/2}} \tag{2.24}$$

Where

$$\varepsilon = \sqrt{1-\left(\frac{R_p}{R_e}\right)^2} \tag{2.25}$$

is the first ellipsoidal eccentricity. $dR_{E,NORTH}, dR_{E,EAST}$ are north and east direction position movement at Earth surface and $d\upsilon_{EN,NORTH}$ and $d\upsilon_{EN,EAST}$ are north and east component of infinitesimal angular rotation vector of N-frame relative to the E-frame. The radii of curvature at a specified altitude (h) is obtained as

$$R_L = R_{north} + h$$
$$R_\lambda = R_{east} + h \tag{2.26}$$

The Earth related constants that are used in the formulations referenced from WGS84 model are given in Table 2-1.

Due to V_{north} the n frame will have an angular velocity of

$$\dot{L} = \frac{V_{north}}{R_{north} + h} \tag{2.27}$$

Due to V_{east} the n frame will have an angular velocity of

$$\dot{\lambda} = \frac{V_{east}}{(R_{east} + h)\cos(L)} \tag{2.28}$$

$$\dot{h} = -V_{Down} \tag{2.29}$$

With these nonlinear navigation equations the general working principle of navigation frame mechanization is shown in Figure 2-3.

Table 2-1 Earth constants for WGS-84 model

Parameter	**Definition**	**Value**	**Unit**
R_e	Earth Equator Radius	6378137.0	m
R_p	Earth Polar Radius	6356752.3142	m
e	First Eccentricty	8.18191908426221e-2	-
ε^2	Square of First Eccentricity	0.00669437999014	-
μ	Earth's Gravitational Constant	3986004.418e–5	m^3/s^2
Ω	Earth Spin Rate	7.292115e–5	rad/s
J2	Gravitational Potential Term	1.082627e–3	-
J3	Gravitational Potential Term	-2.5327e–6	-
g_e	Theoretical(Normal) Gravity at the Equator	9.7803253359	m/s^2
g_p	Theoretical(Normal) Gravity at the pole	9.8321849378	m/s^2

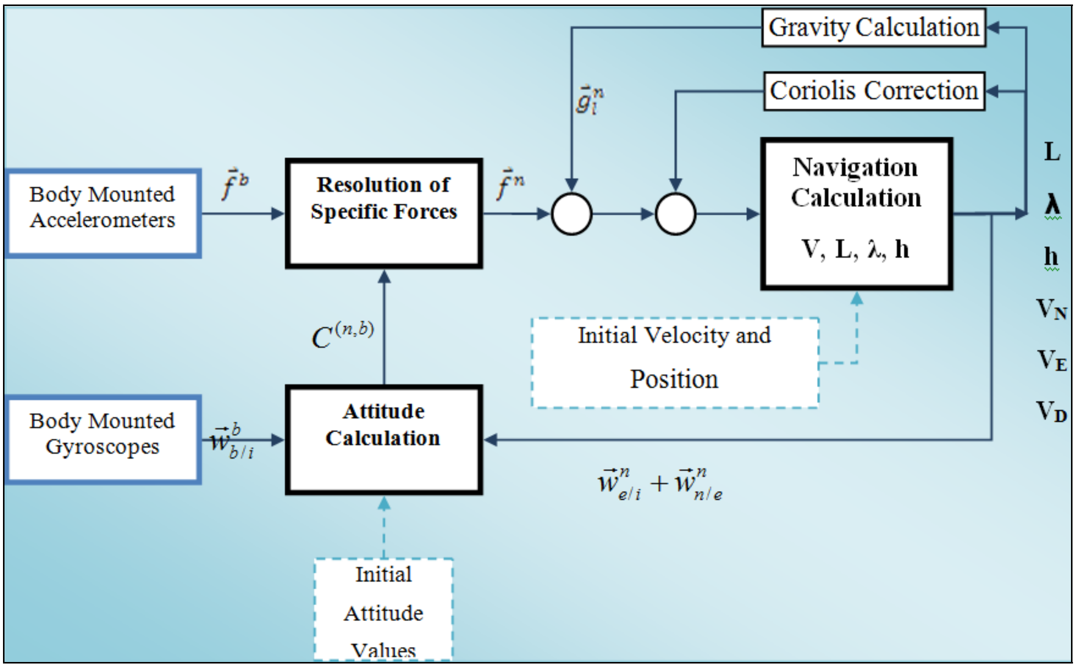


Figure 2-3 Inertial navigation system working flowchart

2.5 Linearization of Navigation Equations

An error model is requires to determine how the computed position, velocity and attitude deviate from the true values. The deviations are due to inertial sensor errors, initial condition errors and computation errors. In order to develop an error model, perturbation method is used.

2.5.1 Derivation of Error Equations

2.5.1.1 Attitude Errors

It assumed that the computed DCM is related to the true navigation frame by relations about 1, 2, 3 axes by $d\alpha, d\beta, d\gamma$ amounts where $d\alpha, d\beta$ are the tilt errors and $d\gamma$ is the heading error.

The estimated attitude $\tilde{C}^{(n,b)}$ may be written in terms of true DCM as follows.

$$\tilde{C}^{(n,b)} = \left[I - d\underline{\Psi}\right]C^{(n,b)} \tag{2.30}$$

$d\underline{\Psi}$ is the skew symmetric cross product matrix of $[d\alpha \quad d\beta \quad d\gamma]^T$

The estimated DCM is $\tilde{C}^{(n,b)} = \left[I - d\underline{\Psi}\right]C^{(n,b)}$ which may be rearranged by leaving $d\underline{\Psi}$ alone,

$$d\underline{\Psi} = I - \tilde{C}^{(n,b)}(C^{(n,b)})^T \tag{2.31}$$

In order to find how $d\alpha, d\beta, d\gamma$ propagates, differentiating the equation leads to

$$d\dot{\underline{\Psi}} = -\dot{\tilde{C}}^{(n,b)}(C^{(n,b)})^T - \tilde{C}^{(n,b)}(\dot{C}^{(n,b)})^T \tag{2.32}$$

it is known that $C^{(n,b)}$ propagates as function of the absolute body rate, $\Omega^b_{b/i}$, and the navigation frame rate, $\Omega^n_{n/i}$, as,

$$\dot{C}^{(n,b)} = C^{(n,b)}\Omega^b_{b/n} = C^{(n,b)}(\Omega^b_{b/i} - \Omega^b_{n/i}) \tag{2.33}$$

The matrices transform in the following way,

$$\boxed{\Omega^b_{n/i} = C^{(n,b)T}\Omega^n_{n/i}C^{(n,b)}} \tag{2.34}$$

using (2.34) in the equation (2.32)

$$\dot{C}^{(n,b)} = C^{(n,b)}(\Omega^b_{b/i} - C^{(n,b)T}\Omega^n_{n/i}C^{(n,b)}) \tag{2.35}$$

$$\boxed{\dot{C}^{(n,b)} = C^{(n,b)}\Omega^b_{b/i} - \Omega^n_{n/i}C^{(n,b)}} \tag{2.36}$$

the same relation holds for the $\dot{\tilde{C}}^{(n,b)}$

$$\boxed{\dot{\tilde{C}}^{(n,b)} = \tilde{C}^{(n,b)}\tilde{\Omega}^b_{b/i} - \tilde{\Omega}^n_{n/i}\tilde{C}^{(n,b)}} \tag{2.37}$$

where $\tilde{\Omega}^b_{b/i}$ is the measured body rate. $\tilde{\Omega}^n_{n/i}$ is the estimated navigation frame rate. By using equations (2.36) and (2.37) in equation (2.32),

$$d\dot{\underline{\Psi}} = -(\tilde{C}^{(n,b)}\tilde{\Omega}^{b}_{b/i} - \tilde{\Omega}^{n}_{n/i}\tilde{C}^{(n,b)})(C^{(n,b)})^{T} - (\tilde{C}^{(n,b)})(C^{(n,b)}\Omega^{b}_{b/i} - \Omega^{n}_{n/i}C^{(n,b)})^{T} \quad (2.38)$$

Transpose of last term. (considering ${\Omega^{b}_{b/i}}^{\mathrm{T}} = -\Omega^{b}_{b/i}$)

$$(C^{(n,b)}\Omega^{b}_{b/i} - \Omega^{n}_{n/i}C^{(n,b)})^{T} = -\Omega^{b}_{b/i}C^{(n,b)T} + C^{(n,b)T}\Omega^{n}_{n/i} \quad (2.39)$$

$$d\dot{\underline{\Psi}} = -(\tilde{C}^{(n,b)}\tilde{\Omega}^{b}_{b/i} - \tilde{\Omega}^{n}_{n/i}\tilde{C}^{(n,b)})(C^{(n,b)})^{T} - (\tilde{C}^{(n,b)})(-\Omega^{b}_{b/i}C^{(n,b)T} + C^{(n,b)T}\Omega^{n}_{n/i}) \quad (2.40)$$

$$d\dot{\underline{\Psi}} = -\tilde{C}^{(n,b)}\tilde{\Omega}^{b}_{b/i}C^{(n,b)T} + \tilde{\Omega}^{n}_{n/i}\tilde{C}^{(n,b)}C^{(n,b)T} + \tilde{C}^{(n,b)}\Omega^{b}_{b/i}C^{(n,b)T} - \tilde{C}^{(n,b)}C^{(n,b)T}\Omega^{n}_{n/i} \quad (2.41)$$

$$d\dot{\underline{\Psi}} = -\tilde{C}^{(n,b)}\tilde{\Omega}^{b}_{b/i}C^{(n,b)T} + \tilde{\Omega}^{n}_{n/i}\tilde{C}^{(n,b)}C^{(n,b)T} + \tilde{C}^{(n,b)}\Omega^{b}_{b/i}C^{(n,b)T} - \tilde{C}^{(n,b)}C^{(n,b)T}\Omega^{n}_{n/i} \quad (2.42)$$

$$d\dot{\underline{\Psi}} = -\tilde{C}^{(n,b)}(\tilde{\Omega}^{b}_{b/i} - \Omega^{b}_{b/i})C^{(n,b)T} + \tilde{\Omega}^{n}_{n/i}\tilde{C}^{(n,b)}C^{(n,b)T} - \tilde{C}^{(n,b)}C^{(n,b)T}\Omega^{n}_{n/i} \quad (2.43)$$

putting $\tilde{C}^{(n,b)} = \left[I - d\underline{\Psi}\right]C^{(n,b)}$ into equation (2.43),

$$d\dot{\underline{\Psi}} = -\left[I - d\underline{\Psi}\right]C^{(n,b)}(\tilde{\Omega}^{b}_{b/i} - \Omega^{b}_{b/i})C^{(n,b)T} + \tilde{\Omega}^{n}_{n/i}\left[I - d\underline{\Psi}\right] - \left[I - d\underline{\Psi}\right]\Omega^{n}_{n/i} \quad (2.44)$$

writing $(\tilde{\Omega}^{b}_{b/i} - \Omega^{b}_{b/i}) = \delta\Omega^{b}_{b/i}$

$$d\dot{\underline{\Psi}} = -\left[I - d\underline{\Psi}\right]C^{(n,b)}\delta\Omega^{b}_{b/i}C^{(n,b)T} + \tilde{\Omega}^{n}_{n/i}\left[I - d\underline{\Psi}\right] - \left[I - d\underline{\Psi}\right]\Omega^{n}_{n/i} \quad (2.45)$$

$$\begin{aligned} d\dot{\underline{\Psi}} &= -IC^{(n,b)}\delta\Omega^{b}_{b/i}C^{(n,b)T} + d\underline{\Psi}C^{(n,b)}\delta\Omega^{b}_{b/i}C^{(n,b)T} \\ &+ \tilde{\Omega}^{n}_{n/i}I - \tilde{\Omega}^{n}_{n/i}d\underline{\Psi} - I\Omega^{n}_{n/i} + d\underline{\Psi}\Omega^{n}_{n/i} \end{aligned} \quad (2.46)$$

$$d\dot{\underline{\Psi}} \cong d\underline{\Psi}\Omega^{n}_{n/i} - \Omega^{n}_{n/i}d\underline{\Psi} + \delta\Omega^{n}_{n/i} - C^{(n,b)}\delta\Omega^{b}_{b/i}C^{(n,b)T} \quad (2.47)$$

in vector form

$$\boxed{d\dot{\Psi} \cong -w^{n}_{n/i}xd\Psi + \delta w^{n}_{n/i} - C^{(n,b)}\delta w^{b}_{b/i}} \quad (2.48)$$

Where the skew symmetric forms of $d\Psi, w^{n}_{n/i}, \delta w^{n}_{n/i}, \delta w^{b}_{b/i}$ are $d\underline{\Psi}, \Omega^{n}_{n/i}, \delta\Omega^{n}_{n/i}, \delta\Omega^{b}_{b/i}$

2.5.1.2 Velocity Error Propagation

The velocity equation may be expressed as,

$$\dot{\vec{v}} = C^{(n,b)}\vec{f}^{\,b} + \vec{g}_l^{\,n} - (2\vec{w}_{e/i}^{n} + \vec{w}_{n/e}^{n}) \times \vec{v} \tag{2.49}$$

the computed values also satisfy equation (2.49).

$$\dot{\tilde{\vec{v}}} = \tilde{C}^{(n,b)}\tilde{\vec{f}}^{\,b} + \tilde{\vec{g}}_l^{\,n} - (2\tilde{\vec{w}}_{e/i}^{n} + \tilde{\vec{w}}_{n/e}^{n}) \times \tilde{\vec{v}} \tag{2.50}$$

to get the differential relation for the error term, equations (2.49) and(2.50) into

$$\delta\dot{v} = \dot{\tilde{v}} - \dot{v} \tag{2.51}$$

and noting that $\tilde{C}^{(n,b)} = \left[I - d\underline{\Psi}\right]C^{(n,b)}$.

Also naming

$$\begin{aligned} \tilde{\vec{f}}^{\,b} - \tilde{\vec{f}}^{\,b} &= \delta\vec{f}^{\,b} \\ \tilde{v} - v &= \delta v \\ \tilde{w}_{e/i}^{n} - w_{e/i}^{n} &= \delta w_{e/i}^{n} \\ \tilde{w}_{e/n}^{n} - w_{e/n}^{n} &= \delta w_{e/n}^{n} \end{aligned} \tag{2.52}$$

$$\boxed{\begin{aligned} &\delta\dot{\vec{v}} = \left[I - d\underline{\Psi}\right]C^{(n,b)}\tilde{\vec{f}}^{\,b} - C^{(n,b)}\vec{f}^{\,b} \\ &+\tilde{\vec{g}}_l^{\,n} - \vec{g}_l^{\,n} - (2\tilde{\vec{w}}_{e/i}^{n} + \tilde{\vec{w}}_{n/e}^{n}) \times \tilde{\vec{v}} + (2\vec{w}_{e/i}^{n} + \vec{w}_{n/e}^{n}) \times \vec{v} \end{aligned}} \tag{2.53}$$

leads to

$$\delta\dot{\vec{v}} = C^{(n,b)}\delta\vec{f}^{\,b} - d\underline{\Psi}C^{(n,b)}\vec{f}^{\,b} - \delta\vec{g}_l^{\,n} - (2\vec{w}_{e/i}^{n} + \vec{w}_{n/e}^{n}) \times \delta\vec{v} - (2\delta\vec{w}_{e/i}^{n} + \delta\vec{w}_{n/e}^{n}) \times \vec{v} \tag{2.54}$$

In equation (2.54),

$$\delta\vec{v} = \begin{bmatrix} \delta v_{north} \\ \delta v_{east} \\ \delta v_{down} \end{bmatrix}$$

$$\delta\vec{f}^{b} = \begin{bmatrix} \delta f_x \\ \delta f_y \\ \delta f_z \end{bmatrix} \tag{2.55}$$

$d\underline{\Psi}$ is the skew symmetric form of $\begin{bmatrix} \mathrm{d}\alpha \\ \mathrm{d}\beta \\ \mathrm{d}\gamma \end{bmatrix}$

2.5.1.3 Position Errors

Position errors can be defined by

$$\delta\dot{\vec{p}} = \delta\vec{v} \tag{2.56}$$

Velocity and position errors are functions of inaccuracies in measurement of specific force, the attitude errors, incorrect assumptions about shape of the earth and wrong calculation of gravity.

2.5.2 ERROR EQUATIONS IN STATE SPACE FORM

These error equations can now be written in state space form.

$$\delta\dot{x} = A\delta x + B\delta u \tag{2.57}$$

Where inputs are the inertial sensor measurement errors from 3 gyros and 3 accelerometers, and the states are the errors at attitude, velocity and position.

$$\delta x = \begin{bmatrix} d\alpha \\ d\beta \\ d\gamma \\ \delta V_n \\ \delta V_e \\ \delta V_d \\ \delta L \\ \delta \lambda \\ \delta h \end{bmatrix} \text{ and } \delta u = \begin{bmatrix} d\phi_x \\ d\phi_y \\ d\phi_z \\ \delta f_x \\ \delta f_y \\ \delta f_z \end{bmatrix}$$

2.6 Inertial Sensor Characteristics

Even though system manufacturers give different forms of inertial system error parameters and names, inertial sensor errors can be classified as;

- Bias
    - Static bias (fixed- turn on)
    - Dynamic bias (bias instability, run to run, in run)
- Scale factor error
- Random walk (white noise)
- Accelerometer offset
- Misalignment

In addition to sensor errors, bandwidth and dynamic range are two important parameters that are used in inertial sensor selection.

2.6.1 Bias

Bias tends to be the largest error in both accelerometers and gyros. It can be split into two components: the static bias (fixed or turn-on or run to run bias), which remains constant throughout the test period, varying only each time the sensor is powered up, and the dynamic bias (in-run bias, bias instability), which varies with time due to the noise in electronic devices.

Aircraft grade accelerometers typically exhibit biases in the order of 50μg, while for weapon and automotive grade accelerometers the value may be in excess of 1000μg, for gyros the values are 0.01 deg/hr and 1 to 100 deg/hr, respectively.

If the system operates unaided (without odometer/velocity or GPS or magnetometer aiding), the gyro bias indicates the increase of angular error over time (in deg/h or deg/s).

If the system is aided with speed information (e.g. odometer or Doppler log), the roll and pitch gyro drift can be compensated in the measurement system and the gyro drift mainly affects the heading accuracy over time.

If the system consists of low drift gyros also the true heading can be estimated using gravity and earth rate information (so-called north-seeking). (IMAR [15])

If the system is aided with position information (e.g. GPS or GLONASS or GALILEO), also heading drift can be corrected and true heading can be provided (even with medium grade gyros). But of course the smaller the gyro drift the better all possible angular corrections and the longer the allowed time where the aiding information may be not present.

If the system is operated in free navigation mode, the gyro bias is responsible for the position and velocity error over time (so-called Schuler oscillation).

2.6.2 Gyro Scale Factor Error

This is an indication of the angular error which occurs during rotation and arises due to the departure from linearity of the sensors response.. E.g. with 300 ppm scale factor error (=0.03%) the angular error is in the area of 0.1 degree after one revolution. (IMAR [15] and IST [16])

$$\frac{300}{1000000} = \frac{x}{360} \rightarrow x = 0.1\deg \tag{2.58}$$

With a laser gyro or high performance fiber optical gyro system with 10 ppm scale factor error the angular error is less than 1 arc-sec (0.0003 deg) if the rotation angle is 30 deg.

For aircraft grade accelerometers the values are less than 10ppm, whilst weapon grade accelerometers are generally larger than 100ppm. For gyros the values are typically 30ppm and 300ppm respectively.

2.6.3 Gyro Random Walk

Random walk is approximated to white noise and can be caused by various factors including resolution limits, electrical noise and quantization errors in the A/D conversion. This value, given in deg/sqrt(hr), shows the noise of the used gyro. The higher the noise the more noise is measured on the angular rates and on the angles. Some manufacturers also specify it as the noise density in deg/h/sqrt(Hz). Both values are equivalent – if the second value is divided by 60, you get it in deg/sqrt(hr). An angular random walk of 0.003 deg/sqrt(hr) indicates, that the angular error (uncertainty) due to random walk is e.g. 0.001 deg after 6 minutes (unaided) or 0.0004 deg after 1 minute (all values one sigma).

$$0.003 \times \sqrt{\frac{6}{60}} \rightarrow x = 0.001 \deg \tag{2.59}$$

The angular random walk is very important for the accuracy of north seeking, because if the random walk decreases times 2 then the needed duration for north seeking decreases by times four (if the resolution of the gyro is high enough).

The source of this error depends on the physical structure of the sensors. For the fiber optic gyros, the source of this error is the shot noise (photon strikes on the detector) which has a poison distribution, and Gaussian thermal white noise, Johnson noise which is a white noise due to electronic circuits and the relative intensity noise which occurs in the laser source (IEEE [17]).

For the ring laser gyros, random walk occurs due to photon movement and dither motion in dithered ring laser gyroscopes (IEEE [18])

For the case of accelerometers, white noise in acceleration is generally caused by the movement of the proof mass, and thermal noise in the electronic circuitry.

For accelerometers the values are <20µg/sqrt(Hz) for aircraft grade to greater than 50 µg/sqrt(Hz) for weapons and automotive grade. For gyros the values are 0.002 °/ √ (hr) and >0.03 °/√ (hr) respectively (QinetiQ [19]).

2.6.4 Misalignment

A misalignment between the gyro axes (or accelerometer axes) causes a cross-coupling between the measurement axes. A misalignment of 0.1 mrad inside of the system (e.g. residual calibration mismatch) leads to a roll error of 0.036 degree during one revolution around the yaw axis (if the system is unaided)

$$0.1 mrad \times 10^{-3} \times 360 = 0.036 \deg \tag{2.60}$$

The smaller the required misalignment the higher the requirements to sensor performance and calibration equipment

2.6.5 Accelerometer Offset

An offset on the accelerometer leads to an error during alignment, i.e. determination of initial roll and pitch angle. An offset of 0.1 mg leads to approx. 0.006 degree angular error (attitude error).

$$\frac{0.1mg}{g} = 0.1 mrad \rightarrow 0.1/17.7 \cong 0.006 \deg \tag{2.61}$$

The sensor offsets can be estimated during operation by the system integrated Kalman filter, using GPS or DGPS data or ZUPT (zero velocity update procedure).

2.6.6 Bandwidth

In general the dynamic performance of an inertial measurement system is as better as higher the internal sampling rate and the bandwidth of the inertial sensors is. Also the proper internal data synchronisation is very important for accurate signal processing if the INS is operated under difficult dynamical environment. A high precision internal time reference therefore is very important to be available inside of the INS.

2.6.7 DYNAMIC RANGE

Dynamic range specifies the dynamic environment in which the inertial sensor can be used. For example if a gyro can effectively measure 100 degree/second motions. It can not be used in high dynamic environments such as an aircraft which can achieve 270 degree/sec roll rate.

The bandwidth and dynamic range are inherent specifications of the inertial sensor and can not be improved in flight. Other inertial sensor errors can be estimated and corrected up to a degree when proper external aiding is available.

Typical sensor error specifications are given for tactical grade and navigation grade IMU's in Table 2-2.

Table 2-2 Sensor error comparison for tactical and navigation grade IMU's

	Parameter	**MEMS IMU**	**NAV GRADE IMU**
Gyro	Bias (turn-on to turn-on)	50 deg/hr	< 0.005 deg/hr
	Bias Instability	1 deg/hr	< 0.003 deg/hr
	White Noise	0.75 deg/√hr	< 0.002 deg/√hr
	Scale Factor	1500 ppm	< 50 ppm
Accel	Bias (turn-on to turn-on)	8.4 mg	< 100 ug
	Bias Instability		< 50 ug
	White Noise	1 m/s/√hr	< 50 ug/√hr
	Scale Factor	2000 ppm	< 50 ppm

2.7 Kalman Filtering

The Kalman filter is a set of mathematical equations that provides an efficient computational (recursive) means to estimate the state of a process, in a way that minimizes the mean of the squared error

The Kalman filter is an estimation algorithm, rather than a filter. The basic technique was invented by R. E. Kalman in 1960. It maintains real-time estimates of a number of parameters of a system, such as its position and velocity,that may continually change. The estimates are updated using a stream of measurements that are subject to noise. The measurements must be functions of the parameters estimated, but the set of measurements at a given time need not contain sufficient information to uniquely determine the values of the parameters at the time (Groves [20]).

The Kalman Filter addresses the general problem of trying to estimate the state of a discrete-time controlled process, x $\in R^n$, which is governed by the linear stochastic difference equation,

$$x_k = Ax_{k-1} + Bu_{k-1} + w_{k-1} \tag{2.62}$$

with a measurement x $\in R^m$, that is

$$z_k = Hx_k + v_k \tag{2.63}$$

The random variables w_k and v_k represent the process and measurement noise (respectively). They are assumed to be independent (of each other), white, and with normal probability distributions

2.8 The Discrete Kalman-Filter Algorithm

The Kalman filter estimates a process by using a form of feedback control: the filter estimates the process state at some time and then obtains feedback in the form of (noisy) measurements. As such, the equations for the Kalman filter fall into two groups: time update equations and measurement update equations. The time update equations are responsible for projecting forward (in time) the current state and error covariance estimates to obtain the a priori estimates for the next time step. The measurement update equations are responsible for the feedback - i.e. for incorporating a new measurement into the a priori estimate to obtain an improved a posteriori estimate.

The weighted mean of $\vec{x}_1$ and $\vec{x}_2$ can be expressed as (Titterton [11]),

$$\hat{x} = \vec{x}_1 + W(\vec{x}_2 - \vec{x}_1) \tag{2.64}$$

$\vec{x}_2$ may be GPS or any other aiding source and may often have different number of states. In this case the relation can be defined as

$\vec{y}_2 = H\vec{x}_2$ where H is an mxn matrix.

We must find the optimum estimate of x from $\vec{x}_1$ with covariance P and $\vec{y}_2 = H\vec{x}_2$ with covariance R.

Letting W=KH where K is an arbitrary weighting matrix.

$$\begin{aligned} \hat{x} &= \vec{x}_1 + KH(\vec{x}_2 - \vec{x}_1) \\ \hat{x} &= \vec{x}_1 + K(\vec{y}_2 - H\vec{x}_1) \end{aligned} \tag{2.65}$$

Where y is measurement and $\vec{x}_1$ is INS

By definition the variance of $\hat{x}$ is

$$P = E\left\{[\hat{x} - x][\hat{x} - x]^T\right\} \tag{2.66}$$

After substituting $\hat{x}$ and noting that y and $\vec{x}_1$ are uncorrelated,

$$P = (I - KH)P_1(I - KH)^T + KRK^T \tag{2.67}$$

Then,

K; (Kalman gain) which minimizes P (variance of $\hat{x}$) is found as;

$$\boxed{K = P_1 H^T (H P_1 H^T + R)^{-1}} \tag{2.68}$$

The general flow down of Kalman filter can be stated as in Figure 2-4.

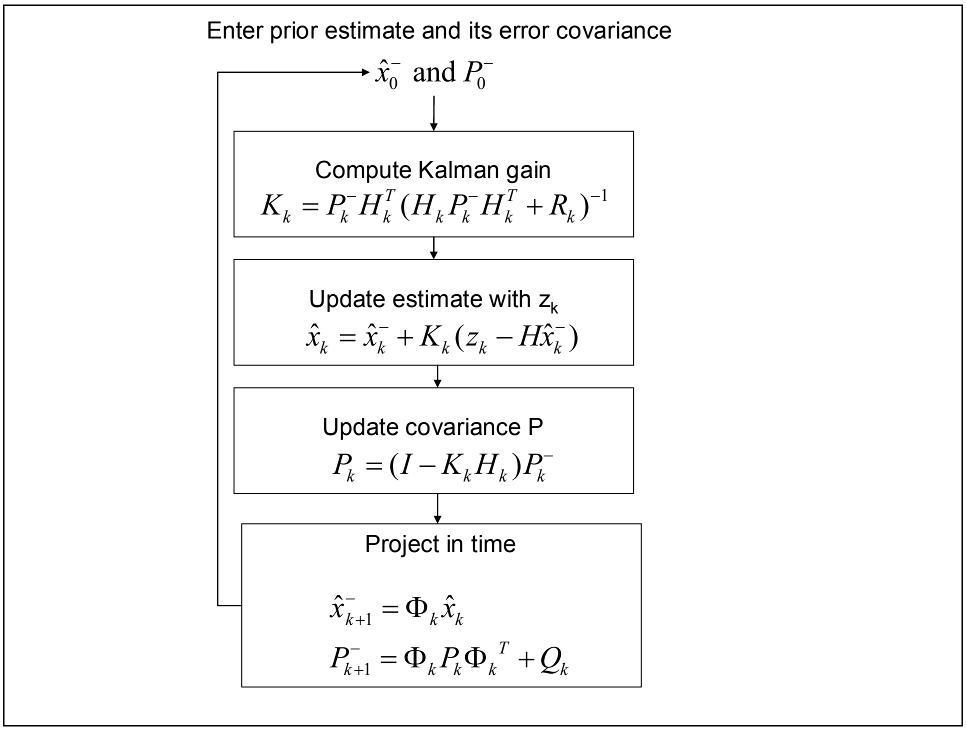


Figure 2-4 Kalman filter flowchart

2.9 Direct vs. Indirect Kalman Filter

In the direct Kalman Filter formulation total states such as position and velocity are among the state variables in the filter, and the measurements are IMU outputs and external source signals (odometer, GPS etc.). In the Indirect Kalman Filter formulation, the errors in the INS-indicated position and velocity are among the estimated variables, and each measurement presented to the filter is the difference between INS and external source data.

In the direct filter formulation, the Kalman Filter is in the INS loop. The IMU sensor data and external source data both feed into the filter.

In the indirect formulation, Kalman Filter estimates the errors in the navigation and attitude information using the difference between INS and external source data. The INS itself follows the high frequency motions of the vehicle and there is no need to model these dynamics explicitly in the filter. Instead, the dynamics upon which the filter is based is the set of inertial system error propagation equations, which are relatively well developed, well behaved, low frequency and very adequately represented as linear. Because the filter is out of the INS loop and is based on low frequency linear dynamics, its sample rate can be much lower than that of a direct filter.

Hence, it is preferred to use error states instead of total (actual) states in the formulation due to the following reasons:

- Kalman filter may run in lower rates, than the inertial process rate,
- It leads to the extended Kalman Filter structure. Linearization of the total state equations is not possible; however linearization of the error states is possible.
- The indirect filter mechanization is more reliable; if the filter should happen to fail in direct mechanization, the entire navigation system fails; the inertial system cannot operate without the filter. It is not the case in indirect formulation.

2.10 State Space Equations for a 15 State Indirect Feedback Kalman Filter in a loosely coupled INS/BNS integration

States are roll, pitch, heading errors, north, east, down velocity errors, latitude longitude, height errors, accelerometer biases in three axes and gyro biases in three axes.

$$\delta x = \begin{bmatrix} d\alpha \\ d\beta \\ d\gamma \\ \delta V_n \\ \delta V_e \\ \delta V_d \\ \delta L \\ \delta\lambda \\ \delta h \\ b_{Xaccel} \\ b_{Yaccel} \\ b_{Zaccel} \\ b_{Xgyro} \\ b_{Ygyro} \\ b_{Zgyro} \end{bmatrix} \quad \text{and } \delta u = \begin{bmatrix} d\phi_x \\ d\phi_y \\ d\phi_z \\ \delta f_x \\ \delta f_y \\ \delta f_z \end{bmatrix} \tag{2.69}$$

A: 15 x 15 system matrix with error states and accelerometer and gyro biases.

$$A^n_{INS} = \begin{bmatrix} A^n_{11}{}_{(3x3)} & A^n_{12}{}_{(3x3)} & A^n_{13}(3x3) & 0_{(3x3)} & \hat{C}(n,b) \\ A^n_{21}{}_{(3x3)} & A^n_{22}{}_{(3x3)} & A^n_{23}(3x3) & \hat{C}(n,b) & 0_{(3x3)} \\ 0_{(3x3)} & A^n_{32}{}_{(3x3)} & A^n_{33}(3x3) & 0_{(3x3)} & 0_{(3x3)} \\ 0_{(3x3)} & 0_{(3x3)} & 0_{(3x3)} & 0_{(3x3)} & 0_{(3x3)} \\ 0_{(3x3)} & 0_{(3x3)} & 0_{(3x3)} & 0_{(3x3)} & 0_{(3x3)} \end{bmatrix} \tag{2.70}$$

Where

$$A^n_{11}{}_{(3x3)} = \begin{bmatrix} 0 & \left(\Omega\sin L + \frac{V_E}{R}\tan L\right) & \frac{V_N}{R} \\ -\left(\Omega\sin L + \frac{V_E}{R}\tan L\right) & 0 & \Omega\cos L + \frac{V_E}{R} \\ -\frac{V_N}{R} & -\Omega\cos L - \frac{V_E}{R} & 0 \end{bmatrix} \tag{2.71}$$

$$A^n_{12\,(3x3)} = \begin{bmatrix} 0 & \frac{1}{R} & 0 \\ -\frac{1}{R} & 0 & 0 \\ 0 & \frac{-\tan L}{R} & 0 \end{bmatrix} \tag{2.72}$$

$$A^n_{13\,(3x3)} = \begin{bmatrix} -\Omega \sin L & 0 & -\frac{V_E}{R^2} \\ 0 & 0 & \frac{V_N}{R^2} \\ -\Omega \cos L - \frac{V_E}{R\cos^2 L} & 0 & \frac{V_E \tan L}{R^2} \end{bmatrix} \tag{2.73}$$

$$A^n_{21\,(3x3)} = \begin{bmatrix} 0 & -f_D & f_E \\ f_D & 0 & -f_N \\ -f_E & f_N & 0 \end{bmatrix} \tag{2.74}$$

$$A^n_{22\,(3x3)} = \begin{bmatrix} \frac{V_D}{R} & -2\left(\Omega \sin L + \frac{V_E}{R}\tan L\right) & \frac{V_N}{R} \\ \left(2\Omega \sin L + \frac{V_E}{R}\tan L\right) & \frac{1}{R}\left(V_N \tan L + V_D\right) & 2\Omega \cos L + \frac{V_E}{R} \\ -\frac{2V_N}{R} & -2\left(\Omega \cos L + \frac{V_E}{R}\right) & 0 \end{bmatrix} \tag{2.75}$$

$$A^n_{23\,(3x3)} = \begin{bmatrix} -V_E \begin{pmatrix} 2\Omega \cos L + \\ \frac{V_E}{R\cos^2 L} \end{pmatrix} & 0 & \frac{1}{R^2}\left(V_E^2 \tan L - V_N V_D\right) \\ \begin{bmatrix} 2\Omega\left(V_N \cos L - V_D \sin L\right) \\ + \frac{V_N V_E}{R\cos^2 L} \end{bmatrix} & 0 & -\frac{V_E}{R^2}\left(V_N \tan L + V_D\right) \\ 2\Omega V_E \sin L & 0 & \frac{1}{R^2}\left(V_N^2 + V_E^2\right) \end{bmatrix} \tag{2.76}$$

$$A^n_{31\,(3x3)} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (2.77)$$

$$A^n_{32\,(3x3)} = \begin{bmatrix} \frac{1}{R} & 0 & 0 \\ 0 & \frac{1}{R\cos L} & 0 \\ 0 & 0 & -1 \end{bmatrix} \quad (2.78)$$

$$A^n_{33\,(3x3)} = \begin{bmatrix} 0 & 0 & -\frac{V_N}{R^2} \\ \frac{V_E \tan L}{R\cos L} & 0 & -\frac{V_E}{R^2 \cos L} \\ 0 & 0 & 0 \end{bmatrix} \quad (2.79)$$

H: m x 15 matrix which relates measurement to the states. If the measurement is GPS or beacon position fixes, latitude, longitude, height measurements exist. H is 3 x 15 for a 15 state Kalman filter.

$$H = [0_{(3x3)} \quad 0_{(3x3)} \quad \mathrm{I}_{(3x3)} \quad 0_{(3x3)} \quad 0_{(3x3)} \;] \quad (2.80)$$

R: covariance matrix of measurement. If the aiding system is GPS, then it is a diagonal matrix with GPS error variances. In the beacon aiding case, beacon geometry at the time of position update affects the covariance of measurements. The DOP values are important in filling the R matrix.

P: 15 x 15 covariance matrix of INS. It starts diagonal with initial condition error variances.

Q: 15 x 15 diagonal matrix including process noise effects. It also includes sensor biases in 15 state Kalman filter.

Kk: 15 x 3 Kalman gain matrix which distributes delta values (obtained from aiding sensor and INS common states) to all states.

Φ state transition matrix which can be obtained as,

$$\Phi = I + A\Delta t + \frac{1}{2}A^2(\Delta t)^2 \ldots$$

In determining where to truncate the expansion of the transition matrix Φ, the maximum magnitude of each higher order term should be estimated by the Kalman filter designer and a determination made as to whether this will have a significant effect on the integration algorithm performance. The truncation does not have to be uniform, so for example, some second-order terms may be neglected whereas others are included. In practice, the state propagation interval, needs to be kept down to 1 second or lower; otherwise, the power series expansion of Φ may experience convergence problems. Where there is a long interval between measurement updates, such as in many loosely coupled implementations, it may be necessary to run the system propagation at shorter intervals to ensure that the power-series expansion converges (Groves [20]). In the Kalman filter algorithm, state propagation is set to 1 second.

CHAPTER III

POSITION FIXING METHODS

3.1 Position Fixing

A “position fix” is a term that originates from the application of naval navigation methods in shore navigation, where the navigator takes bearings to three lighthouses or known landmarks (external sources) and, draws the lines of position on his map. The intersection point of these lines of position hopefully reveals the coordinates of the navigator. Generally these lines do not intersect at the same point but forms an area where the ship is supposed to be in or nearby, due to several errors.

A position fix can be obtained by using several methods and equipment. Externally dependent navigation systems can be classified according to their measurement techniques as distance measurement techniques, angle measurement techniques and a combination of angle and distance measurement techniques.

(Tri or Multi) lateration term is used to define the position fixing algorithms based on distance measurements. Distance measurement techniques can be classified as RSSI (Received signal strength intensity), TDOA (time difference of arrival), TOA (time of arrival) etc.

TOA technique is based on absolute measurement of the distance by using speed of the wave and absolute time. This technique requires time synchronization (accurate clocks) TOA technique is used In GPS system.

TDOA (hyperbolic navigation) is another position fixing technique based on measurement of the difference in distance to two or more known stations which broadcast signals at known times. LORAN C is a hyperbolic navigation system

RSSI techniques rely on loss of signal strength with distance in known medium. RSSI techniques accuracy degrades due to effects like reflection, multipath etc.

Position fixing techniques that are based on angle measurement can be named as triangulation. Angle measurements can be done by optical means, encoders or by receiving special RF emissions such as in the VOR system.

In this thesis, position fixing methods based on angle measurements are preferred. The following sections give information about the proposed position fixing methods that are derived from artillery surveying practices and their implementation to an airborne platform.

3.2 Literature Survey

The literature is searched in terms of beacon navigation methods, current state of beacon technology, position finding algorithms by observing external bodies, and missile navigation concepts. During the timeline of this thesis newly appeared work is also added to this section.

3.2.1 Use Of Beacons for Missile Navigation

Work on missile navigation by use of external cooperating beacons is limited or unreachable. There are several recent studies that are focusing on eliminating the negative effects of GPS jamming on guided weapons, especially for new generation GLNM (gun launched novel munitions) [7], [8]. Beacon navigation has been studied by robotics community and by civil aviation area in the form of VOR beacons but the concept for the missiles is not much considered. Egziabher [21] works on a civil aviation approach aid based on magnetometer and INS system aided with VOR stations. However, it can be thought that SLAM researchers are also using terrain features which can be regarded as landmarks.

3.2.2 Beacon Navigation Concept

Literature search has revealed that the navigation technique by utilizing external beacons is mainly a research area in robotics. The beacon navigation concept is mostly seen in robotics community in which navigation of robots in confined areas is a problem. Most of the literature lies in robotics field in which position finding algorithms along with the beacon types are investigated and implemented on industrial robots.

However the operation environment of robots is different than the missiles. Most works focus on navigation of robots in confined areas such as factories or production lines etc. Robots that navigate using beacon like structures use active or passive localization techniques such as IR, laser, MMW, ultrasonic waves from beacon or the robot itself. These works well worth analyzing since the robots are also trying to find their position by looking at beacons and primarily triangulation algorithms are used to estimate the position of robot.

Csorba [22] gives information about beacon navigation for robots and continues for analysis of SLAM (simultaneous localizing and map building) problem. The main types of signals used by beacon based localization systems are classified as infrared laser, ultrasound and millimeter wave radar. Infrared laser is used, by commercially-available General Electric Company - Caterpillar (GEC-CAT) AGV and the commercially-available Netzler & Dahlgren Company (NDC) AGV [22], [23]. In both systems, the AGV is equipped with a rotating infrared laser emitter/receiver, and the beacons are reflective strips placed at known positions in the environment. The angle of the sensor is registered when a laser reflection is observed, thus giving the bearing of the observation.

In robotic research, electronic counter measures issue is not a concern and any beacon or robot transmitting signals does not pose a problem. Another difference is that the robotics research area is limited with friendly confined environment. The operation area is limited and the ranges that a robot is operating are on the order of meters to hundreds of meters. Another difference is that the robots can stop and employ a triangulation algorithm that can be used thanks to the vehicles' stationary position. This is not possible for a missile or a guided weapon. Another issue is to find the range from the robot to the beacon. Commercial uses can let laser beams to be directed from the robot to the reflective beacon but such a distance measuring capability can not be employed in our case for both stealth characteristics of the missile and the technical difficulties in long range employment.

Betke and Guvitz [25] analyze the positioning algorithms that can be used in mobile robot localization using landmarks. Their work manly focuses on the position calculation algorithms. They use a special robot with a spherical reflector and a camera which sees the reflection from the spherical reflector. It is assumed that the robot can identify the landmarks and measure relative bearing to the landmarks. In the proposed method landmarks are represented with complex numbers and in the proposed position estimator the method of least squares and matrix pseudo inverse are used to obtain position information from over determined data sets.

Cozman and Krotkov [26] use extracting mountain peaks from camera vision and then compare these map features with the database to obtain multiple bearings to previously known mountain peaks from the robot. A database is formed for each possible position of the robot about which mountain peaks can be observed.. The main problems associated with this approach are the problems in map feature extraction and false peaks, along with the error introduced by low gradient peaks and the typical errors in position are stated to be 300 to 1000 meters.

Casanova and Quijada [28] propose a beacon localization system for a mobile robot operating in indoor environment, by the use of laser and RF signals for identification of different beacons. The position finding algorithm is the standard triangulation approach. (3 point resection.).

US patent 6,580,978 B1 [29] offers a high resolution path marking system for land vehicles. The system uses RF tags to mark a route to be traversed by manned or unmanned land vehicles. It's primarily intended to be used for logistic supply convoys. The path marking vehicle lays the beacons, find their location based on its own inertial navigation system. Following vehicles interrogate beacons by RF tagging, triangulate their position and any difference from the main vehicle are corrected. The primary purpose of the invention is to provide an effective way of logistics supply by robotic ground vehicles. The ranges for the operation environment are short.

US patent 6,285,318 B1 [30] offers a new emergency transmitter system for ships and aircraft distress situations. Some information about IR and optical beacon technology is narrated. The beacon signals are received by satellites and a method that uses least square minimization matrix methods, applied to spherical equations are used to find the transmitter location.

US patent 6,608,592 B2 [31] offers a classical two point intersection algorithm by the use of two indoor beacons that work similar to VOR principle. Two signals one stationary and one rotating at the beacon provide angle information to the robot.

Villafuerte [32] classifies localization systems and gives information about IR, ultrasonic, optical, UWB and other localization technologies for indoor applications.

Koyuncu [33] gives information about positioning and object locating systems based on sensor networks briefly.

Hui [34] gives information about localization techniques used in sensor networks and states the performance metrics that are applicable in wireless sensor networks these are stated as accuracy, precision, complexity, robustness, scalability, and cost. RFID, WLAN, UWB, and Bluetooth positioning systems are narrated briefly. These positioning techniques are generally applicable for indoor localization of robots.

For sensor planning and positioning for wide-area surveillance, coverage analysis is emphasized by Besma [35]. In his work, it is stated that, as the placement of a sensor is concerned, this problem, especially in wide-area applications, is the same whether the sensor is trying to capture an image or a signal from a point in a wide area. One example of this would be the placement of a radio or cell phone transmitter tower in an urban or rural area. Another would be selecting an optimal position to place a watch tower in a forest fire prevention system. The common problem solved in these alternative techniques is the one of finding the largest coverage area from a given observation point in 3D space. Manley [36], classifies systems used in sensor networks and categorize localization and tracking systems into a hierarchical taxonomy based on characteristics of the objects being tracked, the application environments, and the sensor network technologies.

For the positioning of the missile during flight by taking bearings on the beacon(s), modified artillery survey methods are used. Artillery surveying deals with finding position and orientation for the units on the battlefield [37]. The main methods of artillery surveying are traverse, triangulation and astronomic observations which solve the spherical triangle.

Traverse is the method of carrying position and azimuth information on the field, by starting from a known position and azimuth line, and measuring angles and distances by using baselines called legs.

The triangulation method of survey uses triangular figures to determine survey data. If the values of certain elements of a triangle are known, the values of other elements of the triangle can be computed.

Intersection is the method of finding the position of an unoccupied point by determining its angles from two known stations.

In resection, the coordinates of an unknown point are obtained by determining the horizontal angles at the unknown point between three unoccupied points of known coordinates.

In the thesis the problem is to find the actual position of the missile by taking bearings from a beacon whose position is previously known.

During literature survey, the position estimation methods that are used by several researchers are also noticed.

An alternative approach to triangulation is to form an estimate of the vehicle pose. Estimation relies on a model of the vehicle and the sensor. The estimate is updated each time a new observation is made, and the vehicle is located from observation to observation using a prediction of the vehicle pose based on the vehicle control inputs,

The Kalman Filter is used to form a probabilistic estimate of the AGV pose, according to Bayesian Estimation Theory, in terms of a mean estimate and the covariance of the estimate. The Kalman Filter is reported to be used in the GEC-CAT AGV to localize the vehicle based on bearing-only observations, and is used by the FRAIT vehicle to localize based on range-bearing observations (Csorba [22]).

Cohen and Koss [27] analyzed four methods for determining the position of a robot from 3 landmarks. These methods are based upon the assumption that the robot is stationary. These methods are iterative search, geometric triangulation, Newton Raphson iterative method and geometric circle intersection

US patent 5,606,506 [38] offers a method and apparatus for improving the accuracy of position estimates in a satellite based navigation system using velocity data from an inertial reference input. For a vehicle operating on land or near the surface of the earth, having navigation equipment comprised of a GPS receiver, Inertial Reference Unit and a computer; a method is proposed. to improve the position estimates of the vehicle that are obtained from GPS; based on an algorithm that compares the position information gathered from GPS receiver and velocity information obtained from IRU at different locations and updates the position estimates by using average velocity, time, GPS position and minimization of error between the GPS position and the improved estimate positions. This work assumes that the error build up during short term flight is neglected.

In this thesis, aim is to look at the previously laid beacons by an imaging infrared seeker and, obtain seeker look angles to the beacons. Looking at a beacon from different positions as the missile flies; provides an intersection algorithm to update the missile position. The intersection algorithm requires a base length which can be provided by the short term distance calculation of the INS.

By this aspect the method in the patent is similar to our study. The base length can be obtained with sufficient accuracy because it is covered in a very short time by the missile. A similar approach is followed by the method described in the patent.

3.3 Suggested Position Fixing Methods

The position fixing algorithms that are mainly used by artillery surveyors are modified and used in order to provide position updates to the missile or UAV platform in this thesis.

In the proposed concept, the following assumptions are made,

- The air vehicle equipped with EO/IIR seeker or camera and an inertial navigation system is stated to be able to lock on beacons that come into range and field of regard of the weapon system and measure angles to these beacons only.
- No range measurement is taken into account since direct distance measurement requires a laser range finder which does not exist in missiles.
- The platform calculates its position by using only its inertial navigation system and, a barometer.

Three techniques are offered for the platform in order to have a position update by performing angle measurements to the deployed beacons. Among these three methods, two point and three point resection techniques do not require the platform to know anything about its location. Suggested position fixing methods are named as three point resection, two point resection and reverse intersection.

“Three point resection” technique can be defined as finding the host platform’s position by observing and measuring angles to three known points at an observation instant without measuring any distance. This method is used when there exist three beacons in the field of view of the seeker at an observation instant. In the literature three point resection technique is used by artillery surveyors to find their position on land and, in robotics area for platforms and robots that can measure angles in stationary operation in confined areas such as in a production facility hangar.

The “two point resection” method can be used when the seeker of the weapon can observe two beacons simultaneously in each of the two discrete observation instants. At each observation instant, only angles to the known beacons are measured and no distance is measured. It is possible to find the coordinates of the two separate observation points by the end of the measurement at the second observation point. In this method, the coordinates of the last observation point are fed to the Kalman filter of the platform as position update aid. In order to employ the two point resection method, it is necessary to compute the distance between the first and second observation points, which is determined by the platform’s inertial navigation system. In this method it is assumed that the error build up between the first and second observation points is negligible regarding the short term stability of inertial navigation systems. No information has been found regarding this method’s application to unmanned platforms in the literature

Intersection is a position fixing method that is used to find the coordinates of an unknown point by performing observations and measuring elevation and azimuth angles to the unknown location at two separate but known points. For the air platform considered, the platform knows its position with error and the position information is not reliable while the coordinates of the observed signal source is known.

In this work a new method based on the intersection method is offered and called as "reverse intersection". In the reverse intersection method, the INS-calculated coordinates of the first and the second observation points and the elevation and azimuth angles to the observed signal sources are used to calculate the coordinates of the observed signal source. The difference between the calculated coordinates and the known location of the signal source is fed to the Kalman filter of the platform at the second observation point as a position aid based on the assumption that the error growth during the first and second observation points is small (short term stability). Several different variations in the application of this method are possible. A major assumption in this method is that the drift in heading of the missile can be regarded smaller and neglected when compared to the position drift. As an example to this assumption, the heading drift of a navigation grade INS is less than 1 mil / hr while the position drift is stated to be 1 nm /hr.

The common property of the three suggested position fixing methods is the passive nature of all three methods No distance measurement is envisaged since most missiles do not have adequate equipment to achieve a reliable distance measurement capability and active distance measurement may compromise the covert operation capability of the platform and the ground based beacons.

Although angle measurement methods are envisioned in this thesis, it is possible to construct a beacon navigation system by using other aforementioned methods. Trilateration techniques based on distance measurements is not completely disregarded and may be as a strong alternative to the angle only triangulation method proposed here, as long as the necessary receivers are implemented on the missiles or UAV's. Another important consideration is the jamming and interception of radio emissions by enemy electronic warfare assets. A detailed analysis may be required regarding these issues and the amount and likeliness of the threats against the trilateration based position fixing techniques, operation doctrine and advantages and disadvantages.

3.4 Intersection Method

Intersection is a position fixing method which is used to calculate the coordinates of a point by bearing observations from two different known locations. The method can be applied to many cases where a distance measurement to the unknown location is not possible. Some cases are passive localization of enemy radars, finding positions of enemy installations or slow moving targets by forward observers without relieving their own position etc.

Intersection method is mostly used by artillery surveyors and several fire control equipments, such as the telemeter system in M48 tanks in which two separate optical systems with nearly 1.5 meter separation are mounted on a common linkage, when the gunner sees the enemy tank in his sight, two optical telescopes are directed to the target and since the angles and the distance between the telescopes are know, the relative distance to the target can be estimated. Stereo vision systems also employ intersection to locate an object in 3D space. Electronic warfare systems use this method to locate the enemy emitters.

3.5 Intersection Method Theory and Algorithm

The primary form of the observation geometry is given in Figure 3-1. B and C are known points. A is the point whose coordinates are to be found. In general, this method is used to find the position of point A (beacon) when B (first observation point) and C (second observation point) coordinates are known. In the original form of the method, position of point A can be found when the coordinates of point B and C are known, the interior angles from B and C to A are measured and the vertical angles from B and C to A are also measured. Then the sine theorem can be used to obtain the unknowns.

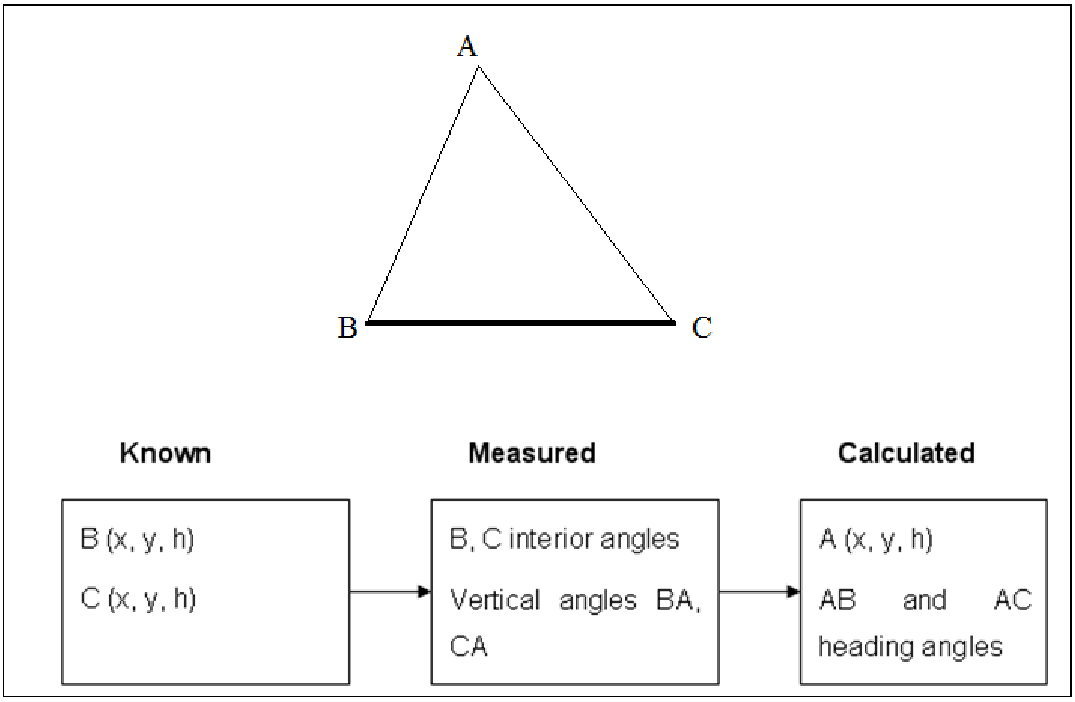


Figure 3-1 Intersection method flowchart

The algorithm for the intersection is as follows,

1. When B and C coordinates are known,
2. Measure azimuth and elevation angles from B and C to A.
3. Calculate horizontal and vertical distance between B and C. and obtain c
4. Calculate A interior horizontal angle by using B and C interior angles.
5. Calculate azimuth angle from B to C
6. Using sine theorem, obtain distances a and b.
7. Using the interior angles and azimuth angle from B to C obtain coordinates of point A.

3.6 Reverse Intersection

In the thesis, it is necessary to find a position fix for the missile which flies through points B and C. Due to the nature of the method, the number of unknowns exceeds the number of known quantities, and an exact position fix can not be obtained. So intersection techniques are not directly applicable to the problem. The missile knows its position and heading with error. These errors must be decreased by using an external position fix. Even though the intersection method is not capable of providing an exact position fix, it can still provide some information about the error of the IMU in the missile.

In this thesis, when only one beacon is available for position update, Intersection is used to calculate the difference between the actual position of the beacon and the calculated position of the beacon. Since the heading of the missile may be known erroneously, resolving the delta position corrections causes an ambiguity. The same solution can be obtained by infinitely many orientations as long as the base line and the interior angles are preserved. This situation can be more easily understood by Figure 3-2. So when distributing the error to point B and C coordinates a decision must be made.

Position error may be added by preserving the easting and northing components directly, which means that the error in heading is ignored. Position error may be added to the B and C coordinates by assuming that the error in heading is smaller than the error build up in position. However in this case the error direction is not resolvable.

The algorithm for the "reverse intersection (RI) method" employed in this thesis is as follows,

1. B and C coordinates are known with error due to INS position and heading errors. Coordinates are expressed in UTM coordinate system as easting, northing and height as $B(x, y, h)_{estimated}$ and $C(x, y, h)_{estimated}$
2. Azimuth and elevation angles from first observation point (B) and second observation point (C) to beacon (A) are measured by the seeker while it maintains lock on to the beacon. (Measured angles are converted to NED frame by using the roll, pitch angles of the platform and azimuth and

elevation angles of the seeker.) Seeker bearing angle is known with respect to missile axis and missile heading is provided with error by IMU.

3. Calculate horizontal and vertical distance between B and C, and obtain c distance. Assuming that for small distances, the drifts in inertial errors are negligible for a limited duration flight.

$$\text{BCslant}=\sqrt{(\text{bx-cx})^2+(\text{by-cy})^2+(\text{bh-ch})^2} \tag{3.1}$$

$$\text{DA}_{\text{BC}}=\text{asin}(\frac{\text{(ch-bh)}}{\text{BCslant}}) \tag{3.2}$$

$$\text{BChorizontal}=\sqrt{(\text{bx-cx})^2+(\text{by-cy})^2} \tag{3.3}$$

4. Calculate A interior horizontal angle by using B and C interior angles.

$$\hat{\text{A}}=3200-\hat{\text{B}}-\hat{\text{C}} \tag{3.4}$$

5. Calculate azimuth angle from B to C and convert to positive azimuth angle convention

$$IA_{BC}=a\tan 2\frac{cx-bx}{cy-by}\ \ (if\ \ IA_{BC}<0\ \ => IA_{BC}=IA_{BC}+6400) \tag{3.5}$$

All azimuth angles are found in the triangle as follows,

$$\begin{aligned} IA_{CB} &= \text{mod}(3200+IA_{CB},6400) \\ IA_{CA} &= IA_{CB}+(2 \text{ x sign-1}) \text{ x } \hat{\text{C}} \\ IA_{BA} &= IA_{BC}-(2 \text{ x sign-1}) \text{ x } \hat{\text{B}} \end{aligned} \tag{3.6}$$

Where sign is variable which takes 1 or 0 depending on the geometry, it is 1 when point A lies left of the BC line and 0 when A lies right of the BC line.

6. Using sine theorem, obtain distances a, and b.

$$\frac{a}{\sin A}=\frac{b}{\sin B}=\frac{c}{\sin C} \tag{3.7}$$

7. Using the bigger distance among b and c, and the interior angles and azimuth angle from B to C, obtain coordinates of point A. By using

elevation angle from B to A or C to A, obtain height of point A. These form the calculated A position $A(x,y,h)_{calc}$.

$$\begin{aligned} Ax &= Bx + c * \sin(IAba) \\ Ay &= By + c * \cos(IAba) \\ Ah &= Bz + c * \tan(DAba) \end{aligned} \tag{3.8}$$

8. Obtain the difference between the known position and calculated position of A.

$$\Delta(x,y,h) = A(x,y,h)_{true} - A(x,y,h)_{calc} \tag{3.9}$$

9. Distribute the error in coordinates of point A in a suitable way to decrease the position error in point B and C.

$$\begin{aligned} B(x,y,h)_{updated} &= B(x,y,h)_{calc} + \Delta(x,y,h) \\ C(x,y,h)_{updated} &= C(x,y,h)_{calc} + \Delta(x,y,h) \end{aligned} \tag{3.10}$$

Since intersection method is mainly a method to find the coordinates of the observed beacon, not the observation point coordinates; there exists an ambiguity in its usage for using the method as a position fixing tool. It is possible to obtain infinitely many intersection triangles with different heading angles. This brings a problem about how to distribute the error between the base points.

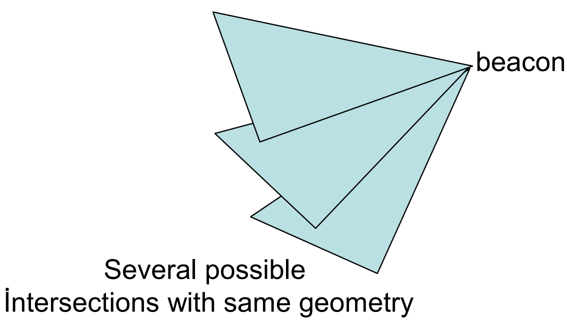


Figure 3-2 Intersection ambiguity

One option is to directly feed the error components to the B and C positions, assuming that the drift in heading is much less than the drift in position since position drift is dependent on multiple sources of error. The results of this approach will be given at the following sections. One option is to use a weighting based on heading and position covariance.

10. Update position of C and feed to the Kalman filter as position update.

3.7 Two Point Resection Method

Two point resection (2PR) method is an artillery surveying method which is used mainly for land survey. It is based on observations to two known points by some means and measuring angles to the known points without any distance measurement. The method can be used when the observer (missile in our case) does not know any information about its location on the earth but can observe two points whose locations are known.

The distances to the known points can not be measured. Only angle measurement information and positions of known stations are used to determine one's own position.

Based on the assumption that the seeker can simultaneously observe two beacons at a time, in the thesis this method can be used as follows,

When the seeker locks on these beacons it can provide bearing and elevation angle information to the stations.

At a second observation point where the seeker still tracks the beacons, another set of bearing and elevation information is obtained.

This method directly finds the locations of the first and second observation points after the second bearing and elevation angle data are obtained. The simulation program uses the second position as the update to the Kalman filter.

3.8 Two Point Resection Theory and Algorithm

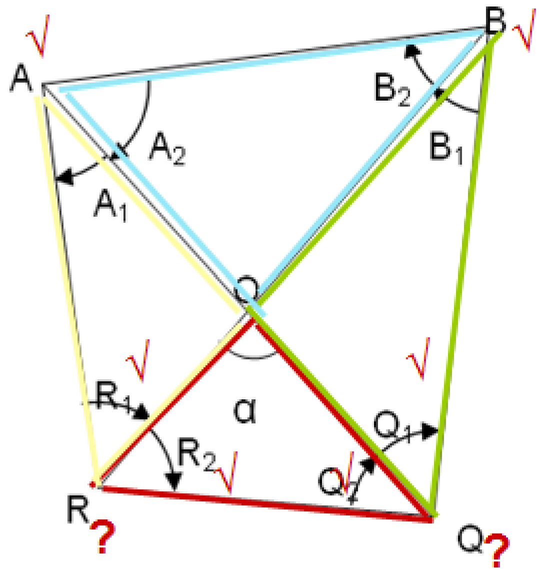


Figure 3-3 Two point resection scheme and angles.

Point A and B are stations with known coordinates. Point R is the first observation point and Q is the second observation point. Available information are internal angles from R and Q to A and B. R1 and Q1 are measured in any case. R2 and Q2 require constant heading flight or known heading at two observation points.

Since AB distance and angles from R and Q to A and B are the only known quantities, all distances are written in terms of a gain k. This gain is solved and then unknown quantities can be solved (Figure 3-3).

$$\frac{|RO|}{\sin Q_2} = \frac{|QO|}{\sin R_2} = \frac{|RQ|}{\sin \alpha} = k \quad \left(\text{Sine theorem for ROQ triangle}\right) \tag{3.11}$$

$$\begin{aligned} |RO| &= k \sin Q_2 \\ |QO| &= k \sin R_2 \\ |RQ| &= k \sin \alpha \end{aligned} \tag{3.12}$$

Sine theorem for AOR triangle and RO distance is written as in equation (3.12)

$$\frac{|RO|}{\sin A_1} = \frac{|AO|}{\sin R_1} = \frac{|AR|}{\sin(180-\alpha)} \quad \Rightarrow \quad \frac{k\sin Q_2}{\sin A_1} = \frac{|AO|}{\sin R_1} = \frac{|AR|}{\sin\alpha} \tag{3.13}$$

$$\begin{aligned} |AO| &= k\frac{\sin Q_2 \sin R_1}{\sin A_1} \\ |AR| &= k\frac{\sin Q_2 \sin\alpha}{\sin A_1} \end{aligned} \tag{3.14}$$

The same operations are performed for the BOQ triangle.

$$\frac{|QO|}{\sin B_1} = \frac{|BO|}{\sin Q_1} = \frac{|BQ|}{\sin(180-\alpha)} \quad \Rightarrow \quad \frac{k\sin R_2}{\sin B_1} = \frac{|BO|}{\sin Q_1} = \frac{|BQ|}{\sin\alpha} \tag{3.15}$$

$$\begin{aligned} |BO| &= k\frac{\sin R_2 \sin Q_1}{\sin B_1} \\ |BR| &= k\frac{\sin R_2 \sin\alpha}{\sin B_1} \end{aligned} \tag{3.16}$$

The same operations are performed for the AOB triangle. And the expressions above are put for AO and BO distances.

$$\frac{|AO|}{\sin B_2} = \frac{|BO|}{\sin A_2} = \frac{|AB|}{\sin\alpha} \quad \Rightarrow \quad \frac{k\overbrace{\frac{\sin Q_2 \sin R_1}{\sin A_1}}^{a}}{\sin B_2} = \frac{k\overbrace{\frac{\sin R_2 \sin Q_1}{\sin B_1}}^{b}}{\sin A_2} = \frac{|AB|}{\sin\alpha} \tag{3.17}$$

$$\frac{a\cdot k}{\sin B_2} = \frac{b\cdot k}{\sin(180-\alpha-B_2)} = \frac{|AB|}{\sin\alpha}$$

$$\begin{cases} \dfrac{a}{\sin B_2} = \dfrac{b}{\sin\alpha\cos B_2 + \cos\alpha\sin B_2} \quad \Rightarrow \quad \tan B_2 = \dfrac{\sin\alpha}{\frac{b}{a} - \cos\alpha} \\ \\ \mathrm{k} = \sin B_2 \dfrac{|AB|}{a\sin\alpha} \end{cases} \tag{3.18}$$

When “k” and “B_2” are found, It is possible to find the AR, AQ distances, AR, AQ heading angles and R and Q points’ easting and northing values can be found as follows.

$$A2 = 3200 - \alpha - B2 \tag{3.19}$$

$$\begin{aligned} |RO| &= k \sin Q_2 \\ |QO| &= k \sin R_2 \\ |RQ| &= k \sin \alpha \end{aligned} \tag{3.20}$$

$|RQ| = k \sin \alpha$ and using the sine theorem for ARQ triangle.

$$\text{AR=k } \sin(\alpha) \ \frac{\sin(\text{Q2})}{\sin(\text{A1})} \tag{3.21}$$

$$\begin{aligned} &\text{AQ=AR+RQ} \\ &\text{AQ=k } \sin(\text{R1}) \ \frac{\sin(\text{Q2})}{\sin(\text{A1})} + \text{k } \sin(\text{R2}) \end{aligned} \tag{3.22}$$

$$|BQ| = \frac{k \sin \alpha \sin R_2}{\sin B_1} \tag{3.23}$$

The difference between the easting and northing coordinates are found

$$\text{dx} = \text{bx} - \text{ax}; \ \text{dy} = \text{by} - \text{ay} \tag{3.24}$$

The azimuth angle from A to B is found and converted to positive CW convention

```
IAab=atan2(dx,dy)*3200/pi;
if IAab<0;
   IAab=IAab+6400;
End
```
(3.25)

Azimuth angle from A to R is found by adding the interior angles to the azimuth angle from A to B.

Coordinates of point R is found by,

$$rx=ax+AR \sin(IAar)$$
$$ry=ay+AR \cos(IAar) \quad (3.26)$$

$$qx=ax+AQ \sin(IAaq)$$
$$qy=ay+AQ \cos(IAaq) \quad (3.27)$$

$$rh=ah-AR \tan(RAver\_angle)$$
$$qh=ah-AQ \tan(QAver\_angle) \quad (3.28)$$

3.9 Three Point Resection Method

Three point resection (3PR) method is a position fixing method which is used by the observer to find his own position when he has no information about his position and azimuth, by the help of angle measurements to three stations whose positions are known (FM 6-2 (1972) [37], KKT 6-2 (1997) [40] and Hmam [41]) .

This method utilizes only angle measurements and does not involve any distance measurement to the known stations. This method is fairly used when there is no equipment or any other chance to measure distance to the known stations.

This method can be used by the missile seeker when there are three beacons visible at the time of observation. One limitation is that, the three beacons should be in the instantaneous FOV of the missile and the IIR seeker should be able to give information about the three targets (beacons) in its FOV. One of the targets are locked and tracked at the center of the seeker FOV and the two others are tracked inside the FOV without centering. There are also some limitations arising from solution geometry which will be narrated at the following sections.

3.10 Three Point Resection Theory and Algorithm

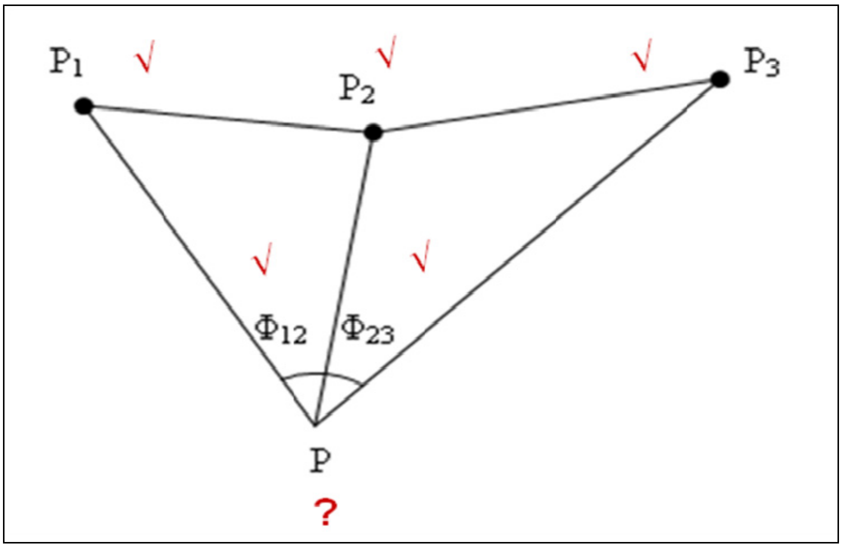


Figure 3-4 Three point resection scheme

Figure 1-1 shows the geometry and the known angles of the 3PR method. The coordinates of P1, P2 and P3 are known in UTM coordinates. (Easting, Northing, Height), and the horizontal and vertical angles from P to P1, P2 and P3 are measured by the missile seeker. (Or converted to horizontal vertical coordinate system). So the angles Φ_{12} and Φ_{23} are known. None of the distances from point P to known stations are measured or known.

The equations used in the calculation of coordinates of point P are derived by using the fact that the circles enclosing the PP_1P_2 and PP_2P_3 triangles intersect at P and P2 (Figure 3-5).

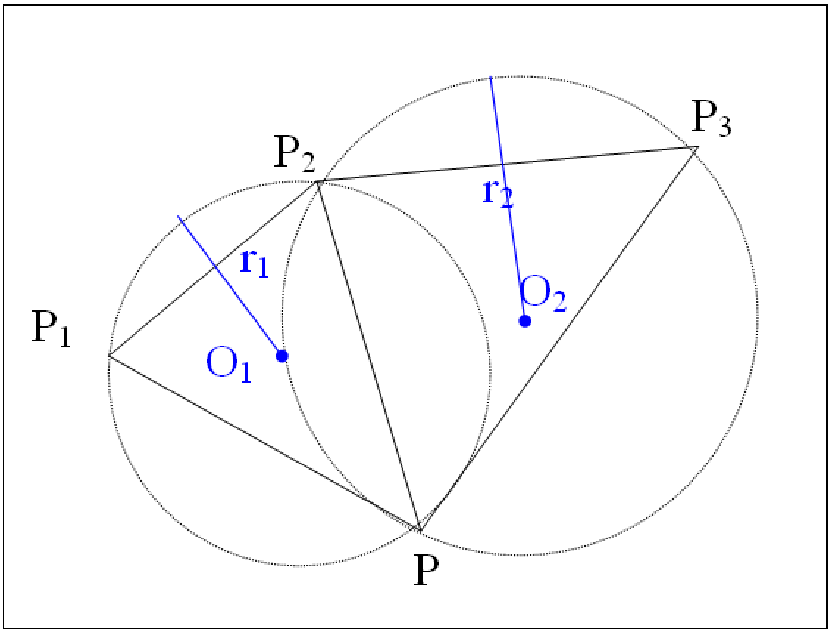


Figure 3-5 Three point resection method enclosing circles

The coordinate calculation algorithm starts with calculation of the centers of the circles enclosing P and P2, namely O1 and O2 (Figure 3-6).

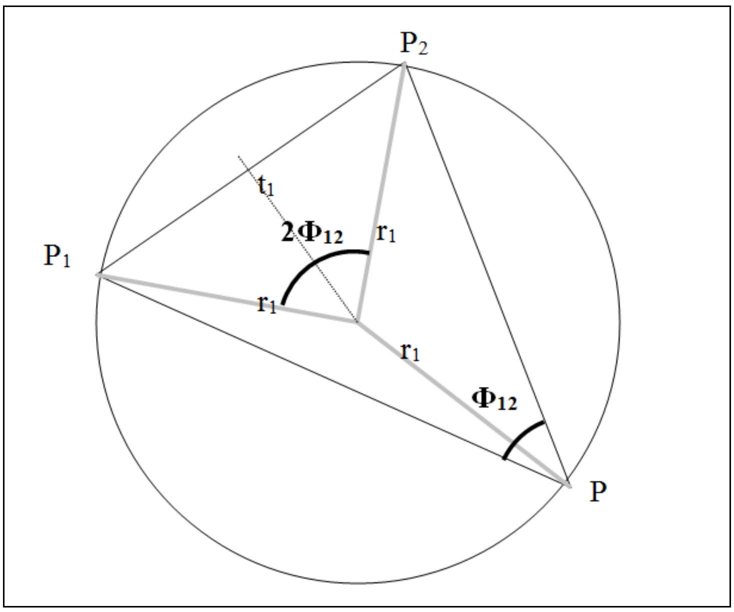


Figure 3-6 Three point resection

a1, b1, a2, b2 are the coordinates of the centers of the circles.

The P_1P_2O triangle is an isosceles triangle. As a result t_1 angle bisector is a side bisector and vertical to P_1P_2 side. If P_1P_2 distance is named as l_1 t_1 distance can be found as follows (Figure 3-7),

$$\tan\Phi_{12} = \frac{l_1/2}{t_1} \quad \Rightarrow \quad t_1 = \frac{l_1/2}{\tan\Phi_{12}} \tag{3.29}$$

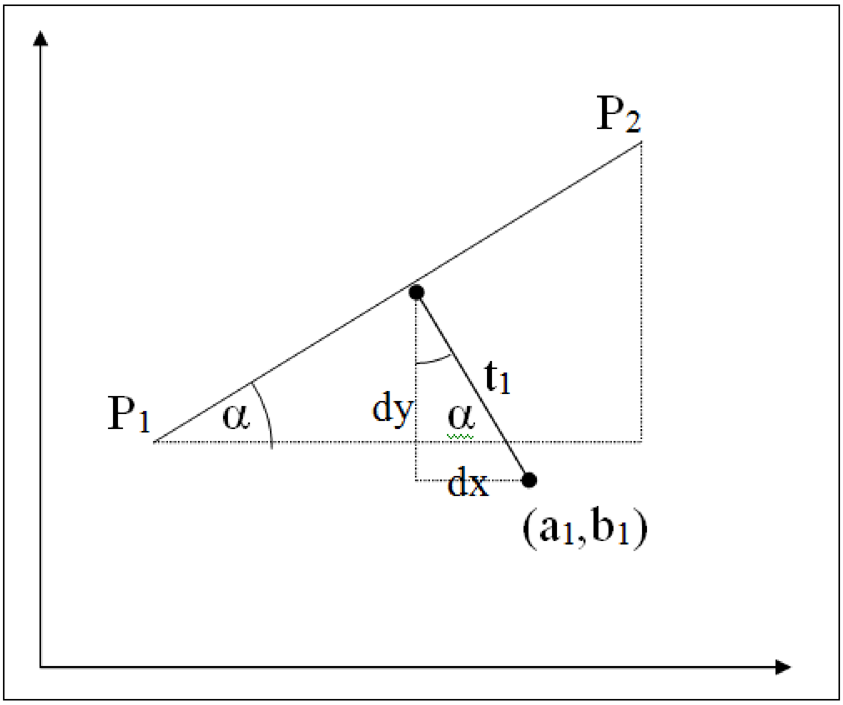


Figure 3-7 Coordinates of the circle center

$$\begin{aligned} a_1 &= \frac{x_1+x_2}{2} + t_1\sin\alpha = \frac{x_1+x_2}{2} + t_1\frac{y_2-y_1}{l_1} \\ b_1 &= \frac{y_1+y_2}{2} - t_1\cos\alpha = \frac{y_1+y_2}{2} - t_1\frac{x_2-x_1}{l_1} \end{aligned} \tag{3.30}$$

The second circles center is found the same way and the coordinates of the centers are given as.

$$
\begin{aligned}
a_1 &= \frac{x_{P1}+x_{P2}}{2}+t_1\sin\alpha = \frac{x_{P1}+x_{P2}}{2}+\frac{y_{P2}-y_{P1}}{2\tan(\phi_{12})}\\
b_1 &= \frac{y_{P1}+y_{P2}}{2}-t_1\cos\alpha = \frac{y_{P1}+y_{P2}}{2}-\frac{x_{P2}-x_{P1}}{2\tan(\phi_{12})}\\
a_2 &= \frac{x_{P2}+x_{P3}}{2}+t_1\sin\alpha = \frac{x_{P2}+x_{P3}}{2}+\frac{y_{P3}-y_{P2}}{2\tan(\phi_{23})}\\
b_2 &= \frac{y_{P2}+y_{P3}}{2}-t_1\cos\alpha = \frac{y_{P2}+y_{P3}}{2}-\frac{x_{P3}-x_{P2}}{2\tan(\phi_{23})}
\end{aligned} \tag{3.31}
$$

when Φ_{12} and/or Φ_{23} angles are 90 degrees, the equations that are used to solve the coordinates of the centers of the circles are changed as follows,

$$
\begin{aligned}
&\mathrm{a1} = (\mathrm{p1x}+\mathrm{p2x})/2;\ \ \mathrm{b1} = (\mathrm{p1y}+\mathrm{p2y})/2;\\
&\mathrm{a2} = (\mathrm{p2x}+\mathrm{p3x})/2;\ \ \mathrm{b2} = (\mathrm{p2y}+\mathrm{p3y})/2;
\end{aligned} \tag{3.32}
$$

Since the equations of the circles satisfy the P and P2 points, we can obtain the following equations.

From the circle equation

$$
\begin{aligned}
(x-a_1)^2+(y-b_1)^2 &= (x_2-a_1)^2+(y_2-b_1)^2\\
(x-a_2)^2+(y-b_2)^2 &= (x_2-a_2)^2+(y_2-b_2)^2
\end{aligned} \tag{3.33}
$$

The first circles equation is written as follows

$$
\begin{aligned}
&(x-x_2+x_2-a_1)^2+(y-y_2+y_2-b_1)^2=(x_2-a_1)^2+(y_2-b_1)^2\\
&(x-x_2)^2+2(x-x_2)(x_2-a_1)+(x_2-a_1)^2\\
&+(y-y_2)^2+2(y-y_2)(y_2-b_1)+(y_2-b_1)^2\\
&=(x_2-a_1)^2+(y_2-b_1)^2
\end{aligned} \tag{3.34}
$$

$$
(x-x_2)^2+2(x-x_2)(x_2-a_1)+(y-y_2)^2+2(y-y_2)(y_2-b_1)=0 \tag{3.35}
$$

The second circle equation is also written and then subtracted from the first.

$$2\left(x-x_2\right)\left(a_2-a_1\right)+2\left(y-y_2\right)\left(b_2-b_1\right)=0 \quad \Rightarrow \quad \frac{x-x_2}{b_2-b_1}=-\frac{y-y_2}{a_2-a_1}=k$$

$$\begin{aligned} x-x_2 &= k\left(b_2-b_1\right) \\ y-y_2 &= -k\left(a_2-a_1\right) \end{aligned} \tag{3.36}$$

When we put x-x_2 and y-y_2 expressions on the equation(3.34), we obtain,

$$\begin{aligned} &k^2\left(b_2-b_1\right)^2+2k\left(b_2-b_1\right)\left(x_2-a_1\right)+k^2\left(a_2-a_1\right)^2-2k\left(a_2-a_1\right)\left(y_2-b_1\right)=0 \\ &k^2\left[\left(b_2-b_1\right)^2+\left(a_2-a_1\right)^2\right]=2k\left[\left(a_2-a_1\right)\left(y_2-b_1\right)-\left(b_2-b_1\right)\left(x_2-a_1\right)\right] \\ &k=\frac{2\left[\left(a_2-a_1\right)\left(y_2-b_1\right)-\left(b_2-b_1\right)\left(x_2-a_1\right)\right]}{\left(b_2-b_1\right)^2+\left(a_2-a_1\right)^2} \end{aligned} \tag{3.37}$$

$$\begin{aligned} x &= x_2+k\left(b_2-b_1\right) \\ y &= y_2+k\left(a_2-a_1\right) \end{aligned} \tag{3.38}$$

And implemented to Matlab as;

$$\begin{aligned} &k=2*((a2-a1)*(p2y-b1)-(b2-b1)*(p2x-a1))/((b2-b1)^2+(a2-a1)^2); \\ &x=p2x+k*(b2-b1); \\ &y=p2y-k*(a2-a1); \end{aligned} \tag{3.39}$$

When the easting and northing coordinates of point P are calculated, the altitude of point P can be calculated from the three known stations as follows,

$$\begin{aligned} &h1=p1h-\sqrt{(p1x-x)^2+(p1y-y)^2}\ tan(\hat{P}1); \\ &h2=p2h-\sqrt{(p2x-x)^2+(p2y-y)^2}\,tan(\hat{P}2); \\ &h3=p3h-\sqrt{(p3x-x)^2+(p3y-y)^2}\,tan(\hat{P}3); \end{aligned} \tag{3.40}$$

The height of the point P is calculated by taking the average of the three height calculations.

$$\mathrm{h}=\left(\mathrm{h1}+\mathrm{h2}+\mathrm{h3}\right)/3; \tag{3.41}$$

3.11 Limitations of Methods

- Points should be seen at the same time. Three or two beacons must be within the FOV of the seeker for 3PR and 2PR.
- The line connecting observation point should not pass through 2 other beacons.
- The beacons and the observation point should not be on the same circle since the solution is based on intersection of two circles in 3PR.

3.12 Geometric Dilution of Precision

For beacon layout objective function, a positioning metric which links the geometry of the beacons with the accuracy of the position estimation is necessary. A candidate for this metric is the DOP (dilution of precision).

In our case dilution of precision metric must be written for different combinations of position finding.

For trilateration, where distances from the beacons can be measured, three beacons are necessary for finding the position of the missile. A DOP metric can be defined similar to GPS.

For triangulation methods, DOP can be formulated differently since measured values are the angles only. The following sections define DOP metric for positioning by trilateration, reverse intersection and three point resection.

In this section DOP is tried to be formulated for several cases.

- General case for two point trilateration and triangulation.
- For two point resection
- For three point resection
- For reverse intersection

3.12.1 General Case for Two Point Trilateration and Triangulation

For the calculation of geometric dilution of precision, the measurement process can be defined as follows. In the general nomenclature, Z stands for measurements. (Range for multilateration and bearing for triangulations), X stands for the states, namely position of the observer (missile). Kelly [42], derived the DOP formulae for the general case with two points, The derivations for RI, 2PR, and 3PR are performed in this thesis in the following sections.

Considering the missile at x and the i^{th} beacon at xi. The i^{th} beacon measurement can be given by:

$$z_i = f(x, x_i) + v_i \tag{3.42}$$

Where z_i is the measurement, f is a nonlinear measurement equation containing missile and beacon position, v_i is the sensor measurement error which can be regarded as zero mean Gaussian($N(0, \sigma^2_i)$).

Denoting an initial estimate of the observer state by x0, the nonlinear measurement (be a range or bearing) can be linearized around the estimate.

when a function z can be linearized around an estimate of x0 it is possible to write,

$$\begin{aligned} & z = z_0 + \delta z = f(x_0 + \delta x) = f(x_0) + H(x - x_0) \\ & z_0 = f(x_0) \\ & so \\ & \delta z = H\delta x \end{aligned} \tag{3.43}$$

H is the Jacobian of the observer, then systematic and random errors in the observations are related to corresponding errors in the states by, $\delta z = H\delta x$ and measurement covariance Cz .

Cx is the associated state covariance. When the errors are assumed as random variables, covariances are defined as

$$C_z = \exp[\delta z \delta z^T]$$
$$C_x = \exp[\delta x \delta x^T] \tag{3.44}$$

When $\delta z = H\delta x$, then

$$\exp[\delta z \delta z^T] = \exp[H\delta x \delta x^T H^T]$$
$$\exp[\delta z \delta z^T] = H \exp[\delta x \delta x^T] H^T \tag{3.45}$$
$$Cx = \exp[\delta x \delta x^T]$$

$$\boxed{C_z = HC_x H^T}$$

In practice δz is considered known and δx is to be determined. Then

$$\delta x = H^+ \delta z \tag{3.46}$$

where H^+ is the pseudoinverse of H.

$$\delta z = H\delta x$$
$$H^T \delta z = H^T H \delta x \quad \text{when we multiply from left with } H^T \tag{3.47}$$

then we multiply both sides with $(H^T H)^{-1}$ to leave δx alone.

$$(H^T H)^{-1} H^T \delta z = (H^T H)^{-1} H^T H \delta x \tag{3.48}$$

$$\delta x = (H^T H)^{-1} H^T \delta z \tag{3.49}$$

$$\exp[\delta x \delta x^T] = \exp[(H^T H)^{-1} H^T \delta z \delta z^T H (H^T H)^{-1}] \tag{3.50}$$

leads to

$$\boxed{C_x = [H^T C_z^{-1} H]^{-1}} \tag{3.51}$$

We are seeking a measure of geometric interpretation of beacon placement. Jacobian determinant is suggested for this role as geometric dilution of precision.

We want to know how sensor errors are magnified to become pose errors. The GDOP can be loosely defined as,

$$GDOP = \|\delta x\| / \|\delta z\| \tag{3.52}$$

Where $\|\delta x\| and \|\delta z\|$ are the magnitudes of pose and sensor errors.

The mapping between sensor error and pose error is a matrix and any sort of norm of the matrix is a measure of the relative magnifying power of the matrix. Among the choices of norm available, the Jacobian determinant is a convenient choice because it avoids eigenvalue computations. When the observer system is square, the Jacobian determinant expresses the scalar multiplier which converts a differential volume in pose space to its corresponding differential volume in measurement space:

$$\begin{aligned} \|\delta z\| &= H \|\delta x\| \\ \|\delta x\| &= \|H^{-1}\| \|\delta z\| = \left\|\frac{1}{H}\right\| \|\delta z\| \end{aligned} \tag{3.53}$$

Where the volumes of the vectors are $\|\delta x\| = \delta x_1 \delta x_2 \delta x_3$ and $\|\delta z\| = \delta z_1 \delta z_2 \delta z_3$.

And $DOP = \|H^{-1}\|$ is the determinant of the inverse Jacobian.

The notation is intended to represent both the volume of a vector and determinant of a matrix

In the more general case, the measurements are implicit functions of the states.

$$\begin{aligned} & f(x,z) = 0 \\ & [f_z]\delta z = -[f_x]\delta x \\ & where \\ & f_z = \frac{\partial f}{\partial z}, f_x = \frac{\partial f}{\partial x} \end{aligned} \tag{3.54}$$

This system can be solved in either direction by pseudo inverse,

$$\boxed{\begin{aligned} \delta z &= -[f_z]^{+} [f_x] \delta x \\ \delta x &= -[f_x]^{+} [f_z] \delta z \end{aligned}} \tag{3.55}$$

When the system is fully determined, both Jacobians are square. Using the rules for the determinant of a product and the determinant of a matrix inverse, we can use the following.

$$\|H\| = \frac{\|f_x\|}{\|f_z\|}$$
$$\|H^{-1}\| = \frac{\|f_z\|}{\|f_x\|} \qquad (3.56)$$

3.12.2 GDOP for Lateration (Range Measurement) With Two Beacons

For range measurements from two beacons, measurements are r1 and r2 and states are x and y of the observer.

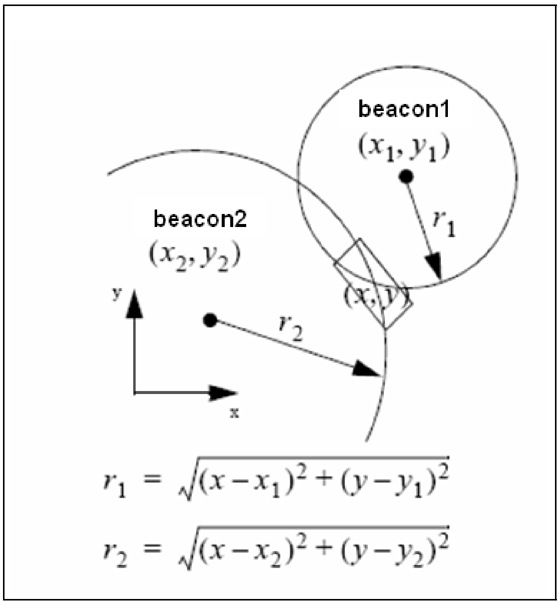


Figure 3-8 Lateration geometry for two beacons [42]

$$\begin{bmatrix} dr_1 \\ dr_2 \end{bmatrix} = \begin{bmatrix} \frac{\partial r_1}{\partial x} & \frac{\partial r_1}{\partial y} \\ \frac{\partial r_2}{\partial x} & \frac{\partial r_2}{\partial y} \end{bmatrix} \begin{bmatrix} dx \\ dy \end{bmatrix} \qquad (3.57)$$

$$r_1 = \sqrt{(x-x_1)^2 + (y-y_1)^2}$$
$$r_2 = \sqrt{(x-x_2)^2 + (y-y_2)^2} \tag{3.58}$$

$$\frac{\partial r_1}{\partial x} = \frac{(x-x_1)}{r_1} \quad \frac{\partial r_1}{\partial y} = \frac{(y-y_1)}{r_1}$$
$$\frac{\partial r_2}{\partial x} = \frac{(x-x_2)}{r_2} \quad \frac{\partial r_2}{\partial y} = \frac{(y-y_2)}{r_2} \tag{3.59}$$

Since cross product of two vectors is defined as

$$r_1 \times r_2 = r_1 r_2 \sin\theta = \begin{vmatrix} a_1 & b_1 \\ a_2 & b_2 \end{vmatrix} = a_1 b_1 - a_2 b_2 \tag{3.60}$$

$$\|H\| = \frac{(x-x_1)}{r_1}\frac{(y-y_2)}{r_2} - \frac{(y-y_1)}{r_1}\frac{(x-x_2)}{r_2}$$
$$\|H\| = \frac{r_1 \times r_2}{\|r_1\|\|r_2\|} = \sin\theta \tag{3.61}$$

$\boxed{\|H^{-1}\| = \frac{1}{\sin\theta}}$ = DOP for distance measurements from two beacons.

It is seen that for distance measurements better positioning accuracy can be obtained when the apex angle is near 90 degrees. The GDOP tends to infinity when either the observer is on the line between the beacons or when it is so far away that the position parallel to the line between them becomes unconstrained.

3.12.3 GDOP for Triangulation (Bearing Measurement) With Two Beacons

In this case two bearings are taken from the observation point to two beacons.

Measurements are θ_1 and θ_2 which are measured from same reference.

Forming $f(x,z) = 0$

$$\sin\theta_1(x_1 - x) - \cos\theta_1(y_1 - y) = 0$$
$$\sin\theta_2(x_2 - x) - \cos\theta_2(y_2 - y) = 0 \qquad (3.62)$$

Letting $\begin{matrix}\Delta x_i = x_i - x \\ \Delta y_i = y_i - y\end{matrix}$ and remembering $\left\|H^{-1}\right\| = \dfrac{\|f_z\|}{\|f_x\|}$

$$\|f_x\| = \begin{Vmatrix}\dfrac{\partial f_1}{\partial x} & \dfrac{\partial f_1}{\partial y} \\ \dfrac{\partial f_2}{\partial x} & \dfrac{\partial f_2}{\partial y}\end{Vmatrix} = \begin{Vmatrix}-\sin\theta_1 & \cos\theta_1 \\ -\sin\theta_2 & \cos\theta_2\end{Vmatrix} = -\sin\theta_1\cos\theta_2 + \cos\theta_1\sin\theta_2 \qquad (3.63)$$

Since $\sin(A - B) = \sin A\cos B - \cos A\sin B$

$$\|f_x\| = \sin(\theta_2 - \theta_1) = \sin\theta$$

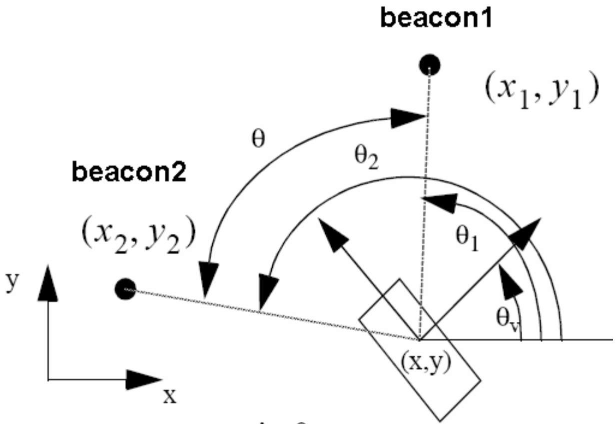
$$\|f_z\| = \begin{Vmatrix}\dfrac{\partial f_1}{\partial \theta_1} & \dfrac{\partial f_1}{\partial \theta_2} \\ \dfrac{\partial f_2}{\partial \theta_1} & \dfrac{\partial f_2}{\partial \theta_2}\end{Vmatrix} = \begin{Vmatrix}\cos\theta_1\Delta x_1 + \sin\theta_1\Delta y_1 & 0 \\ 0 & \cos\theta_2\Delta x_2 + \sin\theta_2\Delta y_2\end{Vmatrix} \qquad (3.64)$$

Since $\cos\theta_1 = \dfrac{\Delta x_1}{|r_1|}$ *and* $\sin\theta_1 = \dfrac{\Delta y_1}{|r_1|}$

$$\|f_z\| = \begin{Vmatrix}\dfrac{\partial f_1}{\partial \theta_1} & \dfrac{\partial f_1}{\partial \theta_2} \\ \dfrac{\partial f_2}{\partial \theta_1} & \dfrac{\partial f_2}{\partial \theta_2}\end{Vmatrix} = \begin{Vmatrix}\dfrac{\Delta x_1^2}{|r_1|} + \dfrac{\Delta y_1^2}{|r_1|} & 0 \\ 0 & \dfrac{\Delta x_2^2}{|r_2|} + \dfrac{\Delta y_2^2}{|r_2|}\end{Vmatrix} = \frac{r_1.r_1}{|r_1|}\frac{r_2.r_2}{|r_2|} = |r_1||r_2| \qquad (3.65)$$

$$\boxed{\left\|H^{-1}\right\| = \frac{\|f_z\|}{\|f_x\|} = \frac{r_1 r_2}{\sin\theta}} \qquad (3.66)$$

From this expression of DOP it is understood that better position updates can be obtained when the apex angle is near to 90 degrees and the distances of beacons to the observer is small.



$$\tan\theta_1 = \frac{\sin\theta_1}{\cos\theta_1} = \frac{y_1 - y}{x_1 - x}$$

$$\tan\theta_2 = \frac{\sin\theta_2}{\cos\theta_2} = \frac{y_2 - y}{x_2 - x}$$

Figure 3-9 GDOP for triangulation to two beacons [42]

3.12.4 GDOP for Reverse Intersection Method

The primary form of the observation geometry is given in. B and C are known points. A is the point whose coordinates are to be found. With this form this problem is similar to the above method.

In general, this method is used to find the position of point A when B and C point coordinates are known. In the original form of the method, position of point A can be found when the coordinates of point B and C are known, the interior angles from B and C to A are measured and the vertical angles from B and C to A are also measured. Then the sine theorem can be used to obtain the unknowns. in the thesis point B and C coordinates are estimated by INS and point A coordinate is known.

In terms of geometry and measured angles, there is not much difference between the 2 pt triangulation and reverse intersection. As shown in Figure 3-10.

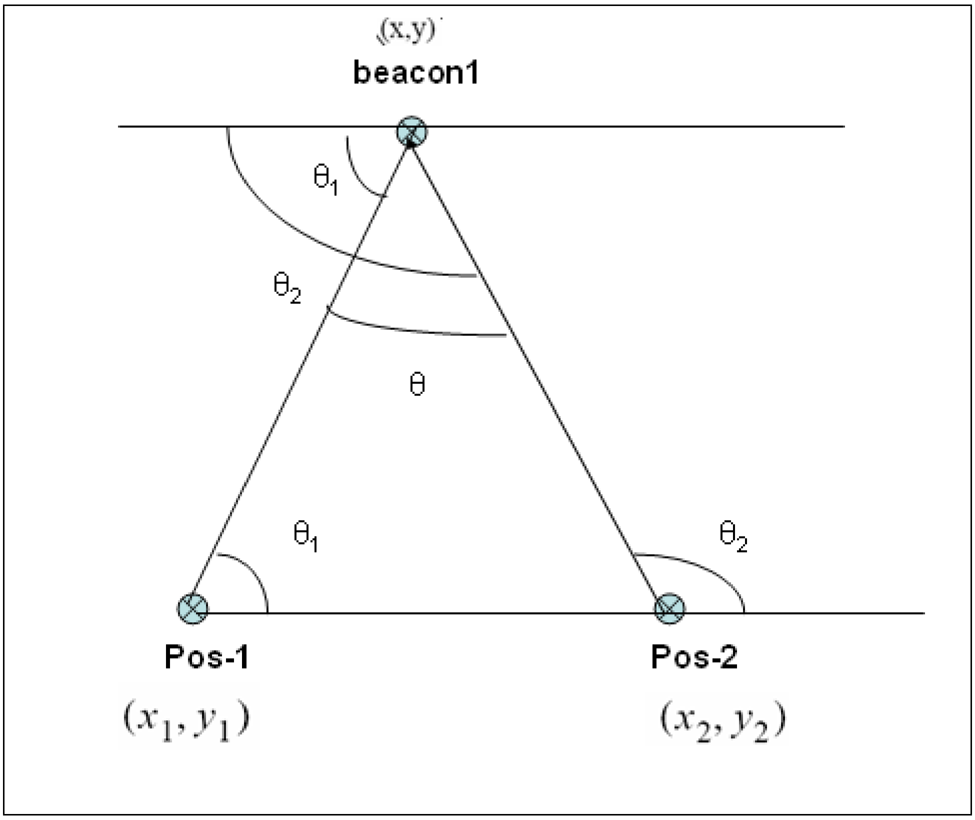


Figure 3-10 Reverse intersection geometry

$$\text{GDOP for reverse intersection } = \left\| H^{-1} \right\| = \frac{\left\| f_z \right\|}{\left\| f_x \right\|} = \frac{r_1 r_2}{\sin\theta} \tag{3.67}$$

3.12.5 GDOP for Three Point Resection

The coordinates of P1, P2 and P3 are known in UTM coordinates. (Easting, Northing, Height), and the horizontal and vertical angles from P to P1, P2 and P3 are measured by the missile seeker. (or converted to horizontal vertical coordinate system). So the angles Φ_{12} and Φ_{23} are measured. None of the distances from point P to known stations are measured or known. For the calculation of DOP, a similar scheme is constructed.

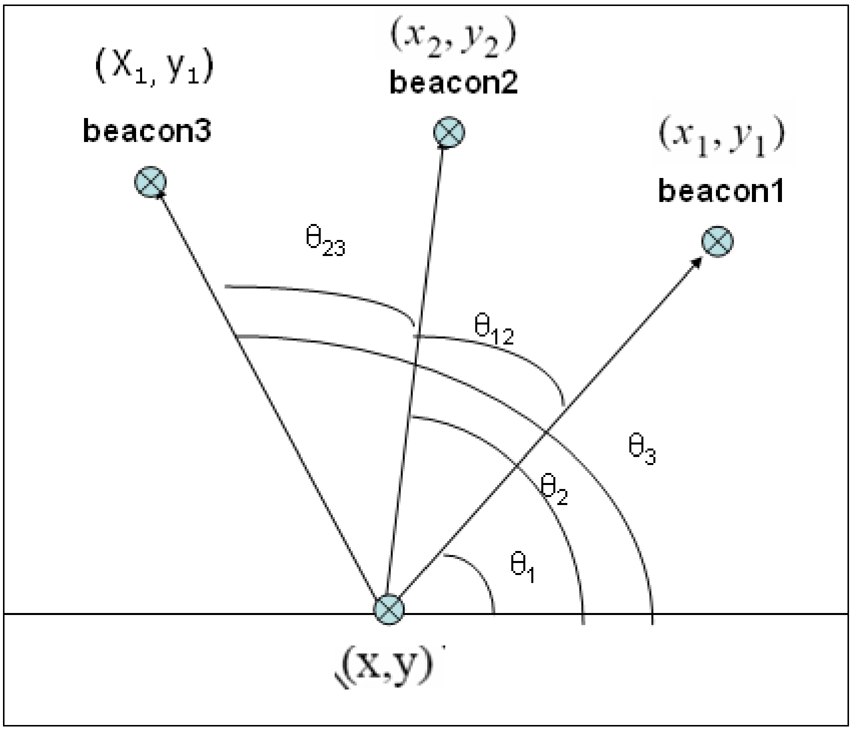


Figure 3-11 Three point resection measurements and states

At an instant seeker locks on three beacons and measures the angles between them (Figure 3-11).

$$Z = \begin{bmatrix} \theta_{12} \\ \theta_{23} \end{bmatrix} \qquad \theta_{12} = \theta_2 - \theta_1 \qquad \theta_{23} = \theta_3 - \theta_2 \tag{3.68}$$

$$\begin{aligned} \tan\theta_1 &= \frac{y_1 - y}{x_1 - x} = \frac{\sin\theta_1}{\cos\theta_1} \\ \tan\theta_2 &= \frac{y_2 - y}{x_2 - x} = \frac{\sin\theta_2}{\cos\theta_2} \\ \tan\theta_3 &= \frac{y_3 - y}{x_3 - x} = \frac{\sin\theta_3}{\cos\theta_3} \end{aligned} \tag{3.69}$$

$$\begin{aligned} f_1 &= \theta_{12} - \theta_2 + \theta_1 \\ f_2 &= \theta_{23} - \theta_3 + \theta_2 \end{aligned} \tag{3.70}$$

$$f_1 = \theta_{12} - \arctan\frac{y_2 - y}{x_2 - x} + \arctan\frac{y_1 - y}{x_1 - x}$$

$$f_2 = \theta_{23} - \arctan\frac{y_3 - y}{x_3 - x} + \arctan\frac{y_2 - y}{x_2 - x} \tag{3.71}$$

$$\|f_z\| = \begin{Vmatrix} \dfrac{\partial f_1}{\partial \theta_{12}} & \dfrac{\partial f_1}{\partial \theta_{23}} \\ \dfrac{\partial f_2}{\partial \theta_{12}} & \dfrac{\partial f_2}{\partial \theta_{23}} \end{Vmatrix} = \begin{Vmatrix} 1 & 0 \\ 0 & 1 \end{Vmatrix} = 1 \tag{3.72}$$

$$\|f_x\| = \begin{Vmatrix} \dfrac{\partial f_1}{\partial x} & \dfrac{\partial f_1}{\partial y} \\ \dfrac{\partial f_2}{\partial x} & \dfrac{\partial f_2}{\partial y} \end{Vmatrix} \tag{3.73}$$

$$(\arctan x)' = \frac{1}{1 + x^2} \text{ and since } \cos\theta_i = \frac{\Delta x_i}{|r_i|} \, and \sin\theta_i = \frac{\Delta y_i}{|r_i|}$$

$$\Delta x_i = x_i - x$$

$$\Delta y_i = y_i - y \tag{3.74}$$

$$\frac{\partial f_1}{\partial x} = -\frac{1}{1 + \left(\dfrac{\Delta y_2}{\Delta x_2}\right)^2} .\Delta y_2 \frac{-1}{(\Delta x_2)^2}.(-1) + \frac{1}{1 + \left(\dfrac{\Delta y_1}{\Delta x_1}\right)^2} \Delta y_1 \frac{-1}{(\Delta x_1)^2}(-1)$$

$$\frac{\partial f_1}{\partial x} = -\frac{\Delta y_2}{\dfrac{(\Delta x_2)^2 + (\Delta y_2)^2}{(\Delta x_2)^2}} \cdot \frac{1}{(\Delta x_2)^2} + \frac{\Delta y_1}{\dfrac{(\Delta x_1)^2 + (\Delta y_1)^2}{(\Delta x_1)^2}} \cdot \frac{1}{(\Delta x_1)^2} \tag{3.75}$$

$$\frac{\partial f_1}{\partial x} = \frac{\Delta y_1}{|r_1|^2} - \frac{\Delta y_2}{|r_2|^2}$$

$$\frac{\partial f_1}{\partial y} = -\frac{1}{1+\left(\frac{\Delta y_2}{\Delta x_2}\right)^2}\frac{1}{(\Delta x_2)}.(-1) + \frac{1}{1+\left(\frac{\Delta y_1}{\Delta x_1}\right)^2}\frac{1}{(\Delta x_1)}(-1)$$

$$\frac{\partial f_1}{\partial y} = \frac{\Delta x_2}{(\Delta x_2)^2 + (\Delta y_2)^2} - \frac{\Delta x_1}{(\Delta x_1)^2 + (\Delta y_1)^2} \qquad (3.76)$$

$$\frac{\partial f_1}{\partial y} = \frac{\Delta x_2}{|r_2|^2} - \frac{\Delta x_1}{|r_1|^2}$$

$$\frac{\partial f_2}{\partial x} = -\frac{1}{1+\left(\frac{\Delta y_3}{\Delta x_3}\right)^2}.\Delta y_3 \frac{-1}{(\Delta x_3)^2}.(-1) + \frac{1}{1+\left(\frac{\Delta y_2}{\Delta x_2}\right)^2}\Delta y_2 \frac{-1}{(\Delta x_2)^2}(-1)$$

$$\frac{\partial f_2}{\partial x} = -\frac{\Delta y_3}{\frac{(\Delta x_3)^2 + (\Delta y_3)^2}{(\Delta x_3)^2}}.\frac{1}{(\Delta x_3)^2} + \frac{\Delta y_2}{\frac{(\Delta x_2)^2 + (\Delta y_2)^2}{(\Delta x_2)^2}}.\frac{1}{(\Delta x_2)^2} \qquad (3.77)$$

$$\frac{\partial f_2}{\partial x} = \frac{\Delta y_2}{|r_2|^2} - \frac{\Delta y_3}{|r_3|^2}$$

$$\frac{\partial f_2}{\partial y} = -\frac{1}{1+\left(\frac{\Delta y_3}{\Delta x_3}\right)^2}\frac{1}{(\Delta x_3)}.(-1) + \frac{1}{1+\left(\frac{\Delta y_2}{\Delta x_2}\right)^2}\frac{1}{(\Delta x_2)}(-1)$$

$$\frac{\partial f_2}{\partial y} = \frac{\Delta x_3}{(\Delta x_3)^2 + (\Delta y_3)^2} - \frac{\Delta x_2}{(\Delta x_2)^2 + (\Delta y_2)^2} \qquad (3.78)$$

$$\frac{\partial f_2}{\partial y} = \frac{\Delta x_3}{|r_3|^2} - \frac{\Delta x_2}{|r_2|^2}$$

$$\|f_z\| = \left\| \begin{matrix} \left(\frac{\Delta y_1}{|r_1|^2} - \frac{\Delta y_2}{|r_2|^2}\right) & \left(\frac{\Delta x_2}{|r_2|^2} - \frac{\Delta x_1}{|r_1|^2}\right) \\ \left(\frac{\Delta y_2}{|r_2|^2} - \frac{\Delta y_3}{|r_3|^2}\right) & \left(\frac{\Delta x_3}{|r_3|^2} - \frac{\Delta x_2}{|r_2|^2}\right) \end{matrix} \right\| \qquad (3.79)$$

Since $\cos\theta_i = \frac{\Delta x_i}{|r_i|}$ *and* $\sin\theta_i = \frac{\Delta y_i}{|r_i|}$

$$\|f_z\| = \left\| \begin{matrix} \left(\dfrac{\sin\theta_1}{|r_1|} - \dfrac{\sin\theta_2}{|r_2|} \right) & \left(\dfrac{\cos\theta_2}{|r_2|} - \dfrac{\cos\theta_1}{|r_1|} \right) \\ \left(\dfrac{\sin\theta_2}{|r_2|} - \dfrac{\sin\theta_3}{|r_3|} \right) & \left(\dfrac{\cos\theta_3}{|r_3|} - \dfrac{\cos\theta_2}{|r_2|} \right) \end{matrix} \right\| \tag{3.80}$$

Taking the determinant

$$\|f_z\| = \frac{\sin\theta_1}{|r_1|}\frac{\cos\theta_3}{|r_3|} - \frac{\sin\theta_1}{|r_1|}\frac{\cos\theta_2}{|r_2|} - \frac{\sin\theta_2}{|r_2|}\frac{\cos\theta_3}{|r_3|} + \frac{\sin\theta_2}{|r_2|}\frac{\cos\theta_2}{|r_2|}$$
$$-\left[\frac{\sin\theta_2}{|r_2|}\frac{\cos\theta_2}{|r_2|} - \frac{\sin\theta_2}{|r_2|}\frac{\cos\theta_1}{|r_1|} - \frac{\sin\theta_3}{|r_3|}\frac{\cos\theta_2}{|r_2|} + \frac{\sin\theta_3}{|r_3|}\frac{\cos\theta_1}{|r_1|} \right] \tag{3.81}$$

$$\begin{aligned} \|f_z\| = {} & \\ & \frac{\sin\theta_1}{|r_1|}\frac{\cos\theta_3}{|r_3|} - \frac{\sin\theta_3}{|r_3|}\frac{\cos\theta_1}{|r_1|} \\ & + \frac{\sin\theta_2}{|r_2|}\frac{\cos\theta_1}{|r_1|} - \frac{\sin\theta_1}{|r_1|}\frac{\cos\theta_2}{|r_2|} \\ & + \frac{\sin\theta_3}{|r_3|}\frac{\cos\theta_2}{|r_2|} - \frac{\sin\theta_2}{|r_2|}\frac{\cos\theta_3}{|r_3|} \\ & + \frac{\sin\theta_2}{|r_2|}\frac{\cos\theta_2}{|r_2|} - \frac{\sin\theta_2}{|r_2|}\frac{\cos\theta_2}{|r_2|} \end{aligned} \tag{3.82}$$

By using $\sin(A-B) = \sin A\cos B - \cos A \sin B$

$$\|f_z\| = \frac{\sin(\theta_1-\theta_3)}{|r_1||r_3|} + \frac{\sin(\theta_2-\theta_1)}{|r_2||r_1|} + \frac{\sin(\theta_3-\theta_2)}{|r_3||r_2|} + 0 \tag{3.83}$$

Since $\begin{aligned}\theta_{12} &= \theta_2 - \theta_1 \\ \theta_{23} &= \theta_3 - \theta_2\end{aligned}$

$$\|f_z\| = \frac{\sin(\theta_{13})}{|r_1||r_3|} + \frac{\sin(\theta_{12})}{|r_2||r_1|} + \frac{\sin(\theta_{23})}{|r_3||r_2|} \tag{3.84}$$

And $\begin{aligned}\sin(\theta_{13}) &= \sin(\theta_3 - \theta_1) \\ \sin(\theta_{31}) &= \sin(\theta_1 - \theta_3) = -\sin(\theta_3 - \theta_1)\end{aligned}$

$$\|f_z\| = \frac{|r_3|\sin(\theta_{12}) + |r_1|\sin(\theta_{23}) - |r_2|\sin(\theta_{13})}{|r_1||r_2||r_3|} \tag{3.85}$$

$$\boxed{\|H^{-1}\| = \frac{|r_1||r_2||r_3|}{|r_3|\sin(\theta_{12}) + |r_1|\sin(\theta_{23}) - |r_2|\sin(\theta_{13})}} \tag{3.86}$$

This expression shows that the three point resection performance increases when the distances from the missile to the beacons are closer. And the combination of angles is as given.

3.12.6 GDOP for Two Point Resection

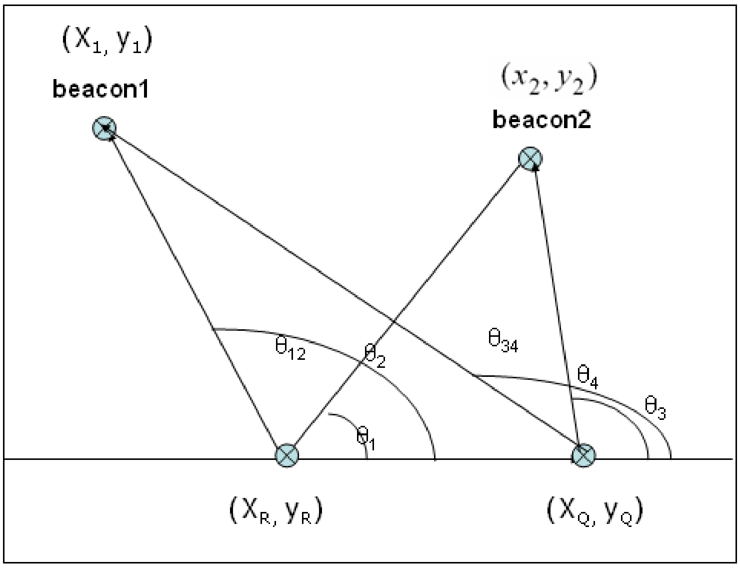


Figure 3-12 Two point resection measurements and states

Measurements are $\theta_1, \theta_2, \theta_3, \theta_2$ (Figure 3-12)

States to be determined are $x = \begin{bmatrix} x_R & y_R & x_Q & y_Q \end{bmatrix}$

$$\begin{aligned} \theta_{12} &= \theta_2 - \theta_1 \\ \theta_{34} &= \theta_4 - \theta_3 \end{aligned} \tag{3.87}$$

$$\begin{aligned}
\tan\theta_1 &= \frac{y_1 - y_R}{x_1 - x_R} = \frac{\sin\theta_1}{\cos\theta_1} \\
\tan\theta_2 &= \frac{y_2 - y_R}{x_2 - x_R} = \frac{\sin\theta_2}{\cos\theta_2} \\
\tan\theta_3 &= \frac{y_1 - y_Q}{x_1 - x_Q} = \frac{\sin\theta_3}{\cos\theta_3} \\
\tan\theta_4 &= \frac{y_2 - y_Q}{x_2 - x_Q} = \frac{\sin\theta_4}{\cos\theta_4}
\end{aligned} \tag{3.88}$$

Forming $f(x,z)=0$

$$\begin{aligned}
&\sin\theta_1(x_1 - x_R) - \cos\theta_1(y_1 - y_R) = 0 \\
&\sin\theta_2(x_2 - x_R) - \cos\theta_2(y_2 - y_R) = 0 \\
&\sin\theta_3(x_1 - x_Q) - \cos\theta_3(y_1 - y_Q) = 0 \\
&\sin\theta_4(x_2 - x_Q) - \cos\theta_4(y_2 - y_Q) = 0
\end{aligned} \tag{3.89}$$

Letting $\Delta x_{ij} = x_i - x_j$; $\Delta y_{ij} = y_i - y_j$; where $i = 1,2$; $J = R,Q$.

The determinant of a block diagonal matrix is the multiplication of its block determinants.

$$\left\| f_x \right\| = \left\| \begin{matrix}
\frac{\partial f_1}{\partial x_R} & \frac{\partial f_1}{\partial y_R} & \frac{\partial f_1}{\partial x_Q} & \frac{\partial f_1}{\partial y_Q} \\
\frac{\partial f_2}{\partial x_R} & \frac{\partial f_2}{\partial y_R} & \frac{\partial f_2}{\partial x_Q} & \frac{\partial f_2}{\partial y_Q} \\
\frac{\partial f_3}{\partial x_R} & \frac{\partial f_3}{\partial y_R} & \frac{\partial f_3}{\partial x_Q} & \frac{\partial f_3}{\partial y_Q} \\
\frac{\partial f_4}{\partial x_R} & \frac{\partial f_4}{\partial y_R} & \frac{\partial f_4}{\partial x_Q} & \frac{\partial f_4}{\partial y_Q}
\end{matrix} \right\| = \left\| \begin{matrix}
-\sin\theta_1 & \cos\theta_1 & 0 & 0 \\
-\sin\theta_2 & \cos\theta_2 & 0 & 0 \\
0 & 0 & -\sin\theta_3 & \cos\theta_3 \\
0 & 0 & -\sin\theta_4 & \cos\theta_4
\end{matrix} \right\| \tag{3.90}$$

$$= \sin\left(\theta_{12}\right)\sin\left(\theta_{34}\right)$$

$$\|f_z\| = \begin{Vmatrix} \frac{\partial f_1}{\partial \theta_1} & \frac{\partial f_1}{\partial \theta_2} & \frac{\partial f_1}{\partial \theta_3} & \frac{\partial f_1}{\partial \theta_4} \\ \frac{\partial f_2}{\partial \theta_1} & \frac{\partial f_2}{\partial \theta_2} & \frac{\partial f_2}{\partial \theta_3} & \frac{\partial f_2}{\partial \theta_4} \\ \frac{\partial f_3}{\partial \theta_1} & \frac{\partial f_3}{\partial \theta_2} & \frac{\partial f_3}{\partial \theta_3} & \frac{\partial f_3}{\partial \theta_4} \\ \frac{\partial f_4}{\partial \theta_1} & \frac{\partial f_4}{\partial \theta_2} & \frac{\partial f_4}{\partial \theta_3} & \frac{\partial f_4}{\partial \theta_4} \end{Vmatrix} \tag{3.91}$$

$$\|f_z\| = \begin{Vmatrix} \cos\theta_1 \Delta x_{1R} + \sin\theta_1 \Delta y_{1R} & 0 & 0 & 0 \\ 0 & \cos\theta_2 \Delta x_{1R} + \sin\theta_2 \Delta y_{1R} & 0 & 0 \\ 0 & 0 & \cos\theta_3 \Delta x_{1Q} + \sin\theta_3 \Delta y_{1Q} & 0 \\ 0 & 0 & 0 & \cos\theta_4 \Delta x_{1Q} + \sin\theta_4 \Delta y_{1Q} \end{Vmatrix} \tag{3.92}$$

$$\|f_z\| = |r_{1R}||r_{2R}||r_{1Q}||r_{2Q}| \tag{3.93}$$

$$\boxed{\|H^{-1}\| = \frac{\|f_z\|}{\|f_x\|} = \frac{|r_{1R}||r_{2R}||r_{1Q}||r_{2Q}|}{\sin(\theta_{12})\sin(\theta_{34})}} \tag{3.94}$$

3.13 Conclusion

In this chapter, position fixing methods are investigated; three methods are proposed to be used for position updates of the platform by using bearing and elevation measurements to beacons. Algorithms for the proposed methods based on angle measurements are introduced. The limitations of the methods are given both literally and by the derivation of dilution of precision formulas that are in consistency with the literal limitations. In the following chapters, information about the decision maker which selects suitable methods based on several variables will be introduced and implementation of methods will be narrated.

CHAPTER IV

OPTIMAL MISSION PLANNING

4.1 Introduction

In this chapter, mission planning problems are analyzed and two classes of problems are defined as path planning problem, where an optimal trajectory is defined based on a given network of beacons, and deployment problem where optimal deployment of beacons are tried to be found for a given reference trajectory. Other possible extensions fall into subsets of these two main categories.

In order to construct a mission planner, evolutionary algorithms are analyzed and a genetic algorithm for solving path planning and deployment problems is constituted based on a variable length chromosome structure.

4.2 Mission Planning Problems

When dealing with the alternative beacon navigation system in an effort to minimize the effects of GNSS jamming, it is necessary to analyze the effects of deployment of beacons.

The ultimate goal for a mission planner is to guarantee that the missile system reaches the terminal area within acceptable limits.

Another important factor is the capability to execute the planned trajectory of the missile throughout the flight. The planned (reference) trajectory may come from a higher echelon decision system which may take into account several factors such as avoiding air defense sites, radar coverage areas or some type of terrain. In that case, the mission planner has to decide where the beacons are to be deployed to provide position updates when required, with the minimum number of beacons possible. In beacon navigation concept, deviations from the desired trajectory may also deteriorate the ability to see the next beacon.

Another face of the problem is to plan a trajectory for a given deployment of beacons. For multiple engagements occurring in a conflict area or navigation in friendly environment, it will be necessary to use a previously laid network of beacons. In that case the trajectory of the vehicle must be planned to pass near as many beacons as possible while considering other constraints such as path length, and turn rate.

The optimization problem may be formulated with many possible objective functions. Possible objective functions (some of them are conflicting), some of which can also be modeled as constraints are given as:

- Minimize location error in terminal phase.
- Minimize location error in midcourse phase
- Minimize number of beacons.
- Minimize cost of beacon deployment
- Minimize FOM throughout the area of deployment
- Maximize coverage area in the area of deployment
- Minimize path length

The problem can be treated as a single objective function with constraints or a multi-objective function. However a multiobjective optimization problem with conflicting objectives ends up with a Pareto frontier where the military authority is obliged to select the relative importance of a parameter from another. This is not a straightforward task.

In this thesis the optimization problems are formulated as single objective constrained optimization problems. The problems are defined as follows.

4.2.1 Path Planning Problem

Path planning problem is defined literally as: “For a given deployment of beacons, what must be path of the aerial vehicle, which provides beast position fix opportunities within maximum range, turn rate limit, position update quality, FOV and FOR constraints?“

The launch site coordinates and target coordinates are known. Beacon deployment scheme is given. A trajectory which can benefit from the beacons to perform high quality position updates while not violating the path length, FOV and FOR constraints is to be found.

Constraints can be stated as,

- Maneuver constraints such as heading change limit.
- There must be at least one beacon visible for position update.
- There must be 3 beacons visible in FOV at an observation instant for three point resection type position update. .
- Beacons must not be collinear at the time of position update.
- Beacons must not lie on a circle.
- 2 beacons and missile must not be collinear at the time of position update. .
- 3 beacons and missile must not be collinear.

4.2.2 Deployment Problem

A reference trajectory for the aerial vehicle is given. The reference trajectory is the route that the mission planner wants the missile to execute. The reference trajectory can be determined by taking several considerations into account.

Missile launch site location may dictate some maneuvers. Missile may have to pass through valleys, critical passages of surface shapes etc. Several maneuvers may exist to achieve this goal. Missile must avoid enemy air defense installations and radar sites to avoid detection and minimize the risk of being hit.

The deployment problem can be stated as follows, “Given a reference trajectory, what must be the deployment of beacons so that the missiles’ possible deviation from the planned reference trajectory is limited and terminal phase error is minimized.“

The relative importance of the missile’s capability to execute a previously defined reference trajectory with respect to the terminal phase accuracy is a merit that is to be determined by the military authority. Several missions may require accurate midcourse navigation to avoid several regions, surface shapes and manmade barriers such as air defense sites or radar installations.

This problem has the following characteristics.

1. There is a given desired path. (Reference trajectory)
2. There are multiple realizations of desired path under the effects of random INS error propagation, Missile may execute several trajectories under the effects of INS errors which are not known before.
3. At each beacon deployment scenario the trajectory of the missile in each real world run will give different results and change the trajectory of the missile, which changes the trajectory of the missile regarding the guidance system that tries to steer to the reference trajectory. So solving the optimization problem for all possible realizations of missile real world trajectories is an ineffective method.

However

- If the guidance is smooth and aggressive maneuvers are not performed, the change in trajectory may not change the sensor error behavior too much.
- The trajectory modification performed by the missile guidance system can be assumed small when compared with the overall trajectory of the missile system.
- Since the true trajectory of the missile can never be known, it is natural to optimize the beacon deployment on the reference trajectory by using

evolutionary algorithms and then check for the several realizations by using simpler simulations.

The approach followed in this thesis is,

1. to perform optimization based on covariance values for the desired path (reference trajectory)
2. Obtain beacon deployment scheme based on optimization algorithm.
3. Show that for several real world realizations of the missile flight trajectory options, showing that the obtained beacon deployment serves the purpose of maintaining near to the desired reference trajectory under guidance system maneuvers.

4.3 Optimization Algorithm

4.3.1 General Information about Evolutionary Algorithms

The sources of evolutionary computing are based on creation of linkage with the genetics. Darwin's theory of evolution emphasizes forces of evolution as survival of the fittest, where individuals with genes that are capable of maintaining and adapting their life in changing circumstances (ecological selection), and with sexual attractiveness (sexual selection) are more likely to pass their gene content to next generations. Recombination, mutation, gene flow and genetic drift are other operators in evolution. Genetic drift is the random increase or decrease in the trait frequencies in the gene pool of a population. Gene flow is the movement of genes from one population to the other which introduces and spreads new alleles to new population.

The human genetic heritage is coded in 32.000 genes in 46 chromosomes. Several genes can affect phenotypical characteristics.

Evolutionary computation methods try to mimic the evolution by using the elements of evolution such as reproduction, random variation, competition in order to achieve global maxima particularly in a large search space. Evolutionary computation methods deal with nonlinear, stochastic problems with multiple local optima.

Evolutionary algorithms are used in several challenging engineering problems, in aircraft design, wireless sensor networks, air traffic control scheduling, weapon target assignment problems, path planning etc. There are several forms of evolutionary algorithms; however there is no superior algorithm to solve all class of problems.

Evolutionary algorithms vary depending on (CENG-713 [43]):

- Representation/encoding of an individual (binary, integer, floating point, or data structures,)
- Population size and organization (multiple populations, parallel evolving populations, single individual populations,)
- The time of selection and selection procedure (selection for recombination, selection survival,)
- Recombination, mutation procedures

4.3.2 Genetic Algorithm

Genetic algorithm is a popular search algorithm with stochastic nature which utilizes multiple solutions that span a search space unlike the deterministic search techniques which stuck to local optimum in problems with multiple local optima.

The genetic algorithms are first devised by Holland, characterized by linear bit-string representation of chromosomes, fitness proportional selection and crossover operators. Genetic algorithms denote a class of evolutionary algorithms having a linear array representation for a group of individuals, and new generations of population are created by crossover, mutation and selection. Each chromosome is a candidate solution to the problem and each meaningful brick of the chromosome is a gene.

There are several variations in chromosome representations as binary integer, floating point representations, selection of population size, crossover and mutation rates etc.

Genetic algorithms approach is often criticized by lack of theoretical basis. There are two main theorems that try to explain the theoretical basis of the genetic algorithms.

Schema Theorem (Holland): Short, low order, above-average schemata (sequence of matching bits in a solution candidate) receive exponentially increasing trials in subsequent generations of a genetic algorithm.

Building Block Hypothesis (Goldberg): A genetic algorithm seeks near-optimal performance through the juxtaposition of short, low-order, high performance schemata called the building blocks.

4.3.2.1 The Genetic Algorithm Terminology

Some terms involved in genetic algorithms are defined as follows,

Fitness: Objective function that is to be optimized. Best fitness value is the smallest fitness value for a genome in a population. For multiobjective optimization normalization of fitness values for each objective in order to evade the dominance of an objective due to unit difference is performed. One way of doing this is to normalize the objective function value using the desired range of the objective function.

Individual / genome / chromosome: A solution of the problem.

Population: Array of individuals

Diversity: Average distance between individuals in population. Diversity is essential to a GA because it enables the GA to search a wider space.

Parents and children: Algorithm selects fitter individuals to generate the next generation by several selection operators.

Crossover: A process of information exchange of genetic material that occurs between adjacent chromatids during meiosis.

Genotype: The sum of inherited characters maintained within the entire reproducing population.

Phenotype: The behavioral expression of the genotype in a specific environment.

4.3.2.2 Comparison with Classical Methods

In dealing with the optimization problems defined in this thesis, GA is used. Genetic algorithms have several advantages over gradient methods.

- Population represents a collected statistics about the search space.
- Exploring search space while using the information gathered during the evolution.
- Suitable for discontinuous functions, non-differentiable, multimodal, noisy surfaces.
- Can be used when numerical differentiation causes problems in some types of problems.
- Provide a list of optimum values, not single solution.
- Work with analytical functions, numerically generated data, experimental data.
- They are suitable for parallel computers.
- Simultaneously search for a wide sampling of search space.

A classical gradient based algorithm generates a single point at each iteration, while a genetic algorithm generates a population of points best of which hopefully reaches optimum solution.

A gradient method selects the next point in the sequence by a deterministic manner, while GA selects the next population by several computations that use random number generators.

Genetic algorithms are suitable for problems that contain multiple local minima, where gradient methods may stuck. GA's may also converge on local minima by premature convergence but the chances are lower.

In this thesis a large area is to be investigated, and obtaining a single fitness value requires a simulation to be run. The fitness function is not analytical and its behavior can not be known a priori. There are several nonlinear effects and position updates cause sudden changes in the value of the covariances. Taking the derivative of the objective function is possible by running the simulation 2 or three times to get the first derivative value.

Three dimensional multiple beacon positions and waypoint positions can be implemented to the chromosome structure directly and by using variable length chromosome genetic algorithm (VLCGA) it is possible to analyze situations for different beacon numbers in a single optimization solution. VLCGA structure has a distinct advantage over other optimization methods since it is possible to see the effects of several numbers of deployed beacons in one run and obtain the result of one less beacon deployment. This provides the decision maker (human in this case) to perform a trade off for deploying one beacon less to the performance difference.

GA is more versatile to analyze different objective functions without changing its structure and does not require a sophisticated knowledge of the behavior of the objective function of the problem.

In the literature path planning problems are generally solved by genetic algorithms, provided that computer power is enough.

4.3.2.3 Literature on Optimal Placement Algorithms

Jıa [44] investigates parallel evolutionary computation to avoid premature convergence for UAV path planning for a shortest path problem.

Zhoa [45] uses GA to plan the path under the constraints such as shortest path, shortest length of first and consecutive segments etc.

Allaire, et al [46], claims that GA is the solution method for UAV path planning that outperforms other methods thanks to its ability to explore search space while preserving best solutions already found.

Nirup [47] deals with adding new beacons on an existing network and gives information about the max and grid methods that are used to find additional beacon adding points that are previously laid by random placement. The localization error is found by a DGPS equipped reference rover to measure actual position and localization result from the existing beacon network for indoor localization.

In robotics, art gallery and pursuit evasion (Besma [35]) problems have been well studied. In the “art-gallery” analogy, the robot’s goal is to move from one position to another to maximize visual coverage of its surroundings, as a human might try to do in a gallery. A complementary set of approaches addresses the pursuit-evasion problem in which a robot tries to move so as to evade observation or capture by mobile trackers. However these approaches are based on modeling the environment as a polygon and account for neither the noise nor the wide variety of terrain conditions one would expect to encounter for ad hoc sensor networks as stated in Nirup [47]. It is also stated that the sources of error in localization are due to beacon placement and density in proximity based systems while it is dependent on geometry for multilateration involving systems.

Hegazy [48] works on dynamic deployment of sensor nodes, deals with a well-defined tracking problem, which can be shown to be an NP-hard problem. First, a stochastic target motion model that can be used by agents for dynamic deployment is introduced. Given the motion model, nodes predict target location probabilities and compute their next near-optimal locations based on the predictions. The proposed approach involves coordination between mobile agents in order to achieve a near-optimal global utility.

Laguna Manuel, Javier O. Roa, [49] employs a local search procedure coupled with a diversification strategy which is developed for deployment problem. The objective function is described as a combination of inaccuracy of the position estimation, its unavailability and its cost, respectively. The objective of the optimization process is finding a design that minimizes the weighted sum of these three components. By changing weightings Pareto frontier is found.

4.3.2.4 Genetic Algorithm Pseudo code and Flowchart

Genetic algorithms (GAs) are stochastic global search and optimization methods that mimic the metaphor of natural biological evolution (Holland. [50]) GA's operate on a population of potential solutions applying the principle of survival of the fittest to produce successively better approximations to a solution. At each generation of a GA, a new set of approximations is created by the process of selecting individuals according to their level of fitness in the problem domain and reproducing them using operators borrowed from natural genetics. This process leads to the evolution of populations of individuals that are better suited to their environment than the individuals from which they were created, just as in natural adaptation.

In this section information about the key issues of the genetic algorithm written for this thesis are given. A genetic algorithm is formed to fit the specialties of the problems encountered in this thesis study.

The general pseudocode of a genetic algorithm is given as steps below.

Outline of the genetic algorithm

1. Create random population
2. Feasibility check (if possible, optional)
3. Evaluate fitness value for each individual
4. Scale raw fitness values to a more suitable range (if necessary)
5. Select members based on their fitness
    a. Some selection processes are tournament selection, rank selection, roulette wheel selection.

6. Produce children from parents by
    a. Crossover (one point, n point, uniform, etc.)
    b. Mutation
7. Replace current population by new generation.
    a. Use all new individuals or
    b. Preserve some number of elite members for the new generation. The number of elite members that are carried directly to the next generation is important since carrying much of the elite members may decrease diversity and cause premature convergence. By elitism it is guaranteed that the fitness value of next generation is at least the same as the previous generation.
8. Continue until stopping criteria is met. (Either a certain number of generations are performed or a predetermined fitness value is achieved.)
    - Fitness limit — The algorithm stops when the value of the fitness function for the best point in the current population is less than or equal to Fitness limit.
    - Stall generations — The algorithm stops when the weighted average change in the fitness function value over Stall generations is less than Function tolerance.
    - Time limit — The algorithm stops after running for an amount of time in seconds equal to Time limit.
    - Stall time limit — The algorithm stops if there is no improvement in the objective function during an interval of time in seconds equal to Stall time limit.
    - Function Tolerance — The algorithm runs until the weighted average change in the fitness function value over Stall generations is less than Function tolerance.

At mutation the algorithm can create mutated individuals by adding a random vector from a Gaussian distribution to the parent.

As the number of generations increase, the individuals in the population are expected to get closer and approach the minimum point.

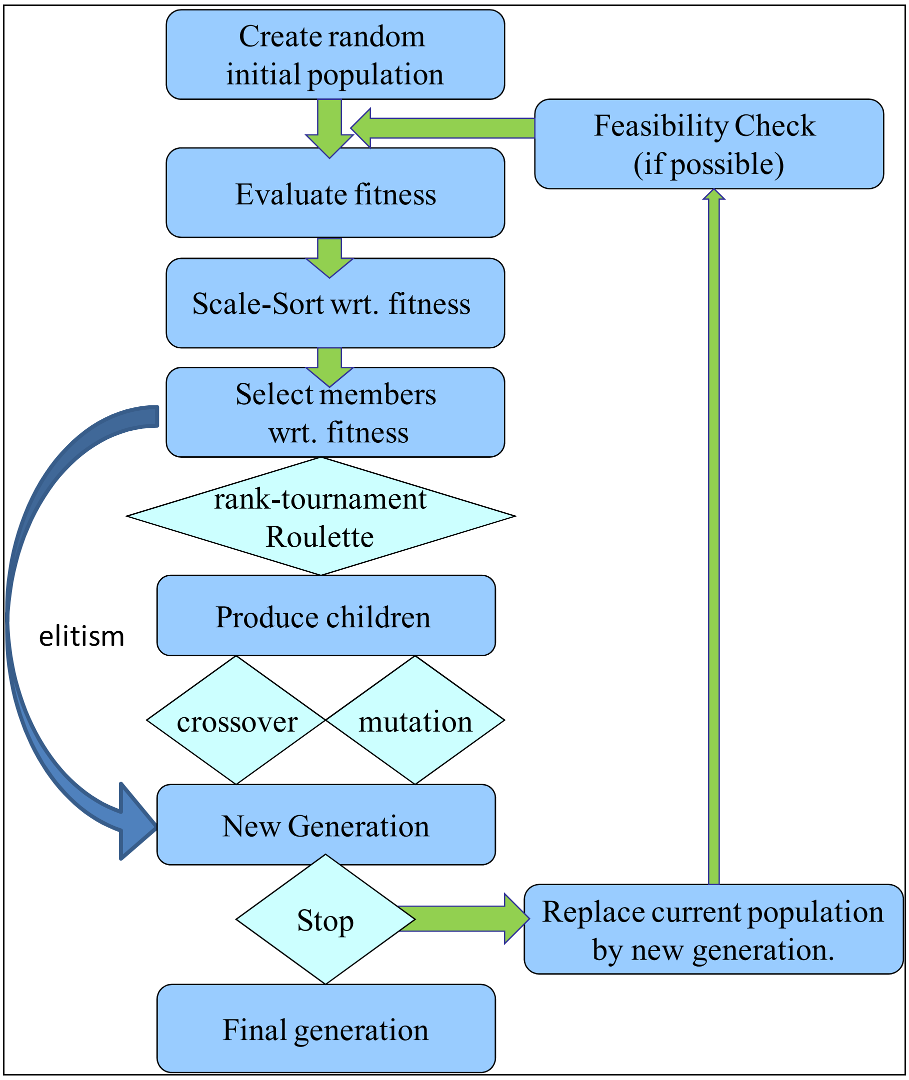


Figure 4-1 General genetic algorithm flowchart.

4.3.2.5 Encoding Type Selection and Phenotype:

Encoding of the genes of an individual (or a solution) is defined by genotype (how it is represented, binary, real etc.) and phenotype (what it represents (physical meaning)). Encoding should favor building block growth, preserve locality and be closed under genetic operators, which means that after genetic operations the resulting genotype should be meaningful. (A valid phenotype)

In a problem the design variables, parameters etc form the genes. The chromosomes are composed of genes and each chromosome is a solution of the optimization problem, for which, when applied to the problem, a corresponding fitness value is obtained. There are several choices of representation of chromosomes such as binary, integers, floating point, or trees.

<u>Binary representation:</u> Holland used the binary representation. Most of the genetic operators operate easily when using binary formulation. The genes are converted to binary representation and stacked. Mutation can be easily performed by changing a 1 to 0 in a chromosome.

<u>Integer Representation:</u> For several problems binary representation may not be suitable. For example a TSP (travelling salesman problem) can be formulated with a permutation based chromosome with integers more easily at which the numbers of cities form the chromosome and the order of visiting is given by the chromosome itself.

Permutation based chromosome for TSP for 5 cities with integer representation can be seen in the second chromosome in Figure 4-2.

<u>Real valued chromosomes:</u> Most optimization problems deal with variables that take integer or real values. Although changing these values to binary form is possible. It increases the size of the chromosome. In this case the range of each gene must be restricted because it is necessary for the mutation operator to work accordingly.

Other forms. Tree structures are also used for chromosome representations. . In this case genetic operators are defined accordingly.

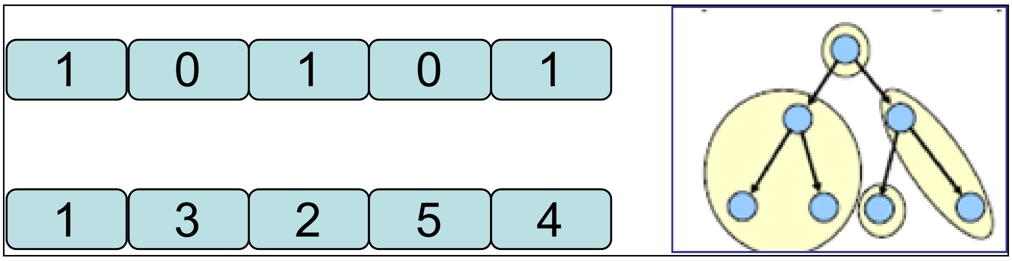


Figure 4-2 Binary, integer and tree chromosome structures.

4.3.2.5.1 Binary or Integer Representation:

it is possible to write the coordinates of beacons in binary form but it is also possible to leave them as real numbers. Each solution, chromosome or an individual will have the locations of these beacons in its structure.

All real numbers of beacon coordinates are rounded to nearest integer (nearest 1 meter) to avoid meaningless over-resolution.

Each gene in a chromosome consists of the location of a beacon in Northing and Easting pairs.

A typical chromosome for beacon deployment problem consists of the beacon coordinates.

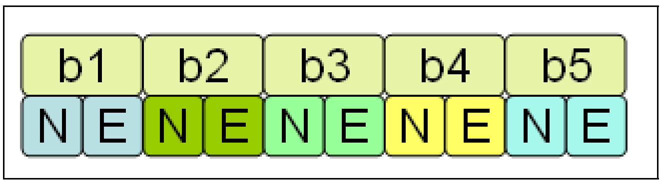


Figure 4-3 Chromosome structure for deployment problem.

A typical chromosome for the path planning problem consists of the waypoint coordinates except the launch point (LP) and target (TGT) coordinates which are fixed.

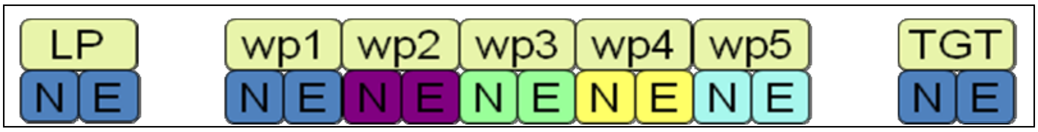


Figure 4-4 Chromosome structure for path planning problem.

4.3.2.5.2 Phenotype

From the phenotype point of view, in the problems investigated in this thesis, the chromosomes contain the locations of beacons in northing, easting coordinates. So chromosome content is only the location of the beacons.

As a note, height of a beacon is determined by the terrain elevation data. So it is not freely selectable. In this thesis a Digital Terrain Elevation Data structure is not used and all heights of beacons are set to a predetermined height which is equal to regarding the flight profile of the missile It is possible to add a DTED matrix and obtain elevation data from true DTED data. However in that case a further check mechanism is required which is the line of sight obstruction criterion. For each point of the missile trajectory, a LOS check must be made for beacons that satisfy other constraints, which adds another constraint to the problem, where constraint violation can be handled by a death penalty or a dynamic penalty.

4.3.2.6 Variable Length versus Fixed Length Chromosome Structure

Due to the nature of the problem, solutions that minimize the location error with the minimum number of beacons are sought.

Since it may be possible with lesser number of beacons to reach a desired positional accuracy, it is necessary to investigate if the desired accuracy can be reached by lesser beacons with a good placement.

In order to handle the minimum beacon number requirement, a variable length chromosome structure is preferred. Since each chromosome consists of genes that are locations of beacons and the number of beacons is also a variable. The chromosome length has been selected variable. A VLCGA (variable length chromosome genetic algorithm) is developed.

The advantage of VLCGA is to handle the terminal phase location error minimization problem while checking for the possible number of beacons to achieve this goal at the same time.

For the path planning problem, increasing the waypoints in a chromosome leads to slower convergence for a shortest path objective function.

4.3.2.7 Initialization Policy

A random initial population is created in genetic algorithms. It is possible to check for the feasibility of the initial population members and select all of them as feasible solutions. In some problems selecting initial population members from feasible solutions may not be possible. In addition selecting initial population from feasible solutions may deteriorate the solution quality. Also for constrained optimization problems it may not be possible to know if a random solution is feasible (satisfies all of the constraints).

Increasing population size increases diversity and representation quality of search space. However large population size increases the complexity of GA and increases calculation time. In general population sizes of 20-1000 are used for different problems.

For the optimization problems in our case, it is possible to start with a feasible solution by running the simulation. Actually a beacon layout that is within the range and forbidden zone constraints can be considered as a feasible solution. So these specialties can be checked. If a randomly generated individual satisfies these constraints it can be accepted to be a member of initial population.

The random population is generated by running a ritual and checking if the deployment zone and range constraints are satisfied. The borders of the deployment zone are defined by northing and easting values.

A beacon is a candidate if it is within the limits defined by the deployment zone and it is also feasible if the missile comes to the sensing range in some part of its flight.

Since VLC is used, a maximum chromosome size is specified which implies number of available beacons for a mission.

The initial population must be generated to be within deployment zone and also within sensing range of the missile for deployment problem.

The primary constraints for a beacon to be feasible:

- It must be located within "detection range" meters of the route of the missile
- It must not trespass the forbidden zones defined. (it must be in the deployment area)

4.3.2.8 Fitness Evaluation

Fitness function or the objective function is the value to be minimized. In deployment problem, the fitness function for each chromosome is evaluated by the flight simulation incorporating navigation system. For a given layout of beacons that are defined the genotype of the chromosome, the simulation runs along with the FOR, FOV and range constraints. At the same time fitness function elements are evaluated.

Limiting the location error throughout the flight and also the final CEP value is desired. It is possible to think that minimizing the terminal phase CEP value may be the utmost importance but limiting the location error throughout the flight is also important since the missile or The UAV may never reach or find the true beacon for position update if the midcourse location error is large and a position update may never be performed. Similar incidents have been reported In WWII, where bombers that are crippled by FLAK (Flugzeug Abewehr Kannon- Anti aircraft artillery) fire whose flight instruments are also damaged flied blindly seeking back their home base, are brought to home by special aircrafts called "shepherds" Shepherds guided the crippled bombers to safely return to their airfields. So keeping the missile on track is also as important as decreasing the final phase location error.

From the initial population with different chromosome lengths, calculate fitness values by using the fitness evaluation function.

- First calculate the desired trajectory of the missile.
- For each position of the missile check which beacons are visible. i.e in range.
- Apply FOV and FOR constraints.
- Operate DECISIONMAKER that selects which position update method is to be used.
- Calculate position covariance at the terminal phase.
- If the deviation from the desired path exceeds the limit constraint, a death or dynamic penalty is used which terminates the chromosome or increase its performance.

4.3.2.9 Rising New Generation

In order to produce the next generation, offsprings must be created by the current generation. In the nature fitter or more attractive individuals have more chance to survive and reproduce. Each generation has members from several generations. A similar thought leads to selection processes. Selection is done for reproducing and for survival.

Selection of chromosomes for mating (crossover) can be done in the following ways.

- Truncation selection
- Fitness proportionate selection (roulette wheel)
- Rank selection
- Tournament selection

The survival selection for the next population can be made as

- Using only the children
- A combination of parents and children

Best parents and children or a random selection of parents and children is possible.

4.3.2.9.1 Selection for Survival

The survival selection for the next population can be made by using only the children or using a combination of parents and children. If parents and children will form the next generation elitism is used. Some of the best individuals of the current generation survive to be a part of the next generation. Elitism improves the performance for most of the problems. The amount of individuals that will be carried the next generation should be decided carefully. Too much elite individuals may decrease diversity.

In order to monitor the evolution and provide that the next generation is at least as fit as the previous one, "elitism" is used. The best "besttosurvive" proportion of the population is carried directly to the next generation.

4.3.2.9.2 Selection for Crossover

Selection of chromosomes for mating can be done in the following ways.

- Fitness proportionate selection (roulette wheel).
- Rank selection.
- Tournament selection

<u>Fitness proportionate selection</u>: Probability of selection of individual I is based on individuals fitness value / sum of all fitness values. So sizes of the wheel pieces are proportional to the fitnesses of the individuals. So the chromosome with the best fitness value has the biggest piece on the wheel and a higher probability to be selected.

Although this selection method is good, it's possible to come up with a gene pool with low fitnesses in a series of wheel rotations. A method called stochastic universal sampling is introduced to overcome this problem. The wheel only spins once in the extended method but there are several pointers to select the individuals. The number of pointers is equal to the number of desired individuals to be selected, and the pointers are evenly placed on the wheel. With this method, actual selection frequency of an individual is nearer to its expected value, compared to the roulette-wheel selection.

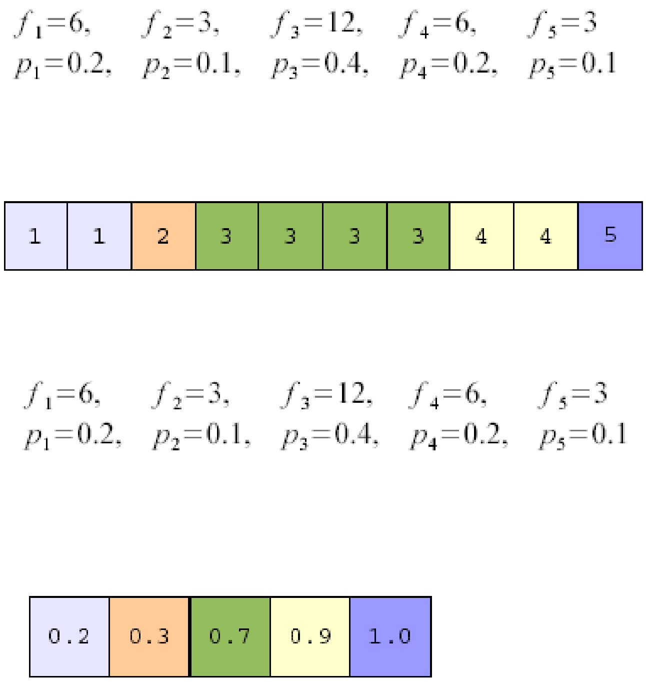


Figure 4-5 Vector based and cumulative roulette wheel selection [43].

Roulette wheel algorithm can be

- Vector based
- Cumulative distribution

Selection pressure is defined as the ratio of best individual's selection probability to average selection probability. Selection pressure can not be adjusted in this method.

Vector based roulette-wheel: Selection probability of an individual increases as its fitness value is better.

Rank selection: Individuals are sorted according to their fitness. Selection probability of an individual is a function of their rank rather than pure fitness values.

The advantage of this method is that it does not let extremely better individuals dominate the next generation in the early generations and lead to premature convergence. Moreover, in the later generations, the differences between the fitness values of individuals may decrease. When using roulette-wheel selection, this situation decreases the effect of better individuals. Conversely, rank selection preserves importance of better individuals (Ketenci [51]).

Tournament selection is based on picking two (or n) individuals at random and choose the better one to mate. Fitness pressure can be controlled by the size of the tournament. Increasing size of tournament leads domination of the elites.

In order not to lose information from worse fitness value genomes, a tournament selection is selected to be used in this thesis. Since there is no golden rule in creating new populations, several variations of population composition are possible.

Mating selection is performed by tournament selection since it up to an extent can prevent fitter individuals to survive and selection pressure can be adjusted based on the tournament size. Goldberg and Deb also noticed that tournament selection has better of equivalent convergence and computational time properties regarding several selection operators.

Selection for crossover is performed as follows,

1. A tournament selection size is defined.
2. Based on this tournament size, random individuals are selected by a randommate which is generated between 0:1 and then mapped to population size.
3. Individuals are sorted according to their fitness values. Best of the tournament is selected as first parent.
4. A second parent is selected in a similar way.

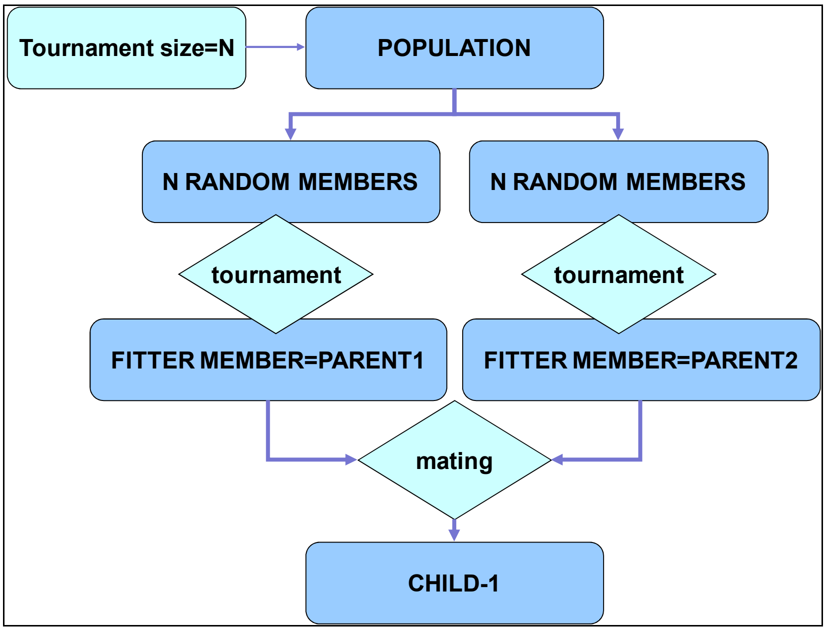


Figure 4-6 Tournament selection for crossover

4.3.2.9.3 Crossover

Combination of gene content of two individuals is provided by crossover operator (meiosis) and produces child(ren). When 2 parents are selected to mate, it is possible to crossover with several methods, such as single point, k point and uniform.

In single point crossover a randomly selected cross point is determined and the children are formed by interchanging the genes from this point. In the k point crossover random cut locations are defined and the genes are switched based on these cut locations. In this thesis a random k point crossover is used on a variable length chromosome structure. The crossover algorithm is as follows:

1. Random chromosomes are selected from the population by an amount of tournament size. Best one is taken as parent-1.
2. Another set of random chromosomes are selected from the population by an amount of tournament size. Best one is taken as parent-2.
3. A random k-point crossover is selected to operate on the parents.
4. Two randomly generated sequences are generated which will be crossover keys for child 1 and child 2.
5. The length of the key is equal to maximum available beacon number. This sequence is then rounded to obtain 0 and 1's
6. key1= round (rand(1,maxavailablebeacons))
7. key2= round (rand(1,maxavailablebeacons))
8. If an element is 1 then it uses the corresponding gene (N, E) in parent1
9. If an element is 0 then it uses the corresponding gene in parent2
10. If the corresponding gene does not exist that slot remains empty.
11. Both N and E values of the chromosome is taken as a whole and crossed over.

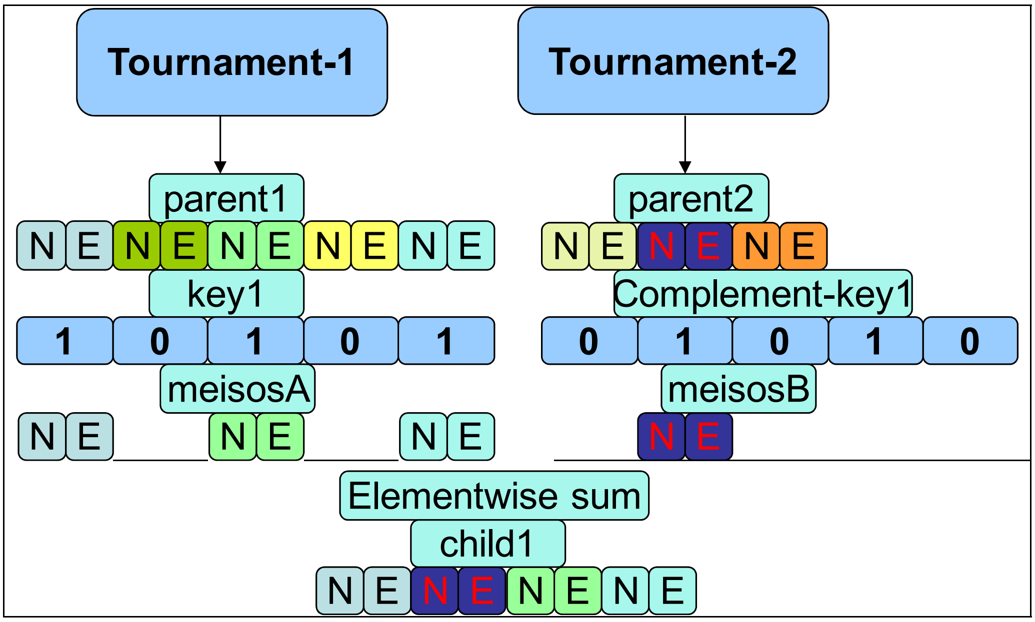


Figure 4-7 Crossover operation

4.3.2.9.4 Mutation

Mutation is the random change in specialties of genes in a chromosome, in nature some genes can not be placed or placed wrongly or simply change specialties due to external factors and new traits become active.

In order to provide diversity and to prevent the algorithm stuck to local optima, mutation is used in genetic algorithms. Some gene positions are changed with a random probability.

The probability of mutation is important since small probability can not provide diversity and very large mutation rates may prevent convergence or increase computation time considerably by changing the medium to random search.

Mutation is used in the algorithm to provide diversity of solutions and to provide better locations to existing solutions. Since the chromosomes consist of locations of beacons, a randomly selected beacon location can be changed by a random amount The use of mutation operator is as follows.

Mutation is performed only on the children matrix which consists of the newly generated chromosomes by crossover to preserve elite members of the previous generation.

Randomly selected coordinates of the chromosome are shifted by “shiftamount”

1. A random number is generated to select a chromosome from the children matrix.
2. Chromosome length is obtained.
3. Another random sequence consisting of ones and zeros is generated
4. If a number in the random sequence is one corresponding member of the chromosome whether it is northing or easting, is decided to be mutated.
5. A random number within the deployment zone is generated with a random sign.
6. This value is added to the selected coordinate on the chromosome.
7. It is necessary to check for the feasibility of the solution.

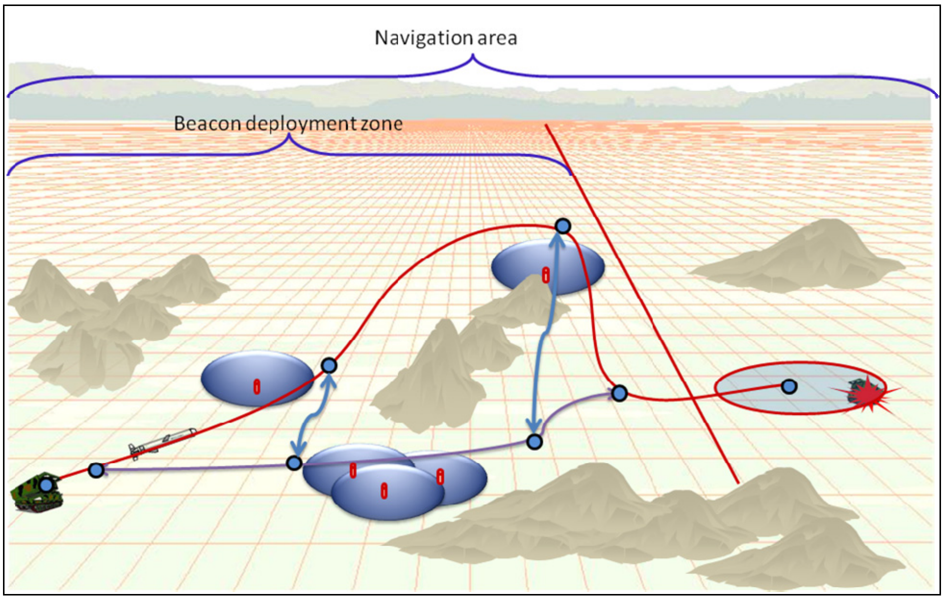


Figure 4-8 Mutation in second and third waypoints.

4.3.2.10 Parallel GA Structure

Evolutionary algorithms such as GA require many computations of fitness functions and those computations can be expensive depending on the fitness function evaluation time. However due to the population nature of the GA's it is easy to parallelize calculations such as independent fitness calculations or parallel evolution of multiple populations (CENG 713 [43]).

Types of parallel EC can be stated as;

- Global parallelism: single population master-slave
    - Single population is used, a master controls flow, workers execute fitness evaluations, and it is identical to single processor GA except the execution time.
- Multiple populations. Coarse grained.
    - The population is divided into subpopulations and these populations evolve independently in island model. There exists transfer of individuals during evoluiion (migration)
        - Multiple subpopulations (demes)
        - Migration of individuals among demes.
        - Different topologies and migration strategies.
- Many populations. Fine-grained.
    - Many subpopulations with small number of individuals.
    - Populations sizes can be as small as 1.
    - Spatial structure of connections.
    - Migration is local, only among neighbors.
- Hierarchical/Hybrid combinations.
    - Multiple populations, each works parallel
    - Combine the benefits of multiple methods.

Parallelization of genetic operators is not effective since genetic operators are fast linear procedures and the communication cost between workers is larger than the computational cost.

In parallel computing there are many design choices such as

- Single/Multiple populations
- Size of the populations
- Number of populations
- Isolated or connected populations
- Connection policy
- Migration rate
- Migration policy

In Isolated demes multiple simple GA's exist and are executed in different processors, than best results are collected.

In fully connected demes, all demes can migrate to each other

Migration frequency:

- At each generation (gets similar to master slave)
- At the end of epoch.

Algorithm:

- Run isolated until some convergence
- Swap a ratio of current population with every other deme.
- Restart the demes

In this thesis multiple populations are run independently with different initial populations and after a convergence is met, best members of each population after a predetermined generation are combined to a single population. The single population which contains the best individuals from multiple populations runs to find the best of the best (Figure 4-9).

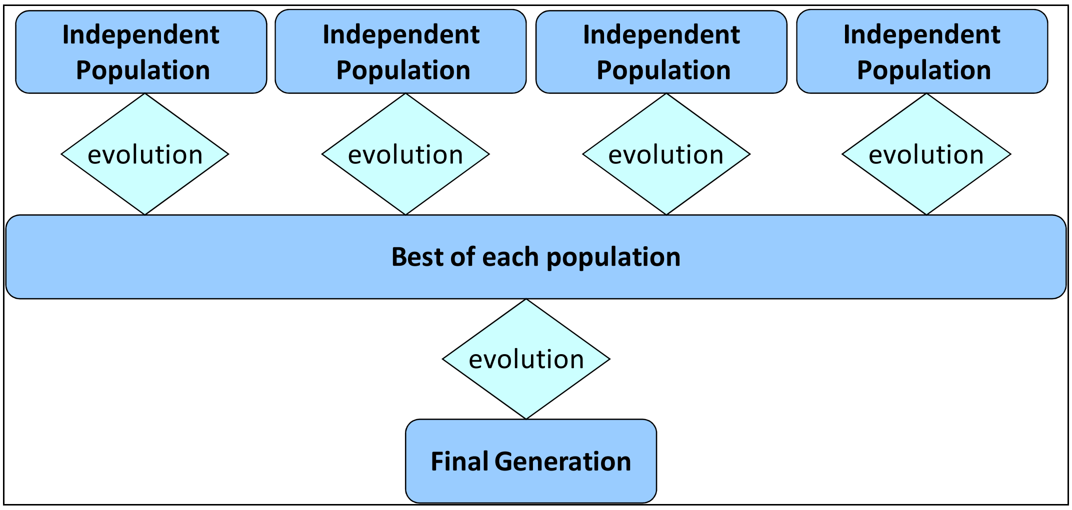


Figure 4-9 Evolution strategy

4.3.2.11 Formulation of Deployment and Path Planning Problems

During formulation of deployment and path planning problems, the following terminology is used.

Navigation area: Navigation area is defined as the area where the missile or missiles are operating starting from launch point to impact point.

Beacon deployment zone: is the permissible area in which beacons can be deployed. It is a subset of navigation area. it is restricted by maximum allowable deployment line and forbidden zones.

Geometrical aspects: there are 3 possible methods for position update for the missile and a link between the geometrical aspects of beacon placement and position update must be formed. This link is the GDOP (geometric dilution of precision) which is a concept originating from GPS positioning. In GPS satellite positions become important as range information is derived. When more than 4 satellites can be seen by the observer, satellite selection can be based on calculation of DOP to see which combination of the satellites is best to obtain better position solution.

For the deployment problem, fitness function is position covariance value at target intercept.

Constraints

- Deviation of position covariance value throughout the trajectory in midcourse phase is less then "maximum allowable midcourse deviation" which is handled by dynamic or death penalty added to fitness function.

Inherent constraints

- Visibility: if a beacon comes into detection range throughout the trajectory.
- FOV, FOR constraints.

4.3.2.12 Flow Diagram for Deployment and Path Planning Problems

The flow of the Genetic algorithm is given below, where black regular typing is common for both deployment problem and path planning problems, *Blue italic* typing is only for path planning problem and *green italic* typing is only for deployment problem. The structure of the GA is tried to be as similar as possible for the two problems.

1. Define atmospheric conditions.
   - Detection range
2. Define seeker parameters.
   - FOV, FOR
3. Define battle area.
   - navigation area
   - beacon deployment zone
   - forbidden zones
   - *launch point coordinates*
   - *target coordinates*
4. *Define heading constraint*
5. *Define beacon coordinates (given scheme of deployment)*

6. Define genetic algorithm parameters.
   - population size
   - maximum available beacons / *waypoints (Constant for path planning problem)*
   - Maximum generation number
   - Number of best members to survive
   - Number of parents to mate
   - Number of children
   - Tournament size
   - “Mutationrate”
   - “Shiftamount” (maximum shift in coordinates in mutation)
7. Generate initial population.
   - Start filling in chromosomes
   - Create random eastings and northings in beacon deployment area
   - *Check if during entire flight of the missile beacon comes into range.*
   - *If yes add beacon to chromosome*
8. Initial population formed.
9. For each member of the initial population.
   - *Operate “decision maker” and obtain observation points for best position update geometry*
   - Inherent constraints are range, FOV, FOR.
10. Evaluate fitness values for members of the population.
    - *Input observation points to “navigation simulation” and run simulation*
    - *Calculate fitness based on position covariance at the final point.*
    - *Inherent constraint “deviation from planned trajectory” limit is active. Any chromosome which violates this constraint is treated with a penalty function.*

    - *Run fitness calculator (FITNESSCALC)*

    For each path and beacon scheme:

- *Evaluate total path length of each fullpath* ***(pathlengthcalculator)***
- *Evaluate total path length in beaconrange* ***(pathlengthinbeaconrangecalculator)***
- *Evaluate path length in FOR, which calculates the distance a missile goes within the hemisphere of every beacon while being capable of observing the beacon in its FOV and FOR.*
- *Define fitness by using these parameters.*

11. Sort individuals based on fitness (POPandFITsorted).

12. Select best(s) of generation based on “numberofbesttosurviv”e.

13. Perform mating by tournament selection.
    - select first parent by a tournament defined by “tournamentsize”
    - select second parent by a tournament defined by “tournamentsize”
    - crossover with k point random crossover key.

14. Perform mutation based on “mutationrate”.
    - find the number of rows of the child matrix. Childmatrix is the output of the crossover and all members are newly generated individuals.
    - Crate a random permutation of numbers.
    - In order to detect how many mutations will be performed. “Mutationrate” is multiplied by the child population.
    - Generate a for loop along which mutated children will be created by the number of wanted mutations.
    - Generate random number which determines which genes are to be mutated in the chromosome bu using “chromosomekey” which generates random 1’s and zeros along the length of the chromosome
    - A shiftkey is generated which decides the amount of random value to be added or subtracted from the corresponding gene.

- Totalshift is found by the elementwise multiplication of shiftkey with the chromosomekey.
- Totalshift is added to the chromosome, elementwise.
- The corresponding row now comprised of mutated child is inserted back into the childmatrix. With a new index and also a fitness.

15. Create new generation consisting of best of previous generation and children

16. Evaluate fitness values.

17. Continue until "maxgenerationnumber" is reached.

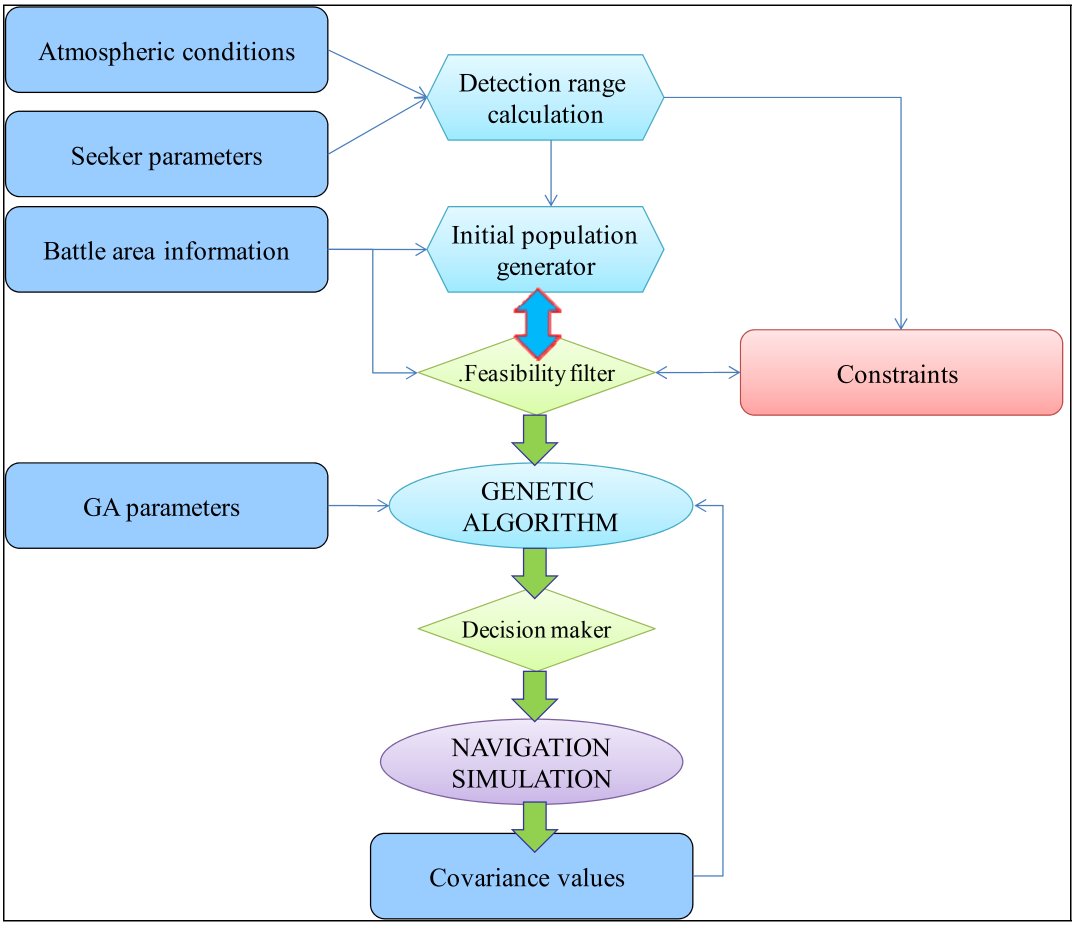


Figure 4-10 Genetic algorithm flowchart for deployment problem.

4.3.2.13 Differences between the Flowcharts of Deployment Problem and Path Planning Problem

Chromosomes of deployment problem are consisting of beacon coordinates. Chromosomes of path planning problem are waypoint coordinates but launch point and target coordinates are not included since they are fixed.

Path planning problem has the input of a given deployment scheme of beacons, while deployment problem does not have a deployment scheme.

Path planning problem has a heading change constraint where the heading difference between any sequential path segments is limited by "headingconstraint"

Chromosomes of deployment problem are not stacked in increasing order. That is their location is also random. This provides the possibility of 2 point and three point resections to increase. Chromosomes of path planning problem are sorted according to their distance from the launch point.

Fitness function of the deployment problem is calculated by employing a navigation simulation using the accelerometer and gyro measurements for the reference trajectory and position covariance at the terminal phase is tried to be minimized. Fitness function for the path planning problem is obtained by using observation instants inside beacon ranges which satisfy FOV, FOR and method specific constraints.

4.3.2.14 Constraints due to Seeker Range, FOV, FOR

4.3.2.14.1 Range

A range constraint due to seeker lock on range is defined. Let Yi be the visibility based on beacon (bi) and missile (mj) positions. Position of beacon can be defined as $[E,N,h]_{bi}$ i= 1.2…..n where n is the number of beacons. Position of missile can be defined as $[E,N,h]_{mj}$ j=1,2…ngrids. Where ngrids is the total number of positions where the missile can be.

A beacon is identified as visible to the missile seeker if the visibility flag is 1 which is set by at least range limit.

4.3.2.14.2 FOV and FOR

FOV of a missile with gimbaled seeker is the instantaneous field of view of the seeker at a glance.

FOR of a missile is the total angle covered by the missile seeker's ability to move within the limits of the gimbal or half of it depending on the definition.

A typical capability for a missile is given below.

- The FOR can be taken as +/- 25 to +/-90 degrees.
- And the FOV is assumed to be 5-10 degrees.

For an unmanned aerial vehicle equipped with a FLIR, the FOR is much higher, while the tracking capability of multiple targets is also high.

A typical capability for ASELFLIR-300T is given below,

- FOR is 360 degrees in azimuth +20 / -105 ° in elevation.
- FOV values are NFOV: 1.32 x 1.75 °
- MFOV: 4.8 x 6.4 °
- WFOV: 22.5 x 30 °

For reverse intersection, the same beacon should be observed for a period of time as the missile flies by. The requirement in this observation is that the beacon must lie in the FOR of the missile during first and second observations.

For 2 point resection and 3 point resection, 2 and 3 beacons respectively, must lie inside the instantaneous FOV of the missile seeker or FLIR. Also these beacons must lie in the area which is covered by the FOR of the seeker.

Table 4-1 Active constraints based on method

Method selection	**Condition**	**time-space**	**RANGE constraint**	**FOR constraint**	**FOV constraint**	**DOP LİMİT**
for reverse intersection	1 beacon visible	at 2 instances	range <Range lock-on	1 beacon in FOR	x	YES
for 2 pt resection	2 beacons visible	at 2 instances	range <Range lock-on	2 beacons in FOR	2 beacons in FOV	YES
for 3 pt resection	3 beacons visible	at one instance	range <Range lock-on	3 beacons in FOR	3 beacons in FOV	YES

Let b_i be the vector formed by ith beacon coordinates $b_i = (N_i, E_i, h_i)$

Let m_j be the missile coordinates at point j $m_j = (N_j, E_j, h_j)$

Range flag for Ith beacon and jth missile position.

$$\text{Rflagij}= \begin{cases} 1 & if\sqrt{\Delta N^2 + \Delta E^2 + \Delta h^2} \le range_{seeker\,lockon} \\ 0 & otherwise \end{cases} \qquad (3.95)$$

FOR constraint is implemented as follows.

For a beacon to be within the FOR of the missile, the angle, between the heading of the missile and the line joining the missile to beacon, must be smaller than FOR.

Here missile heading is assumed to be same with its course, which means angle of attack sideslip angles are assumed to be zero.

Missile course direction is determined by $m_j - m_{j-1}$

The cross product between missile longitudinal axis and missile-beacon line is used to find the angle between the LOS and missile axis.

$$\text{FORflag}_{\text{ij}} = \begin{cases} 1 & \textit{if} \arcsin \dfrac{(b_i - m_j) \times (m_j - m_{j-1})}{\left|(b_i - m_j)\right|\left|(m_j - m_{j-1})\right|} \le FOR \\ 0 & \qquad otherwise \end{cases} \tag{3.96}$$

FOV constraint can be implemented as follows. When there are more than one beacon in FOR, this constraint forces the beacons to be within FOV of the missile seeker.

$$FOVflag = \begin{pmatrix} 1 & if & \left(\sum_{i=1}^{nbeacons} FOR_{ij} = 2\right) \Lambda \ \left(\theta_{12} < FOV\right) \Lambda \ \left(\theta_{34} < FOV\right) \\ 1 & if & \left(\sum_{i=1}^{nbeacons} FOR_{ij} = 3\right) \Lambda \ \left(\theta_{12} + \theta_{23} < FOV\right) \\ 0 & & otherwise \end{pmatrix} \tag{3.97}$$

Where

θ_{12} and θ_{34} are the angles between beacon pair and the missile and

θ_{12} and θ_{23} are the angles enclosing left-middle and middle-right beacons.

Then the problem can be formulated as

Minimize f (fitness function) subject to

$$\begin{aligned} &\text{Rflag}_{\text{ij}} \quad\ = 1 \\ &\text{FORflag}_{\text{ij}} = 1 \\ &\text{FOVflag}_{\text{ij}} = 1 \end{aligned} \tag{3.98}$$

4.4 Conclusion

In this chapter, a variable length chromosome genetic algorithm (VLCGA) is developed to solve the deployment problem and path planning problems which are classified as the two main branches of problems related with the beacon navigation concept. Tournament selection, crossover and random mutation along with elitism are employed to rise the new generations. Both GA structures are tried to be designed similar for both problems. The chromosomes are beacon locations and waypoints. The deployment algorithm uses the navigation simulation and position covariance values for fitness evaluation while the path planning algorithm uses the maximum quality position update geometry for a given network of previously laid beacons.

CHAPTER V

MODELING AND SIMULATION

5.1 General Structure of the Simulation

For the two problems that are defined in this thesis, a mission planner algorithm that operates in MATLAB is constructed. It uses beacon detection ranges, seeker specifications, IMU specifications, and accepts genetic algorithm design parameters to calculate the beacon deployment scheme for the deployment problem and the path for the path planning problem.

Beacon detection ranges are calculated by using a laser model for laser emitting beacons and by using NVTHERM program for infrared wavelength emitting beacons. Optimization is then run regarding the obtained detection ranges for given visibility, seeker and beacon specifications.

Desired flight path is generated regarding similar trajectories of tactical strike missiles. The flight path contains climb, heading change, coordinated turns, dive, heading change maneuvers.

A 50 deg/hr MEMS IMU has been selected to be used in the simulations. Accelerometer and gyro measurement data is generated for the desired trajectory based on the error specifications of the given IMU. The navigation simulation uses indirect feedback Kalman filter which uses error states.

The positioning methods are implemented to the simulation by the use of a decision maker structure. The general form of the mission planner is given in Figure 5-1.

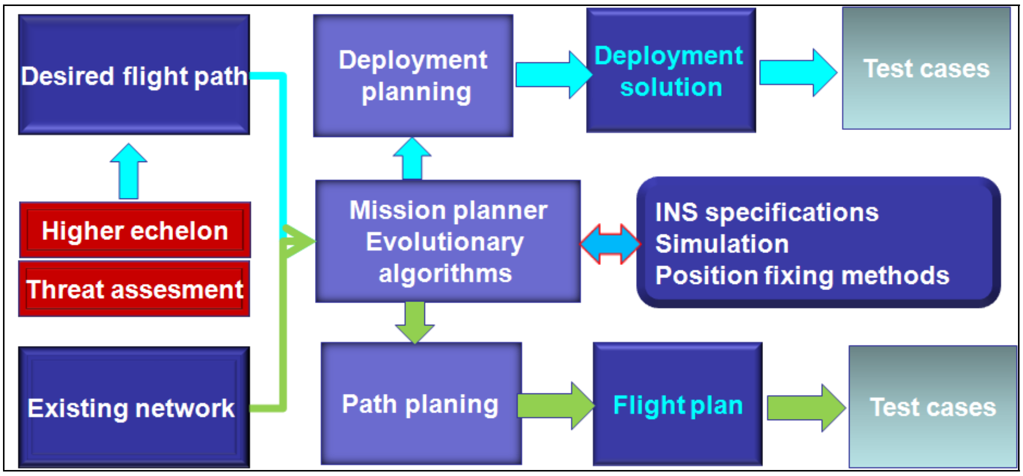


Figure 5-1 Mission planner structure

5.2 IMU Specifications

A 50 degree /hr class tactical grade MEMS IMU has been selected for use in the simulations. The reasoning behind this selection is that, this type of IMU's are widely used in smart weapons. Table 5-1 summarizes the primary specifications of the error sources in this type of IMU. Pulse quantization is not included to the analysis since it's effect is permanent and not related to the current analysis.

Figure 5-2 BAE SiIMU02 MEMS IMU

Table 5-1 IMU Error Specifications

Gyro		
Parameter	**Value**	**Unit**
Angle Random Walk	1	deg/√(hr)
Pulse Quantization	NI taken as 0	arc-sec
Gyroscope Gauss-Markov Bias Instability	300	sec
Gyroscope Gauss-Markov Correlation Time	1	deg/hr
Gyroscope Fixed Bias	50	deg/hr
Gyroscope Axis Misalignment	400	microrad
Gyroscope Scale Factor	250	ppm
Gyroscope Scale Factor Asymmetry	20	ppm
Accelerometer		
Parameter	**Value**	**Unit**
Accelerometer Velocity Random Walk	1700	microg/√ (Hz)
Accelerometer Quantization Error	NI taken as 0	m/s
Accelerometer Gauss-Markov Bias Instability	5	microg
Accelerometer Gauss-Markov Correlation time	600	sec
Accelerometer Fixed Bias	5000	microg
Accelerometer Misalignment Error [xy,yz,xz]	400	microrad
Accelerometer Scale Factor Error	1000	ppm
Accelerometer Scale Factor Asymmetry Error	100	ppm

5.3 Reference Trajectory Generation for Deployment Problem

A missile trajectory is defined to simulate a standoff missile launched from a surface launcher. Climb, heading change, coordinated turns, dive, heading change maneuvers are included in the reference trajectory. The reference trajectory is characterized by a steep climb to cruise altitude, (relatively) high altitude, altitude hold phase to reduce drag and save energy, dive to low altitude to avoid and minimize exposure time to air defense fire, a shaped lateral maneuver to avoid a natural or man-made barrier and a terminal target intercept phase. Flight time is 224.025 seconds. Speed is around 300 m/seconds (Figure 5-3).

The trajectory is defined with several segments.

1. 5 seconds of waiting time
2. Climbs with 45 degrees while it accelerates to 300 m/second velocity in 10 seconds
3. 2 seconds constant flight
4. Corrects pitch angle within 3 seconds
5. Constant flight: 20 seconds
6. Coordinated turn with -55 degrees bank angle, heading change 90 degrees, final heading ~180 degrees
7. Constant flight: 10 seconds
8. Coordinated turn with 55 degrees bank angle, heading change 90 degrees, final heading ~180 degrees
9. Constant flight: 20 seconds
10. 45 degrees dive 3 seconds transition and 5 seconds dive with constant velocity
11. Recover pitch in 1 second
12. Constant flight 20 seconds
13. Heading change in 10 seconds
14. Constant flight: 1 second
15. Heading change in 10 seconds
16. Constant flight: 20 seconds

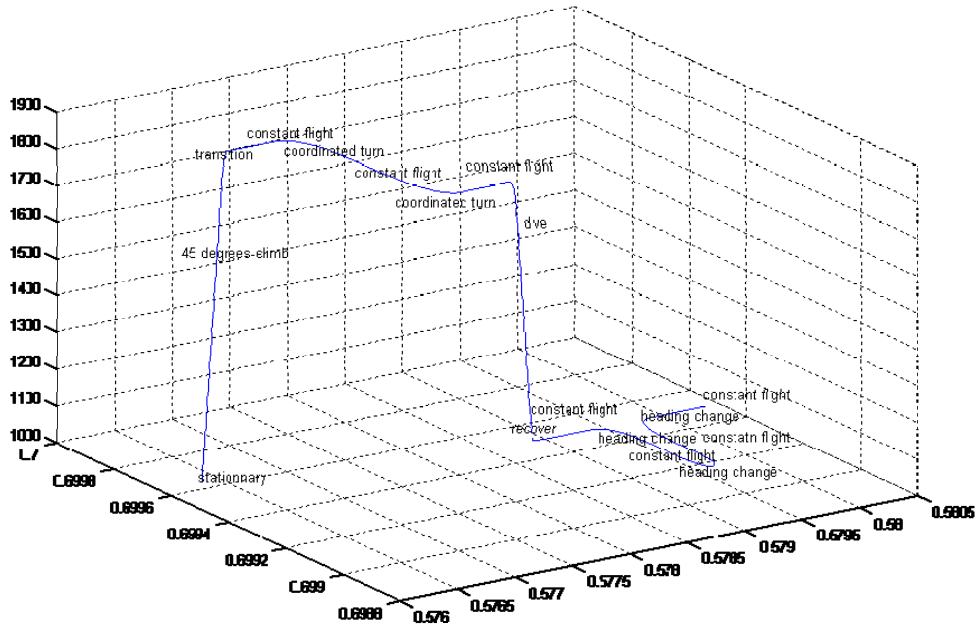


Figure 5-3 Reference trajectory for missile.

IMU data including accelerometer data (ax, ay, az) and gyro data (p, q, r) are loaded into Matlab as a .mat file.

5.4 Usage of UTM Coordinate System

A position on Earth is defined in a datum and by a coordinate system. Datum is a reference surface which has parameters about the orientation and shape of the earth. There are more than 200 datums currently used on the earth but most of them are local datums where they are valid on the region they are defined. There are also global datums. WGS-84 is a global datum which gives positions on a reference ellipsoid with respect ot the center of mass of the earth. MGRS (military grid reference system), UTM (universal transverse Mercator and the geographic coordinate system are the three coordinate systems currently used worldwide. Geographic coordinate system gives the coordinates of a point in terms of latitude, longitude, height.

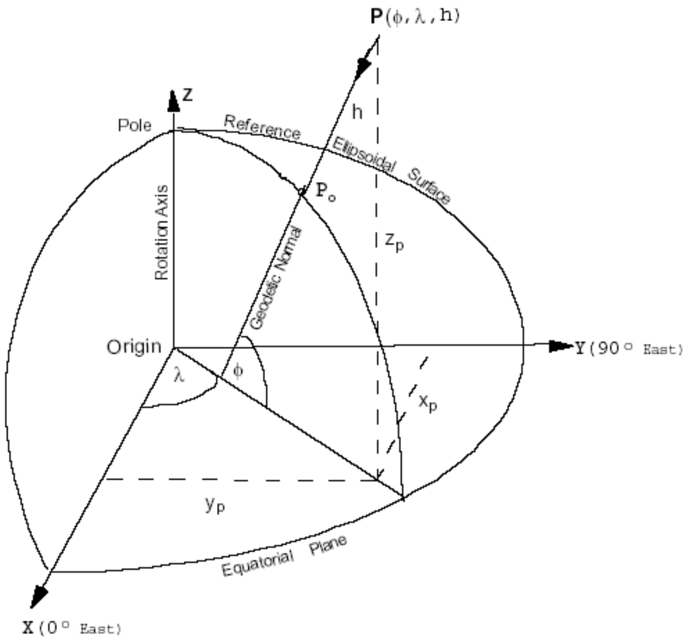


Figure 5-4 Defining a position on Earth.

UTM coordinate system has easting and northing components and height. The earth is divided to 6 degree wide strips which are named as “zones”. There are 60 zones on earth. Zones are numbered to east, starting from 180 degrees east meridian. The meridian passing through the mid of the zone is called central meridian and the easting value is 500.000 in this meridian. Northing starts from 0 at equator for north hemisphere and from 10.000.000 for the southern hemisphere. The reasoning behind this is to avoid negative numbers when defining coordinates.

MGRS’ coordinate system is based on the UTM but position reporting system is different in which all coordinates are reported in a single specific line of strings and numbers.

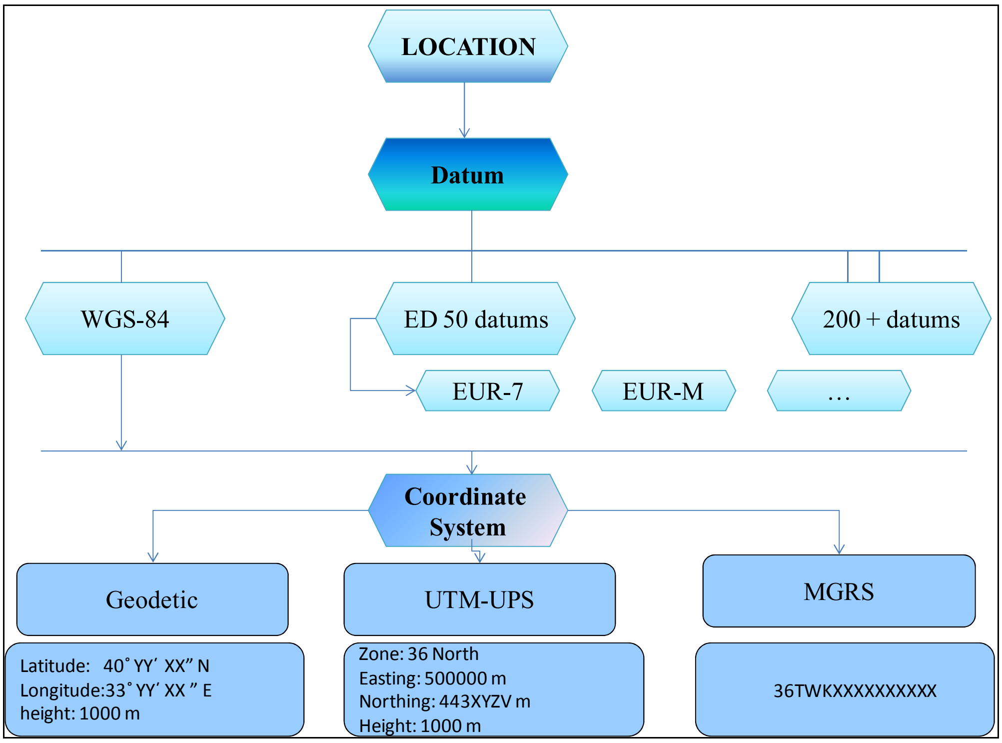


Figure 5-5 Representation of position

In the thesis the navigation equations are solved for the earth as is, but for beacon position updates, flat earth assumption is used. This is mainly because of the fact that the missile seeker will have a lock on range around 3-5 km's and for this range flat earth assumption is valid. The position fixing algorithms are designed to work on flat earth assumption.

In the simulations, navigation is performed on geographical coordinate system and when a position fix will be obtained by beacon position fixing algorithms, the observation positions are converted to UTM coordinate system, calculations are made in terms of easting, northing and height and then the position updates obtained are converted back to geographical coordinates for navigation. Two functions are used to convert between geographic coordinates to UTM and back conversion to geographic coordinates based on the formulae presented at Defence Mapping Agency technical manual, "The universal Grids, Universal Transverse Mercator (UTM) and Universal Polar Stereographic (UPS)" [53].

5.5 Indirect Feedback Kalman Filter Structure

An indirect feedback Kalman filter structure is formed since it has many advantages when compared with direct feedback Kalman filter which were emphasized at Chapter-2. Details of the navigation algorithm and the Kalman filter are given in Figure 5-6.

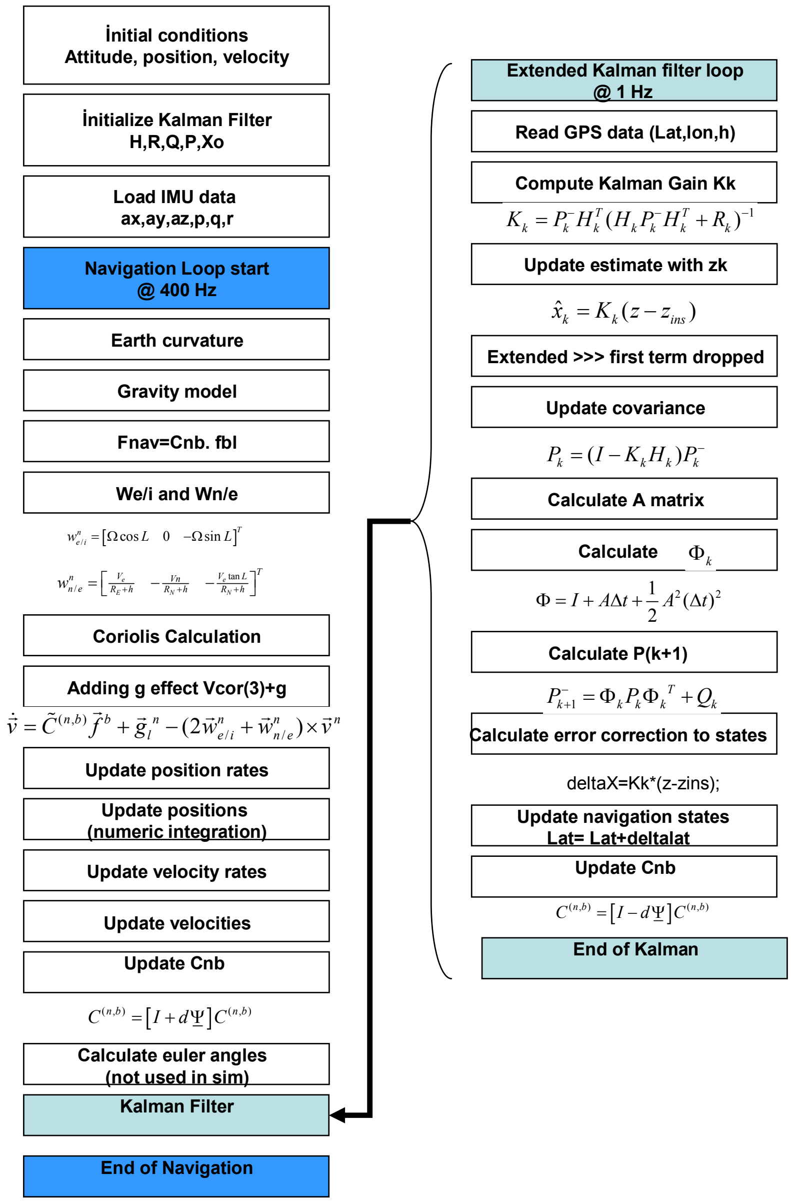


Figure 5-6 Navigation system and indirect feedback Kalman Filter structure

5.6 Detection Range Calculations for an IR Beacon

The IR emitting beacons are envisioned as battery powered, heated small surfaces which are charged by solar panels. In this section a preliminary detection range analysis has been performed to give an indication of seeker / FLIR detection ranges of the IR emitting beacons.

For this purpose, NVTHERM (Night Vision Thermal and Image Processing Performance Model) program is used. NVTHERM is a PC based computer program which models parallel scan, serial scan, and staring thermal sensors that operate in the mid and far infrared spectral bands. Although the program is designed to evaluate thermal imagers performance, it is also possible to analyze for the lock on ranges of a missile as a preliminary analysis tool.

It should not be forgotten that there are many factors that change the results of a detection range analysis and the analysis should be treated with care, as all analysis programs may end up with results that may differ from real case situation due to user and program assumptions. Variations in atmospheric conditions also change the detection range values drastically.

Most missile systems have IR seekers that operate in 3-5 micron (MWIR) or 8-12 micron (LWIR) bands. The reason behind this is the high atmospheric transmission in these wavelengths. Other portions of the IR spectrum are not suitable for use in long range IR detection.

Johnson’s criteria is a widely used metric for discrimination of targets. Three main discrimination levels are detection, recognition and identification. Detection is the sensing of target without knowing its spatial properties, recognition is defined as classification of the target as a tank, and vehicle etc. identification is deciding if the tank is an M-48A5T1 (U.S origin- Turkish) or a T-80U (Russian).

NATO STANAG 4347 specifies these discrimination levels which are specified as follows,

Resolution criteria, according to a 50% probability:

Detection : 1 line pair / target

Recognition : 3 line pairs / target

Identification : 6 line pairs / target

The specification for line pairs may vary slightly.

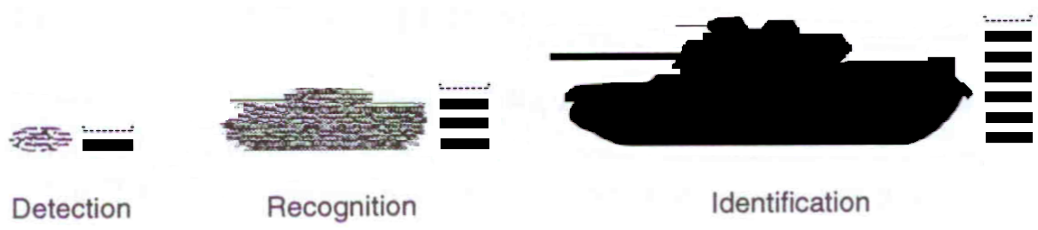


Figure 5-7 Detection, recognition and identification according to Johnson criteria

Since the detection, recognition and identification values are dependent on the human senses which can easily vary from person to person, it is more reasonable to give probabilistic range performance values instead of definite values. (Holst [54]).

For a missile seeker locking on a beacon which is small and act like a point target, recognition and identification is not necessary. So for the analysis detection values can be used as lock on distances as an assumption.

In a detection range analysis target size, target temperature difference with respect to surroundings and atmospheric conditions are very important. In this work several detection ranges are obtained by using NVTHERM program for several variations of the above parameters.

Three atmospheric conditions are specified ranging from bad to good visibility conditions as haze, light haze and clear. The atmospheric attenuation coefficients for these 3 conditions are converted to atmospheric transmittance by using Beer's law taking the range as 1 km in order to achieve the transmission values required for the NVTHERM program.

$$T = e^{-\sigma R} \tag{4.1}$$

The corresponding atmospheric transmission values are

Table 5-2 Atmospheric transmission values for three visibility conditions

Atmospheric attenuation coefficient	Transmission
0.75	0.47
0.404	0.67
0.1	0.9

Two beacon areas are defined to analyze the minimum effective beacon dimensions as 0.25 m^2 and 1 m^2.

Two temperature difference values are also specified for each visibility and beacon dimension. 2 Kelvin is the standard target temperature difference used in thermal analysis for non-cooperative targets. 10 Kelvin is also analyzed for a cooperative beacon which generates IR emissions.

A generic seeker model is used with similar parameters as existing air to surface weapons. The seeker or camera is assumed to be operating at LWIR band with a an uncooled staring array detector of 640 x 512 pixels with 25 micron pixel pitch size. F# (which is the ratio of focal length to diameter of the optics) is taken as 1 and field of view of the system is assumed to be 10 x 8 degrees in conjunction with the detector dimensions.

Typical parameters of the IIR seeker are as follows,

Table 5-3 Generic seeker parameters

Wavelength:	8-12um
Detector Format:	640x512
Detector Pitch Size:	25um
F#	1
EFL:	9.14cm
HFOVxVFOV:	10°x8°

Inputs are introduced to the NVTHERM program ([55]). The sensor altitude with respect to the beacon altitude is selected as 300 m. Beer's law is used for the given three atmospheric conditions. An example of NVTHERM input screens are given in Figure 5-8.

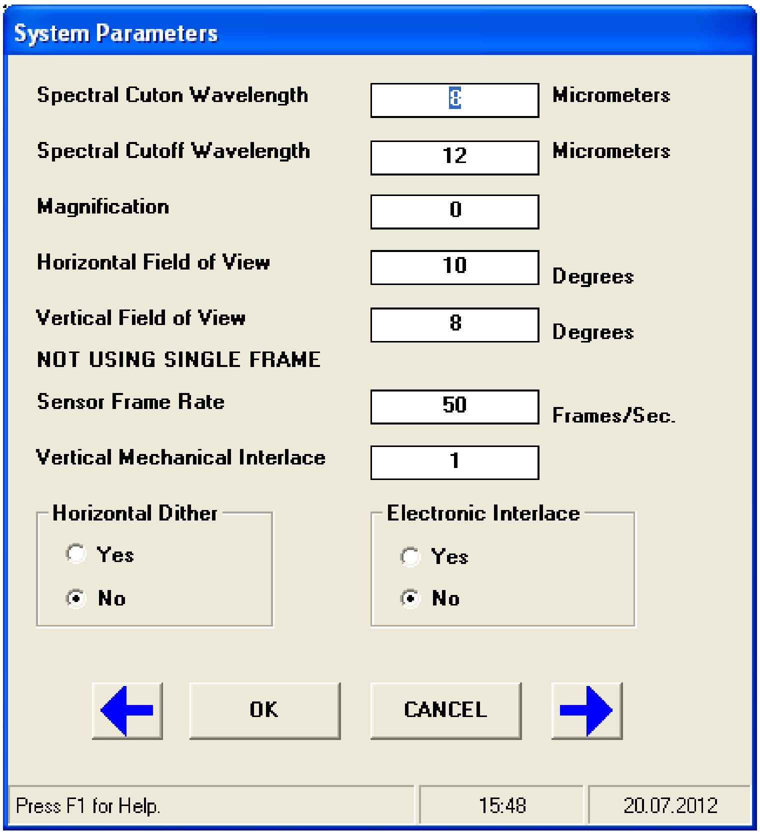


Figure 5-8 One of the input parameter screens of NVTHERM

Table 5-1 Detection ranges for two beacon sizes with two ΔT's in three weather conditions.

		Det Range (km)	
Target area (m^2)	Transmission	ΔT=2	ΔT=10
	0.9	1.48	3.04
	0.67	1.25	2.27
0.25	0.47	1.07	1.81
	0.9	2.76	5.38
	0.67	2.1	3.53
1	0.47	1.69	2.65

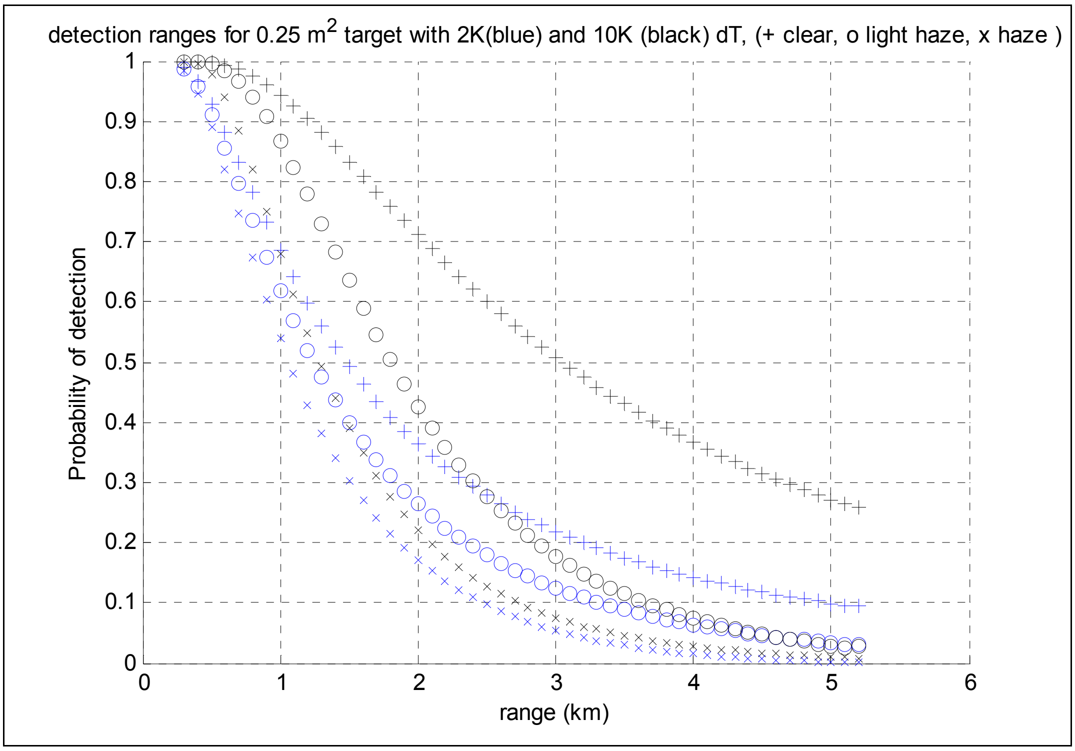


Figure 5-9 0.25 m^2 IR beacon detection ranges for three visibility conditions

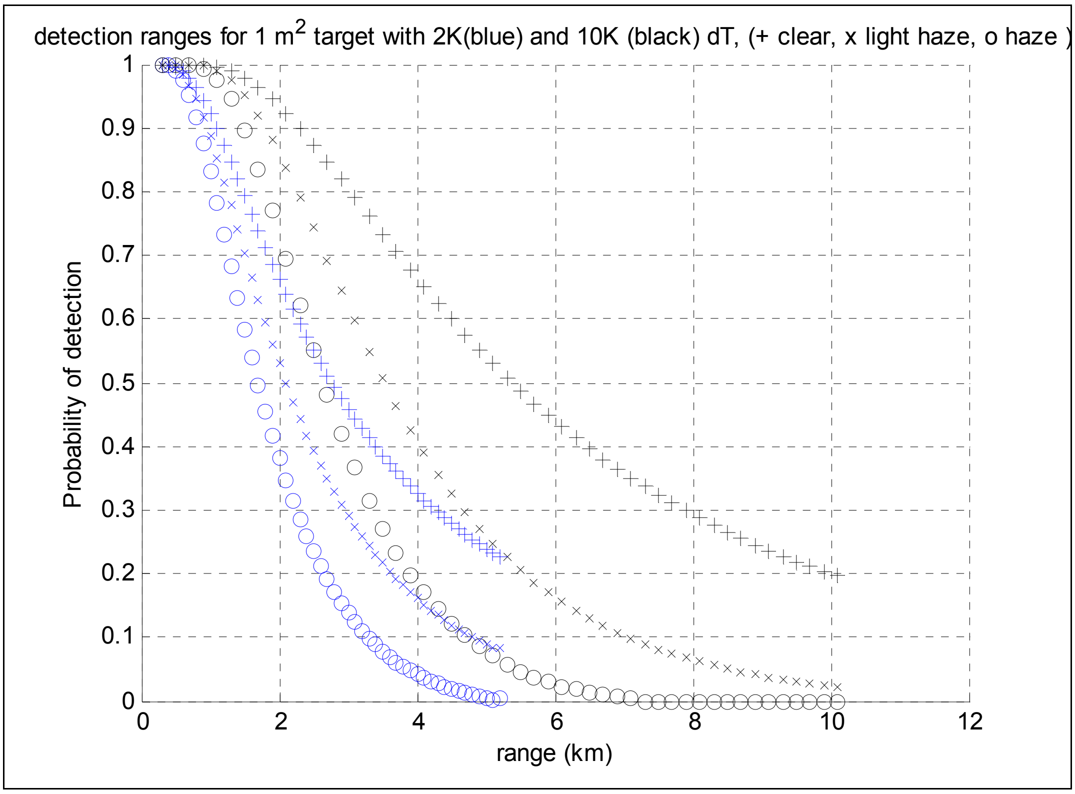


Figure 5-10 1 m^2 IR beacon detection ranges for three visibility conditions

5.7 Detection Range Calculations for a Hypothetical Diffuse Reflecting Laser Beacon

Brief information has been given about a hypothetical laser beacon system in Chapter I. For missiles and FLIR systems that have semi active laser seekers or laser spot trackers, an alternative form of a beacon may be a laser beacon with diffuse emission characteristics. This beacon may or may not be realized due to power requirements or any other reason but the preliminary analysis will be performed here.

Traditionally semi active laser guidance is employed in air to ground missiles and bombs, and is an effective way of achieving precise hits. Many air to ground weapons are equipped with semi active laser seekers to home on their targets. The first generations of laser guided bombs have velocity aligning seekers with 4 quadrant detectors which are guided to their targets with velocity pursuit guidance and bang bang type control. The first examples of these types are the Paveway I and Paveway II laser guided bombs (LGB). These versions do not have INS/GPS guidance and rely solely upon their wind aligning seeker heads and 4 quadrant detectors to home on laser reflected from target by using velocity pursuit guidance. Advanced versions of these weapons have INS/GPS systems in addition to the semi active laser gimballed seekers coupled with search patterns to look for the reflected laser from the target.

Along with trajectory shaping algorithms, and bigger control/stabilization surfaces these new generation LGB's can reach longer ranges especially when equipped with wing extension kits such as diamond back from MBDA or Long shot from Leigh Aerosystems.

The maximum range of Paveway III LGB is 30 km's when released from 33000 ft. The projected range of an LGB equipped with a wing extension kit is around 60+ kilometers.

Paveway III is equipped with a gimbaled laser seeker that can scan and search for a laser reflection from target in several search patterns such as conical and bar scans.

A hypothetical laser beacon is assumed to have a laser pulse generator that generates 10 Hz coded or uncoded pulses. However, unlike laser designators it may have a diffuser or illuminates a nearby diffuse reflecting surface with high reflectance.

The diffuse reflecting surface provides a hemisphere of laser radiation that can be detected by the 4 quadrant laser seeker onboard the missile. A gimbaled seeker with a 4 quadrant detector can lock on this emission and can null the pointing error of the seeker, obtaining the angle between the missile and the seeker LOS for few instances can provide a position fix without measuring the distance. Due to the nature of the 4 quadrant detector it is not possible to lock on two or three beacons simultaneously unlike imaging infrared systems.

For this purpose a hypothetical laser beacon shall have a laser source, a diffuse reflecting surface with high reflectance, power source (battery) to generate energy for the laser illuminator, and a solar panel to charge the batteries. A typical small battery pack with 2 Li-ion batteries (10 Amper-28V) can operate the laser source and cooler for 1.5 hours. Since laser illuminator will require cooling and operating the laser beacon for prolonged periods is not possible, it will require an RF trigger from an external source such as the ordnance deploying aircraft or an incoming missile.

A detection range analysis for a hypothetical diffuse reflecting beacon is performed.

Laser propagates through the atmosphere according to Beer's law.

$$T = e^{-\sigma R} \tag{4.2}$$

Where T is the transmission which takes a value between 0 and 1, σ is the atmospheric attenuation coefficient (1/km), and R is the range (km). Atmospheric attenuation coefficient can be found by

$$\sigma = \frac{3.91}{V} . \left(\frac{550}{\lambda} \right)^q \frac{1 - e^{-0.82\, x h_{LGB\ or\ designator}}}{0.82\, x\, h_{LGB\ or\ designator}} \tag{4.3}$$

Where V is visibility (km), λ is wavelength (nm), and q is the size distribution of the scattering particles (1.6 for high visibility for V>50 km, 1.3 for average visibility for 6 km<V< 50 km).

If the visual range is less than 6 km due to haze, the exponent q is related to the visual range by the following empirical formula,

$$q = 0.585 V^{1/3} \tag{4.4}$$

where, V is expressed in kilometers.

In general, the power at the target P_{target}, can be found by multiplying the designator output power $P_{designator}$ with the transmission coefficient. T, Then the power at the target is multiplied by the target reflectance and the diffuse reflection from the target forms a hemisphere like shape whose radius is determined by laser seeker sensitivity, atmospheric transmission from target to the missile seeker, target seeker geometry etc. The beacon surface is regarded as a diffuse reflecting surface and the specular reflection component is neglected since its direction can not be known a priori for the missile.

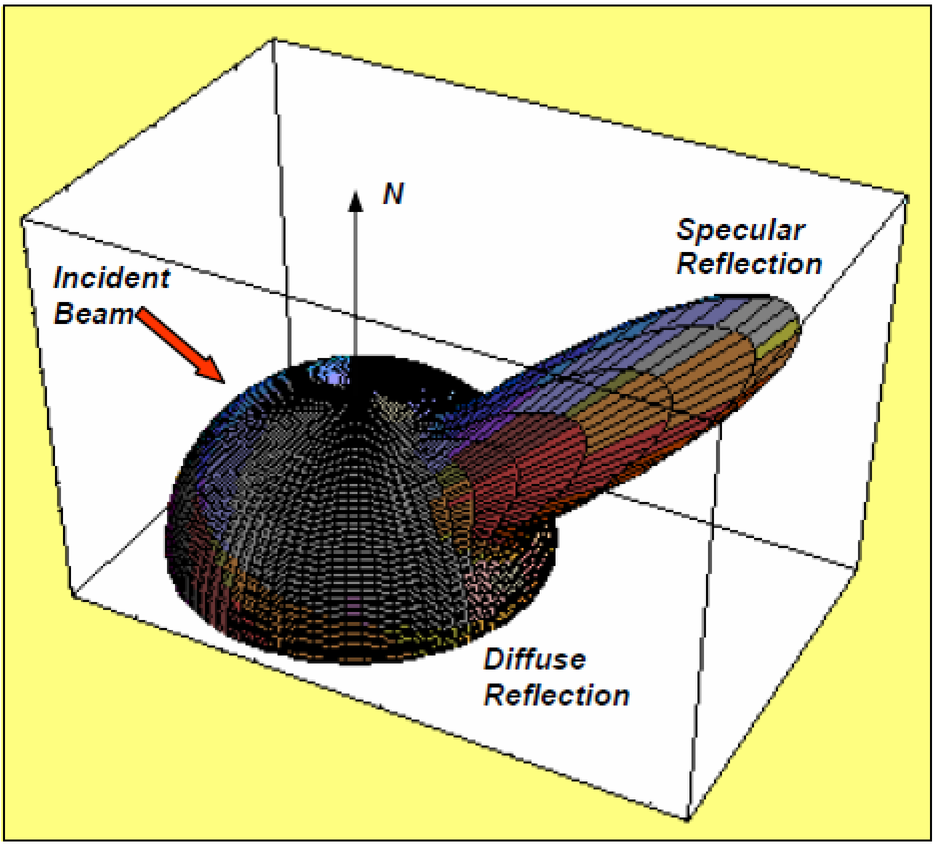


Figure 5-11 Diffuse and specular components of laser reflection [NATO [56]]

For the case of a laser beacon the laser source and the reflecting surface are co-located, which makes the atmospheric attenuation from source to target negligible, target surface is a cooperating surface with high reflectivity. The reflection pattern of the target surface can be regarded as a diffuse reflecting surface.

Regarding these considerations the power reflected from the diffuse beacon can be found with following equations.

$$P_{target} = P_{source}\, x\, T1 \tag{4.5}$$

T1 is 1 since laser source and target (diffuse reflecting surface) are collocated.

$$P_{reflected} = P_{target}\, x\, G\, x\, (1 - spillover) \tag{4.6}$$

Where G is the target reflectivity. Since a cooperative target surface or a diffuser is used, G can be taken as 0.9. Similarly spillover is negligible since the laser source is very near to the surface.

Assuming a dominant diffuse reflection from all target surfaces, the reflected power is radiated uniformly into a hemisphere and a fraction of this power is sensed by the seeker. The power collected by the seeker, $P_{received}$, is equal to $P_{reflected}$ multiplied by the atmospheric transmission, and the ratio of the seeker optics to the area of a hemisphere with a radius equal to range as an approximation.

$$P_{received} = P_{reflected}\, x\, T2\, x\, \frac{A_{lens}}{2\pi Range^2} \tag{4.7}$$

T2 is the atmospheric transmission between the laser seeker and the beacon.

$$P_{received} = P_{source}\, x\ G\ x\, T2\, x\, \frac{A_{receiver}}{2\pi Range^2} \tag{4.8}$$

If $P_{received} > P_{\text{minimumdetectable}}$ then the seeker can lock on the beacon.

Typical output powers of laser designators are 50-100 milijoules and frequencies 10 or 20 Hz.

A detection range analysis is performed based on a low output power laser source for different output energies ranging from 1 milijoule to 50 milijoules for visibility range between 1 to 6 km's, considering the general specifications of laser guided weapons.

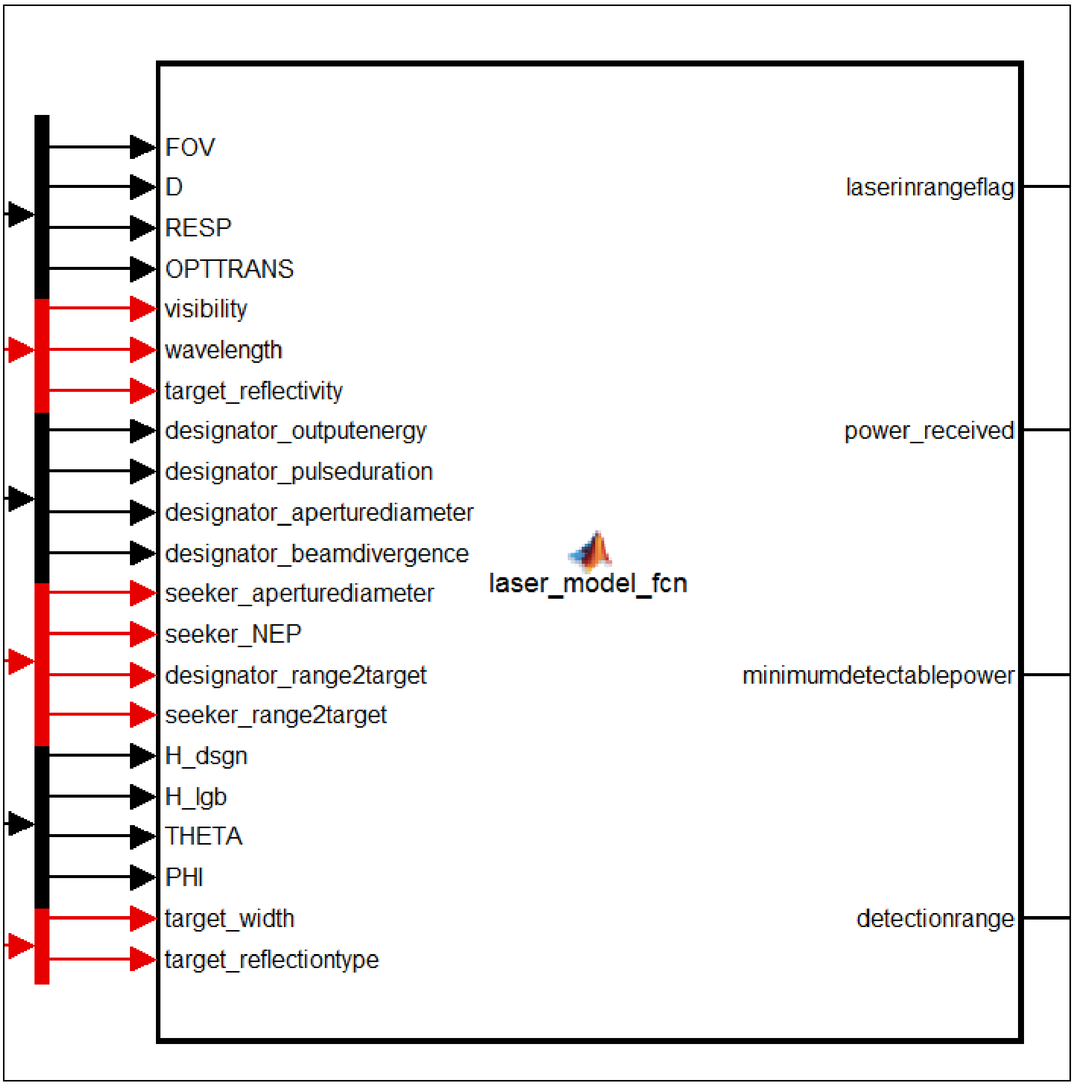


Figure 5-12 Laser model

For below average visibility conditions, a 20 milijoule output power beacon is necessary to achieve 2+ km detection ranges as can be seen from Figure 5-13.

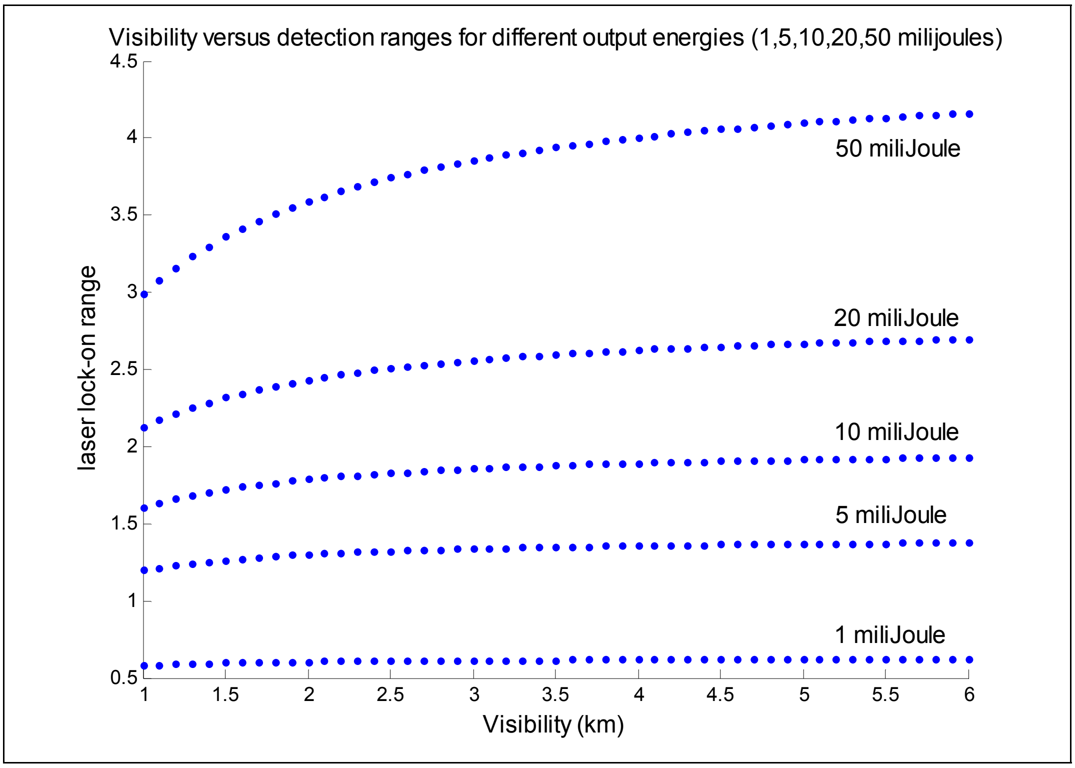


Figure 5-13 Seeker laser detection ranges for different laser source energies

5.8 Implementation of Position Fixing Methods

The three position fixing methods suggested in this thesis are implemented taking into account their capabilities and air platform specifications. Details are given below.

5.8.1 Implementation of the Reverse Intersection Method

If due to the beacon deployment, the seeker sees only one beacon, RI method can be used by observations of the beacon from two observation stations.

Reverse intersection name is chosen, since normally intersection method is used to determine triangle apex coordinates from two known observation points. In our case estimated observation points coordinates are used to calculate estimated beacon position and this estimation is compared with the actual position and a correction to the IMU-estimated observation points is provided.

The seeker produces the vertical and horizontal angles to the known point. In the simulation, these angles are computed by using the true coordinates of the observation point A and the true coordinates of observation points B and C.

Then the angles to the beacon A are fed to the “reverse intersection algorithm”. The algorithm calculates the coordinates of A (A_estimated) from estimated ground station coordinates (B_estimated, C_estimated) and observed angles.

The difference between the true coordinates of A and estimated coordinates of A are fed to the observation point coordinates and updated points coordinates B_updated and C_updated are obtained. Updated point C coordinates are fed to the Kalman filter.

5.8.2 Implementation of Two Point Resection Method

Since actual seeker data when it measures the angle to the stations is not available, the angles which must be observed by the seeker are generated using the method below.

The desired trajectory is formed. When the position update algorithm is about to operate, an algorithm which calculates all necessary information for the given beacon(s) and observation point geometry operates and calculates the angles that are to be measured by the seeker in the actual case. Desired path observation point coordinates are used to calculate seeker elevation and bearing angles to the stations. After this calculation, computed internal angles are fed to the “Two point resection algorithm” which takes known station coordinates, observed angles and LOS error which is created to induce error into the computations, which is assumed to be near to the seeker LOS pointing error in terms of magnitude, and calculates the coordinates of observation points which are termed as R and Q.

When the position update is generated by the “Two point resection algorithm” second observation point on the trajectory of the missile is fed to the Kalman filter as aiding. The first calculated point (R) s not used.

5.8.3 Implementation of the Three Point Resection Method

If the seeker is capable of tracking 3 points at a time and observes three stations simultaneously, this method can be used for a one shot position update.

When the seeker observes three of the beacons at a time, it produces the angles to the points. In the simulation, these angles are also computed by using the true coordinates of the observation point P and the 3 known stations by the same algorithm which computes true angles for the 2 point resection method. It takes point Q as a known station and calculates the necessary data. Then the angles to the three stations are fed to the "three point resection algorithm" This algorithm calculates the coordinates of P from ground station coordinates and observed angles.

When the position update is generated by the "Three point resection algorithm" point P coordinates is fed to the Kalman filter.

The inputs and outputs of the functions involved are as follows.

"Distanceanglecalculator" is the algorithm which takes 4 point coordinates, calculates the azimuth angles of all the lines, and calculates internal angles for all triangles formed. Outputs are angles, horizontal ranges, slant ranges, vertical ranges, azimuth angles, reverse azimuth angles, elevation angles for the given geometry.

"Reverse intersection algorithm" takes the coordinates of IMU estimated observation points, true observation points, true beacon coordinates and LOS error of the seeker and outputs estimated beacon coordinate, updated observation point coordinates, errors in point coordinates and difference between the beacon A true and estimated coordinates.

"2 point resection algorithm" takes into account the two beacon coordinates, horizontal and vertical angles to the beacons from two observation points, LOS error magnitude of the seeker and outputs calculated observation point coordinates, vertical angle from R to A, heights and AR distance.

“3 point resection algorithm” takes 3 beacon coordinates as A,B,Q, internal angles and vertical angles from observation point to beacons and seeker LOS error magnitude and outputs observation point coordinates.

Figure 5-14 shows the general flow diagram of the program.

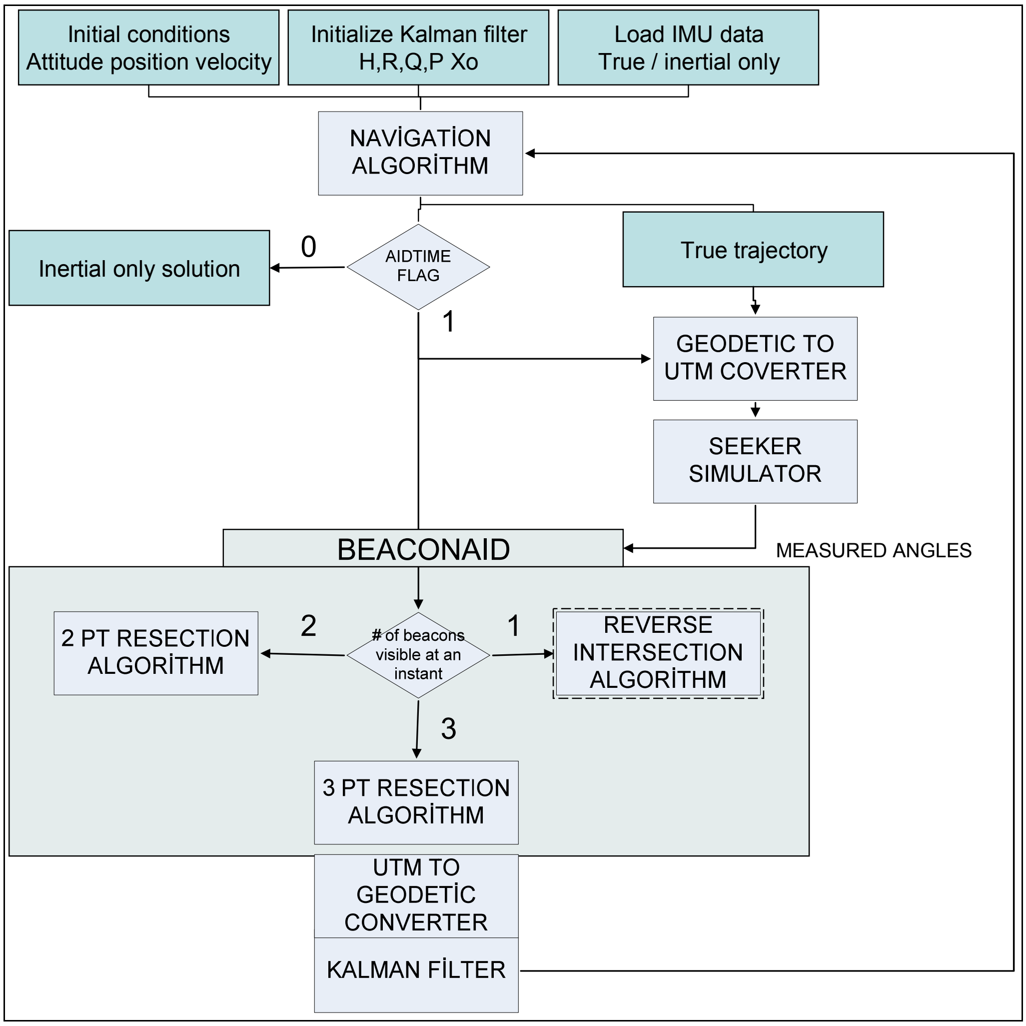


Figure 5-14 Position update logic block diagram

5.9 Decision Maker

Forms visibility matrix whose rows are beacons in chromosome and columns are instances of flight trajectory. Which is formed by 1, and 0's by checking if a beacon is within range.

After visibility matrix is formed, it decides when to make an update and what kind of update is to be performed.

Three point resection is performed at an instant when 3 beacons are within range. For the reverse intersection method to be applied, the decision maker checks if only one beacon is visible to the seeker. If a beacon enters into range a track gate is initiated. The decision maker than searches if the same beacon is staying visible for a while. If the same beacon is not visible in a second instant the track gate is closed and search is continued.

If the same beacon stays visible for some time, the last visible istant is taken as the second observation point. If the number of beacons visible to the seeker increases to 2 or 3, the reverse intersection is terminated in favor of 2 point or 3 point resections.

The search algorithm also searches for instants where 2 beacons are visible at the same instant to the seeker. If 2 beacons are visible a track gate is initated, the algorithm determines which beacons are visible and continues tracking until the same two beacons case vanishes either by one of them getting out of range or 3 beacons entering the visibility, FOR and FOV range.

2 point resection's second observation point is taken as the last instance the same two beacons are observed.

If 3 beacons enter into the seeker FOV, two point resection is terminated in favor of 3 point resection algorithm.

Figure 5-15 shows a two beacon case. Assuming that the FLIR has a wide FOV and a FOR around 120 degrees, when the first beacon enters the detection range of the FLIR RI is started. It is necessary for the beacon to be in the FOR of the FLIR or seeker t start RI. If not, the flight direction or the search direction is not god enough for the platform to perform a position update. RI continues until both beacons are in range of the missile and also in FOR when compared with the flight direction and also both beacons must stay in FOV when the FIR or camera turns to them. 2PR method is selected and used during this phase until one of the beacons leaves the FOV or the FOR of the platform, whichever occurs first. Then both beacons are still in detection range but one of them does not meet the FOV of FOR constraint. RI is started for B2 until it goes out of FOR.

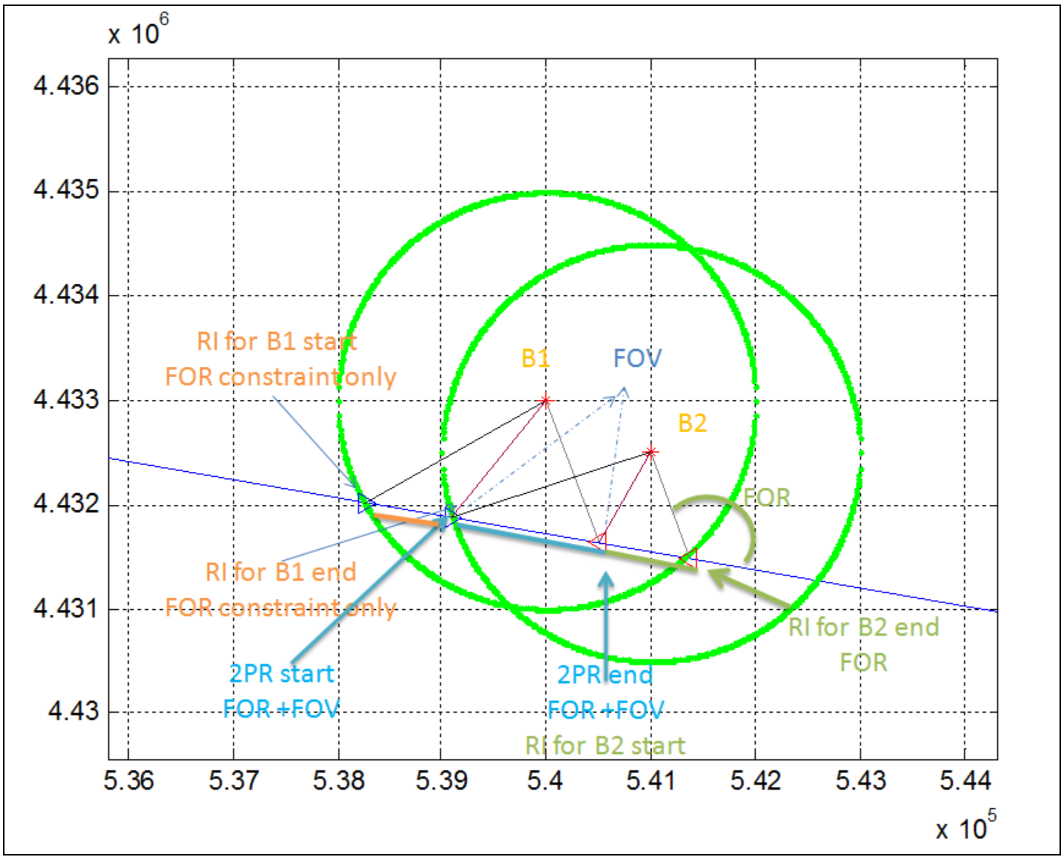


Figure 5-15 Method selection based on constraints for 2 beacon case.

The various layers of decision maker and method selection conditions are summarized in Figure 5-16.

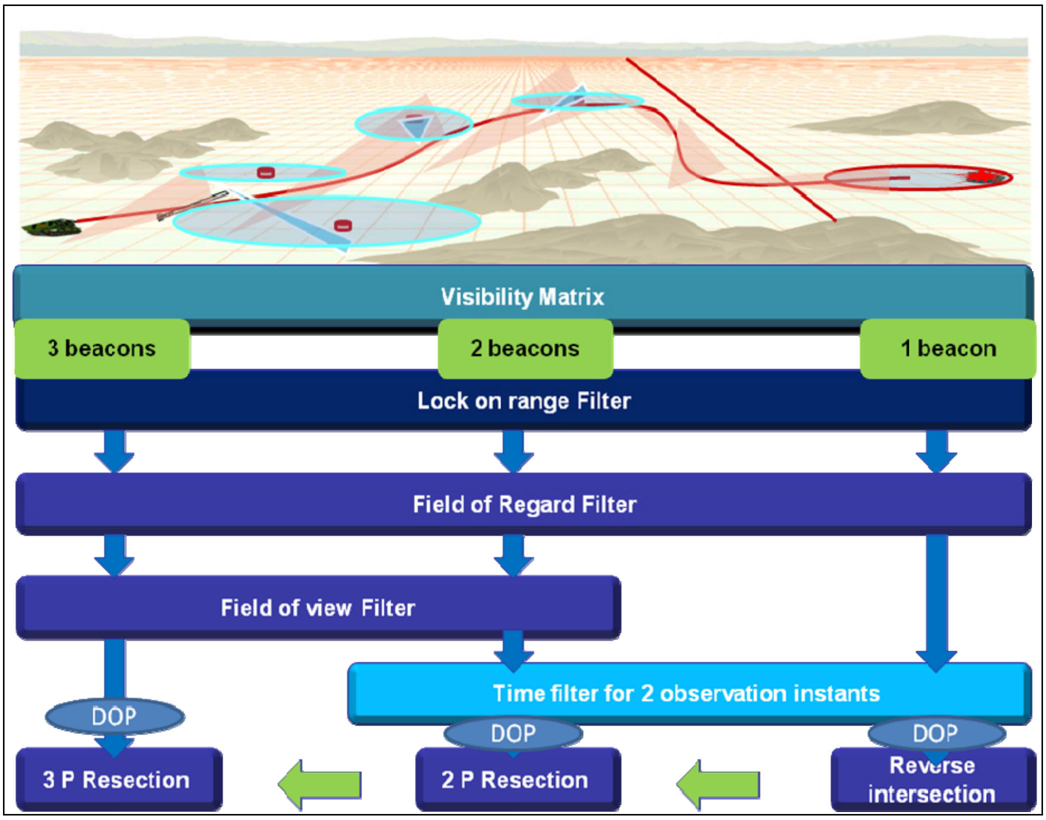


Figure 5-16 Decision maker layers

CHAPTER VI

CASE STUDIES AND RESULTS

6.1 Introduction

In this chapter information GA optimization program and its layout is given. Optimization case study results for both path planning and deployment problems are given. Several test cases are defined with different objective functions and constraints to test the GA and for the operational scenarios and results of several independent GA runs are shown. Best of generation (BOG) graphs provide an insight about the improvement with generations. Trajectories of optimum solutions from GA runs are given with beacon coordinates, corresponding observation windows and path information of the path planning GA.

Deployment problem solutions are given in the form of position covariance bounds and error growth for a realization of inertial sensor errors, trajectory, north, east and, down velocity histories. Deployment problem involves VLCGA structure to allow the analysis of beacon numbers at one run. On the other hand path planning algorithm takes constant number of waypoints since in that case number of waypoints is not important in terms of minimization as long as maneuver constraints are satisfied.

6.2 Optimization Program

The layout and operation of the optimization program for path planning problem is as follows.

GA_PP Is the main program that takes FOV, FOR, heading constraints, deployment and navigation area boundaries, GA parameters, detection range as input and outputs best population and best fitness value obtained, along with a history of BOG (best of generation) information. It can also perform multiple sequential independent runs and let's BOG and fitness comparison between the GA runs.

GA_PP calls for "*Fitnesscalctraj"* function which calculates the fitness values based on selection of *fitnessoption*. Fitness option changes the fitness function definition as minimum path length, minimum pathlength and maximum observation window, maximum observation window with method preference etc.

Objective functions:

1- Minimize path length while maximizing the distance spent in beacon ranges where position fixing is possible. (Maximizing points of observation where FOV and FOR constraints are satisfied.)

2- Minimize path length while maximizing the distance spent in beacon ranges where position fixing is possible. (maximizing points of observation where FOV and FOR constraints are satisfied.) and reflect the preference of 3 pt resection to two point resection and reverse intersection.

3- Minimize path length while maximizing the distance spent in beacon ranges where position fixing is possible. (Maximizing points of observation where FOV and FOR constraints are satisfied.), reflect the preference of 3 pt resection to two point resection and reverse intersection and reflect the quality of position fix.

GA_PP takes *fullpath* which is composed of waypoints that the vehicle is to pass through as input and calculates trajectory points, then calls for *"Decisionmaker* " to obtain the observation segments.

"Decisionmaker "function calculates the "*observationpointsFOVFOR"* matrix for a given *fullpath* trajectory.

The function calls "*spline trajectory generator*" to obtain easting, and northing values of trajectory points. *"Trajectory Generator"* generates a path based on waypoints in northing and easting coordinates and outputs *pointsoftrajectoryEN* in easting northing order.

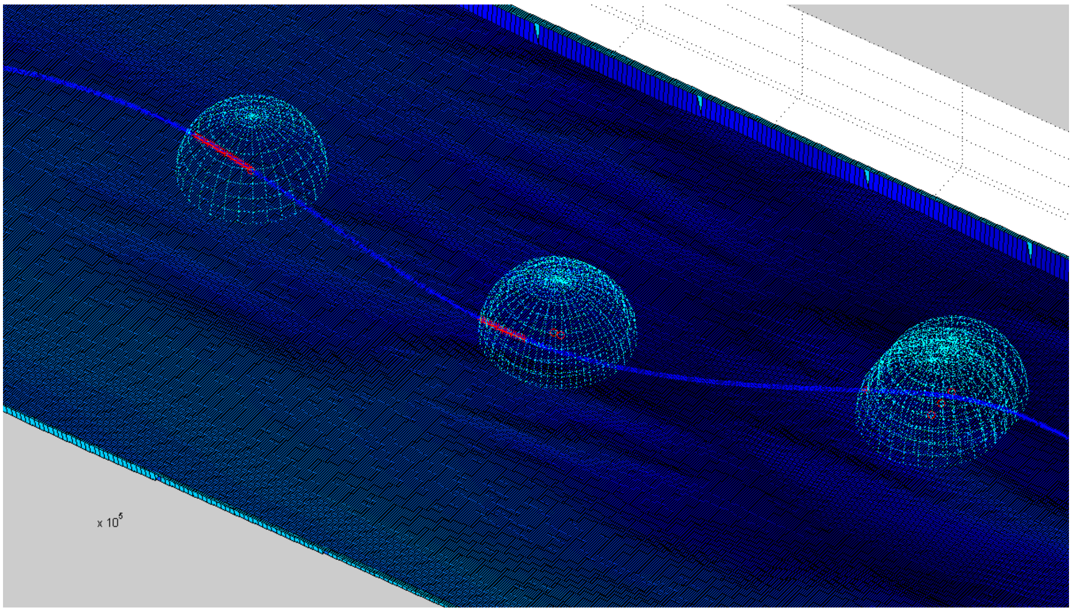


Figure 6-1 Sample trajectory, beacons and observation windows

"Decisionmaker" evaluates visibility matrix for each point of the trajectory and obtains *visibilitymatrix* which consists of 1's and 0's based on which beacons are in detection range.

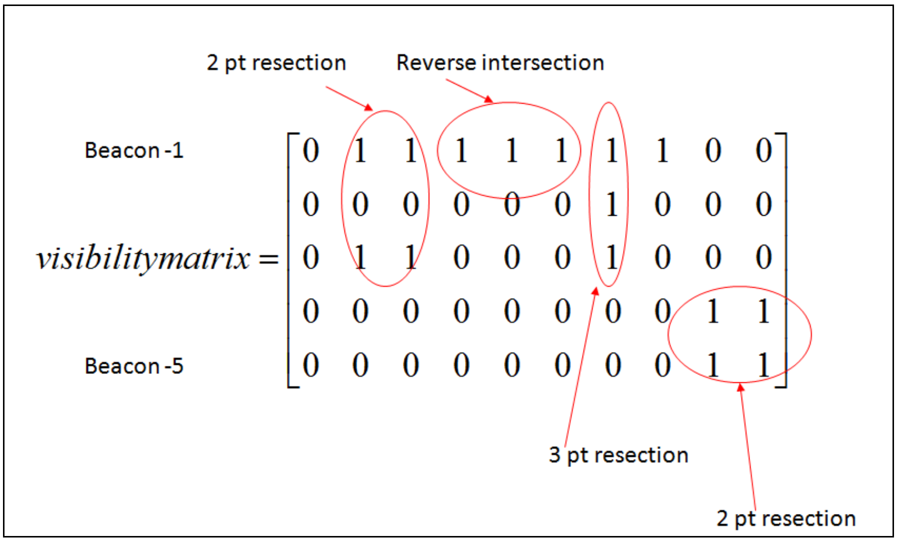


Figure 6-2 Visibility matrix and position fix method information

The function calculates *observationpointssorted* matrix which gives information about from which instant to which instant, which beacons are visible.

It also decides which method to use based on how many beacons are visible and the identities of the visible beacons. If the same 2 beacons are seen for a period, a 2 point resection method is used. If same three beacons are in range for a period, three point resection is preferred and for one beacon case reverse intersection method is selected.

Observationpointssorted matrix provides information about which beacons are visible at what instants, preferred position update method and corresponding coordinates of the said beacons.

More operations are performed on this matrix based on method type. All segments of flight where any 3 same beacons are in *detectionrange* of the platform, are fed to the FOV and FOR constraint checker functions for the different conditions of the three positioning methods.

If 3 or more beacons exist, *"FOVFORchecker3pt"* function is called. *FOVFORchecker3pt"* function takes the coordinates of the trajectory points, relevant row of the *observationpointssorted* matrix which has information of observation start and end indices and coordinates of beacons in range, FOV, FOR and any other relevant information.

"FOVFORchecker3pt" function checks the angular constraints of the three point resection method at every point of a flight segment which is fed to the function where the same three beacons are available. The function checks if a 3 pt. resection is possible, by controlling

- if all of the bearing angles between the missile heading and missile to beacon LOS are less than the FOR of the missile (*inFORflag* set to 1)
- and all 3 beacons are inside FOV of the missile both horizontal and vertical directions at the same observation instant.

"FOVFORchecker3pt" function calculates distances and angles of the defined geometry, by using "anglesanddistances" and "coordinateanglecalculator" functions, sorts the beacons in CW order, checks if the beacons are in FOR, and if the beacons are in FOR, checks if the beacons are in FOV and any of the two beacons are not coincident on a line within tolerance.

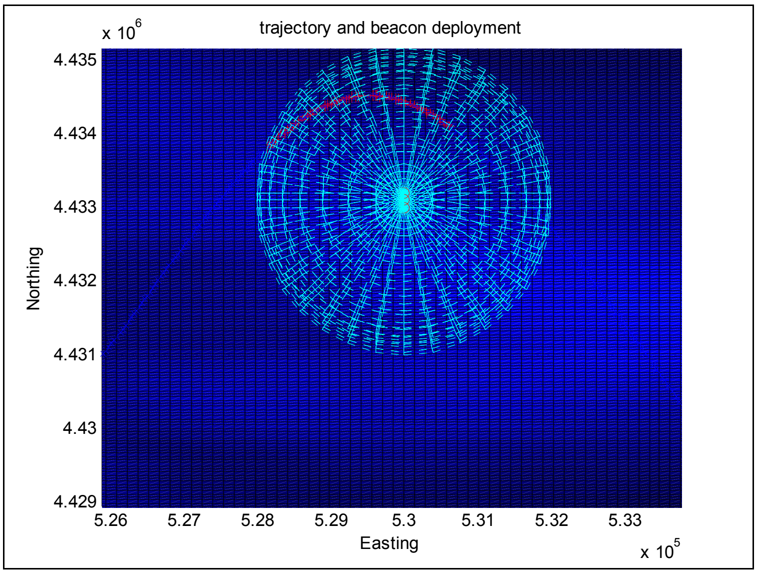


Figure 6-3 Optimization trajectory trying to hold the 3 beacons in its FOR/FOV.

FOVFORcheckerflag is set to 1 if all conditions are satisfied. İf not *FOVFORcheckerflag* is set to 0 and multiplied by the corresponding flight segment row of the *observationpointssorted* matrix, which row is then cleared.

"FOVFORchecker2pt" function is called If for a flight segment two same beacons are in detection range, "FOVFORchecker2pt" function checks the angular constraints of the two point resection method at every point of a flight segment which is fed to the function where the same two beacons are available for a slight segment. The function checks if a 2 pt. resection is possible, by controlling

- if both of the bearing angles between the missile heading and missile to beacon LOS and missile to second beacon LOS are less than the FOR of the missile (*inFORflag* set to 1)
- For the first and the nearest second observation points both beacons should be in FOV of the missile at the same time.
- The missile-beacon#1 and missile-beacon#2 LOS must not be coincident within a specified limit.

It is possible to come up with a situation that; for a flight segment within a range of two beacons there may be multiple sub segments where range, FOV and, FOR constraints are satisfied. In such a situation, "*FOVFORchecker2pt"* function detects those segments and outputs the start and end points of those segments along with the beacon coordinates. These rows are added to *observationpointssortedFOVFOR* matrix.

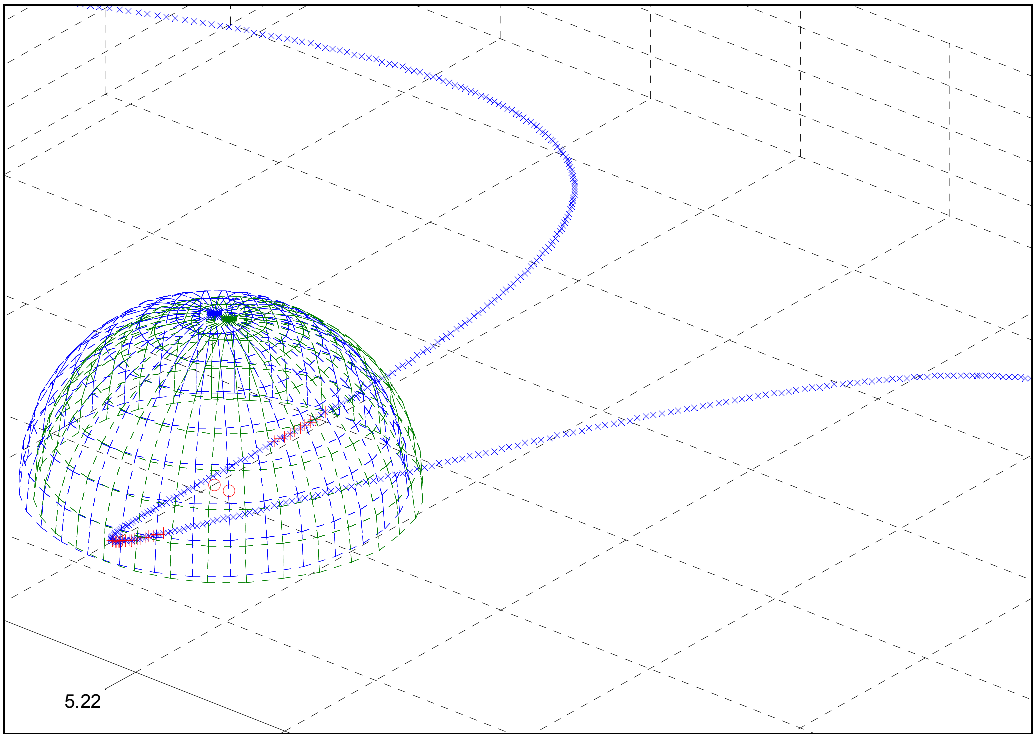


Figure 6-4 2PR method observation windows (red) for FOV=10 degrees and FOR =90 degrees for a test case with sharp turn inside beacon range.

If for a flight segment, only one and same beacon is seen for an observation period, "*FOVFORchecker1pt"* function is called to find the parts of the segment where the beacon is inside the FOR of the platform. For this purpose the flight direction of the missile vector is compared with the seeker-beacon LOS vector throughout all points of the trajectory segment. This function also finds if there are multiple sub-segments of the given segment where the beacon can be locked and tracked by the seeker in it's FOR.

"*Pathlengthcalculatorfortrajectorysegments*" calculates path length information for trajectory segments which were obtained by "*decisionmaker"* function. It outputs both the path segment lengths for each segment and total path suitable for position update.

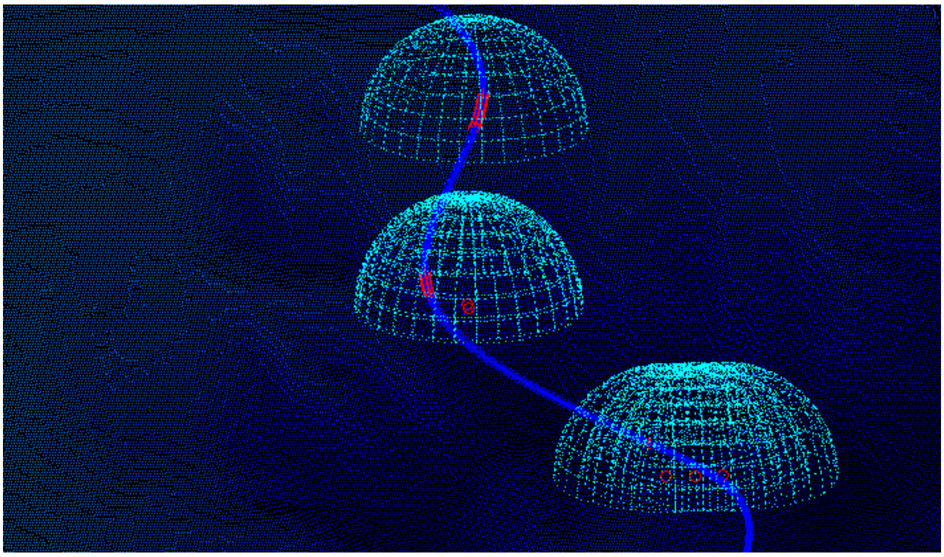


Figure 6-5 Observation windows (red) that are created using FOV, FOR and method constraints along a trajectory passing thorugh 6 beacons.

"*Pathlenghtcalculatorfortrajectory*" calculates the total trajectory length by using poinrs of trajectory.

"Plotter" plots beacon centers, beacon detection ranges in the form of hemispheres, trajectory of the platform, observation segments within range, FO, FOR constraints fort the three position fixing methods.

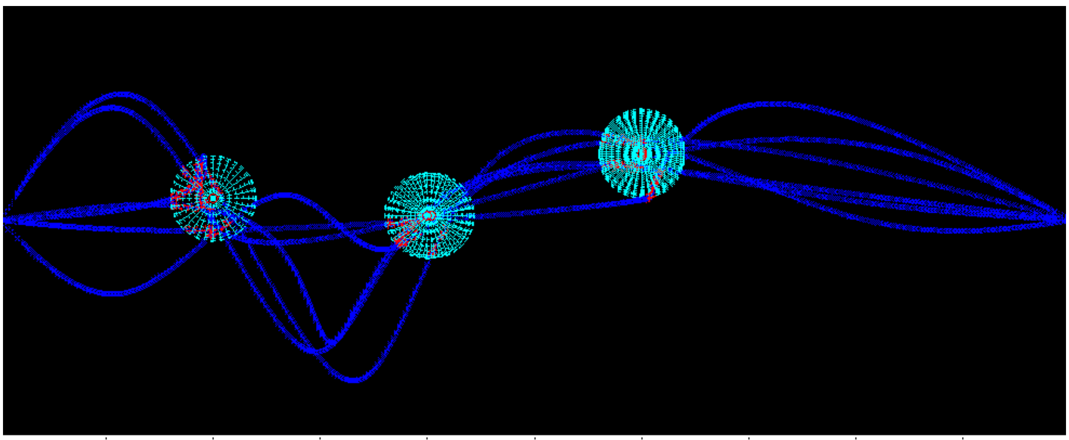


Figure 6-6 Multiple chromosomes and corresponding trajectories

6.3 Path Planning Problem Optimization Case Studies

6.3.1 Case -1: Test Case, Shortest Path

A test case is run in order to check the genetic algorithm developed for the path planning problem. The problem is formulated to find the shortest path between the missile (M) and the target (T) to check if the optimization algorithm finds a straight path.

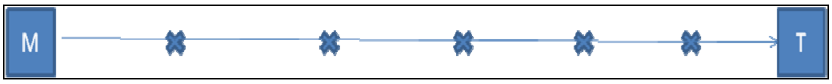


Figure 6-7 Shortest path problem from missile to target with n waypoints.

The missile is positioned at coordinates (4430000 500000 0) and target is located 50 km's away in northing, easting, height coordinates (4430000 550000 0). The shortest path is 50.000 meters and along aa straight line between missile and target. The fitness function is the sum of all path lengths of sub-path segments. Figure 6-8 shows the trajectory and Figure 6-9 and Figure 6-10 show the BOG improvement with generations. With 5 independent GA runs to find the shortest path with 20 members with 3 waypoints and 50 generations, all solutions reached <50005 meters

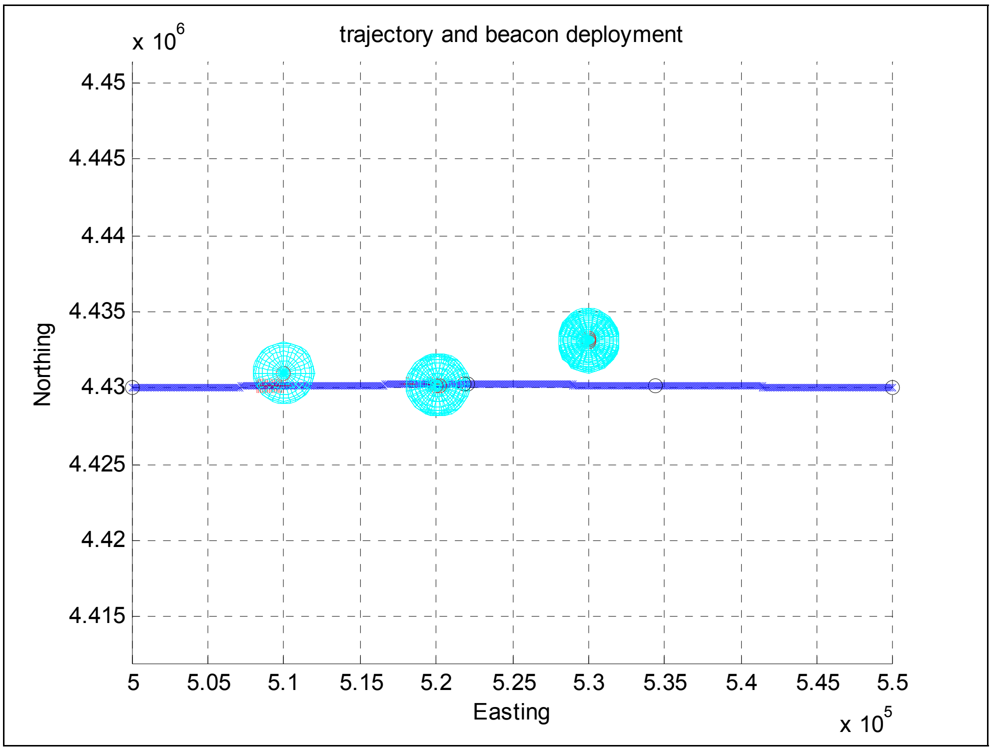


Figure 6-8 Shortest path test case trajectories

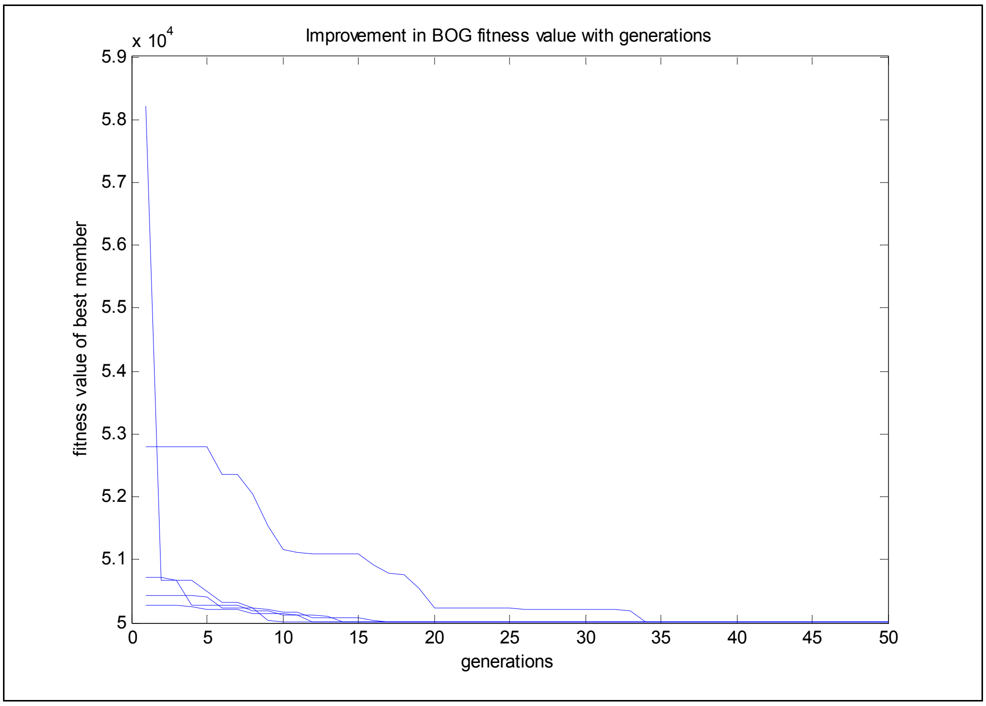


Figure 6-9 BOG improvement with generations for shortest path.

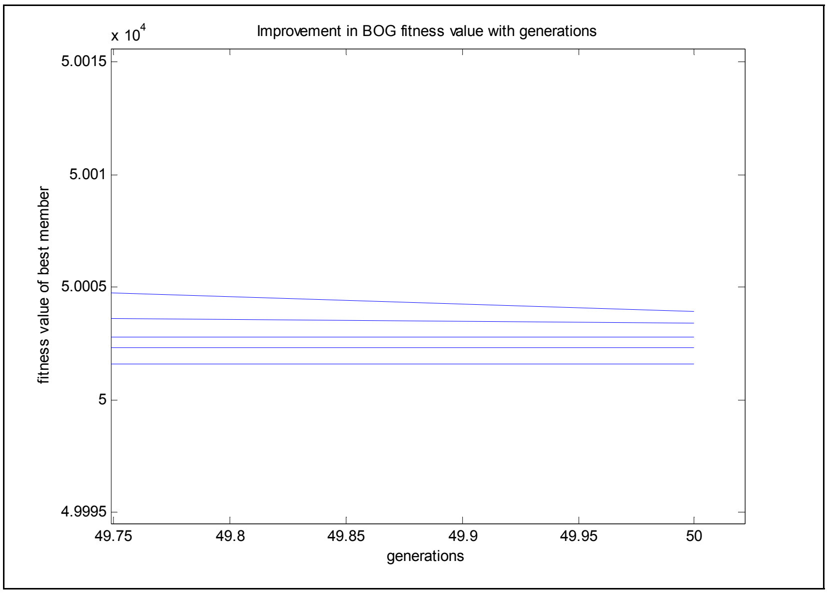


Figure 6-10 BOG improvement with generations for shortest path (magnified)

Table 6-1 Optimization results for shortest path test case with 2 wp's

problem	path planning	path planning
objective function	shortest distance	shortest distance
FOR constraint	none	none
waypoints	2	2
populationsize	20	50
generations	120	50
mutation rate	0.40	0.40
expected best fitness	50000.00	50000.00
Generation	BOG	BOG
1	50426.34	50276.00
10	50010.38	50002.00
120/50	50000.10	50000.00

6.3.2 Case-2: Test Case - One Beacon

The objective function in test case 2 is “minimization of the path length / spent distance in beacon range” quantity which leads to shortest path which passes through the diameter of the sphere whose center is the beacon.

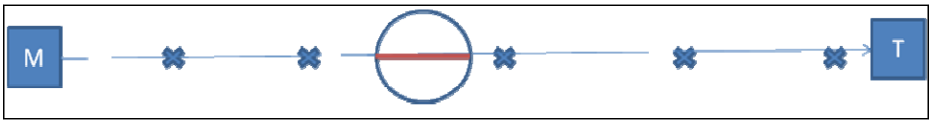


Figure 6-11 Maximize path length in beacon range to overall path length.

Table 6-2 Sample test case results for CASE-2.

problem	path planning	path planning
objective function	Minimize (path length / path length in beacon range)	minimize (path length / path length in beacon range)
FOR constraint	none	FOR=90
waypoints	2	2
populationsize	50	50
generations	20	20
mutation rate	0.4	0.4
expected best fitness	12.50	25.00
Generation	BOG	BOG
1	12.9551	27.0275
5	12.5467	25.0444
10	12.5461	25.0016
20	12.5000	25.0006

6.3.3 Case-3: Test Case - Three Beacons

The objective function in test case 3 is minimization of the path length / spent distance in beacon range quantity which leads to shortest path which passes through the diameter of the sphere whose center is the beacon. The expected value of the best fitness function is 4.1667 (50000/ (3 x 4000)). A better result is found by the GA as shown in Figure 6-13 and Figure 6-14.

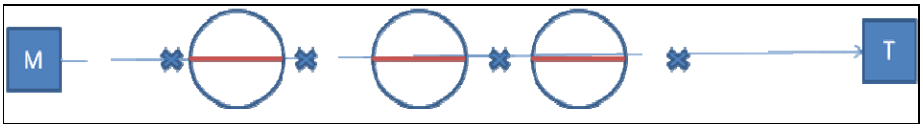


Figure 6-12 Case-3 schematic

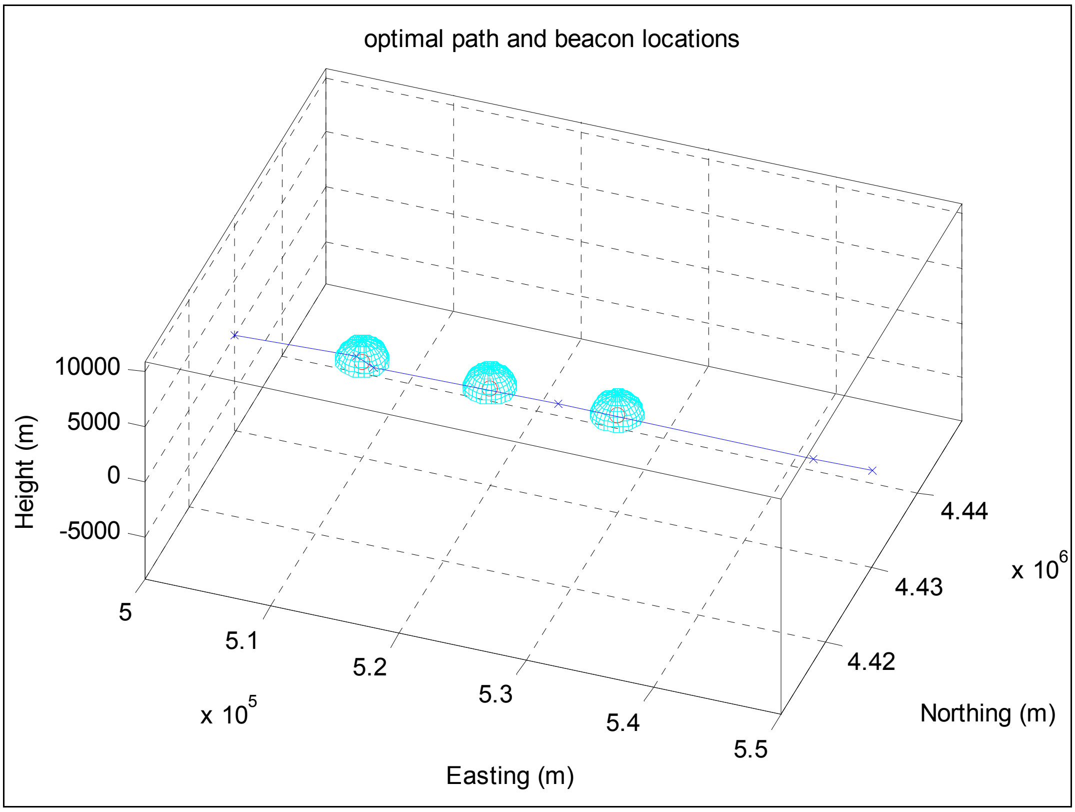


Figure 6-13 Optimization result for three beacons with 4 waypoints and 30 degrees turn constraint

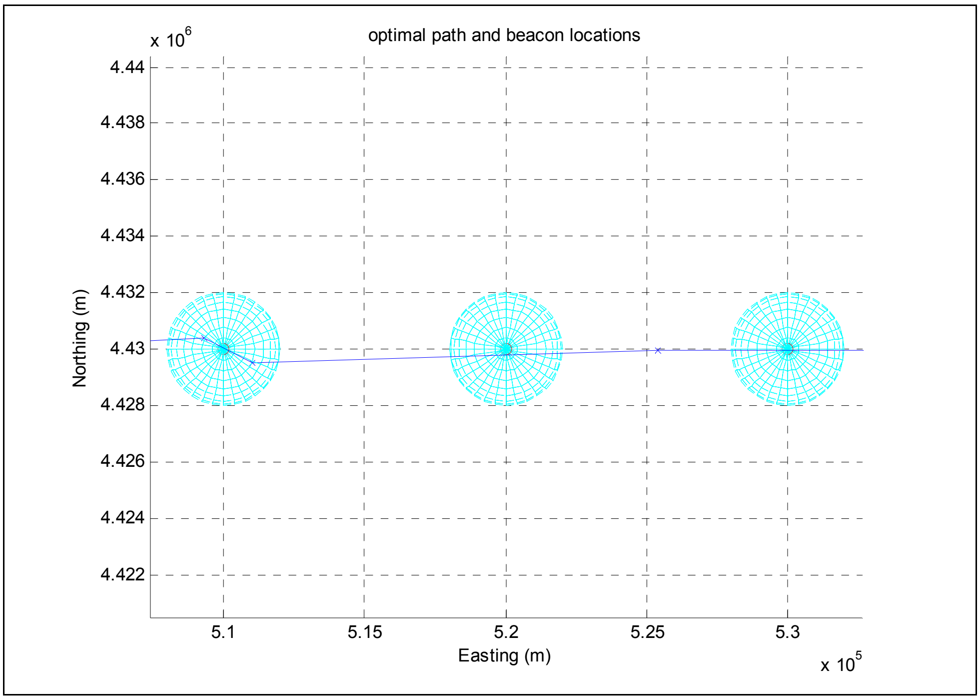


Figure 6-14 Optimization result zoomed.

Table 6-3 Sample test case results for CASE-3.

problem	path planning
objective function	shortest distance
FOR constraint	none
waypoints	2
populationsize	20
generations	40
mutation rate	0.40
expected best fitness	
Generation	BOG
1	12.25
10	4.19
15	4.18
40	4.14

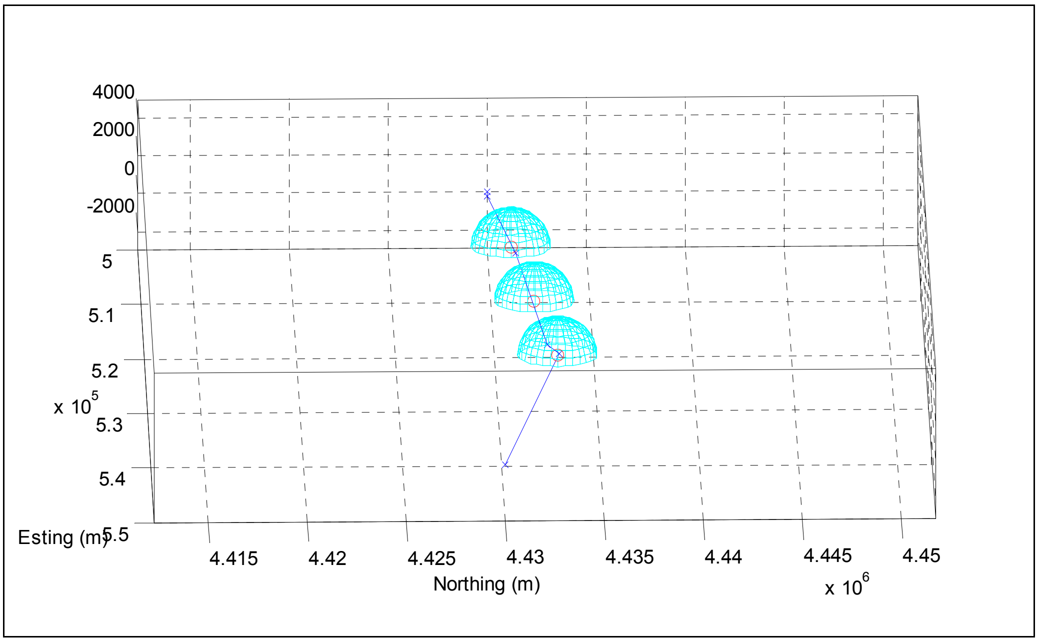


Figure 6-15 Optimization result for three beacons offset by 1000, 2000 and 3000 meters in northing with 4 waypoints and 30 degree turn constraint

6.3.4 Case-4: 6 Beacons - Operational Scenario

Operation area is 50 km's by 20 km's wide.

In this scenario, 6 beacons are deployed such that the first beacon is left alone to allow RI, while second and third beacons are located near to each other in order to allow 2PR. 4th, 5th, and 6th beacons are deployed to allow 3PR method to be applied. Beacon detection range is set to 2000 meters.

Heading constraint is applied in the form of dynamic penalty function, thus total heading constraint violation throughout the trajectory is found and fitness value is modified by adding a term which is a function of fitness and heading constraint violation. The objective function is defined to minimize the path length from launch site to target while maximizing the observation windows in beacon ranges. Observation windows are found by segments of trajectory inside beacon ranges. Multiple run results converge to the trajectory shape given in Figure 6-16 and Figure 6-17.

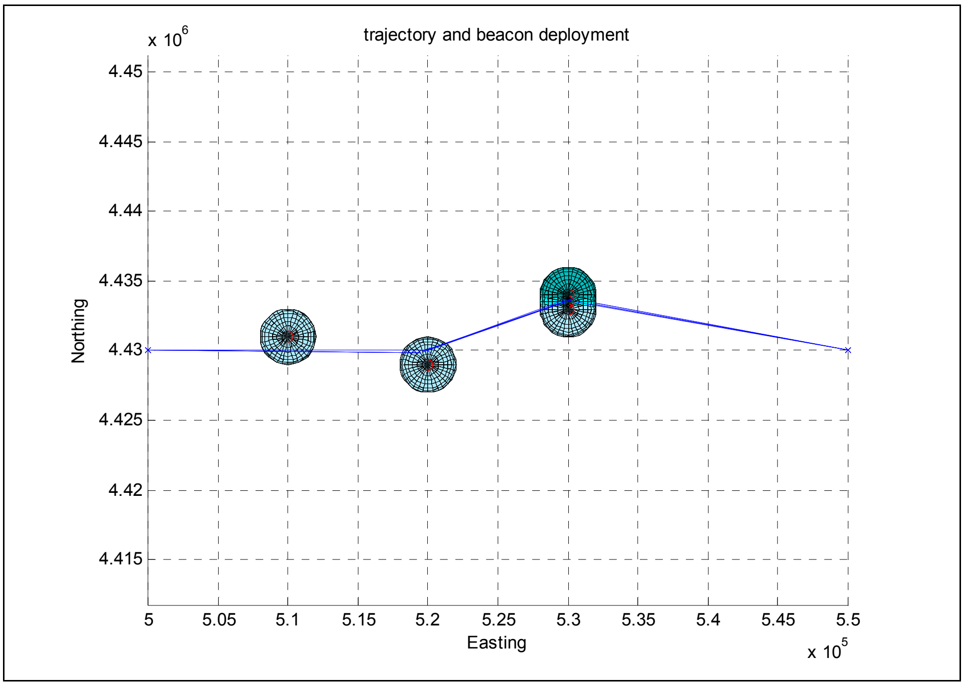


Figure 6-16 Multiple independent GA runs superposed for a case of 6 beacons. (Top view)

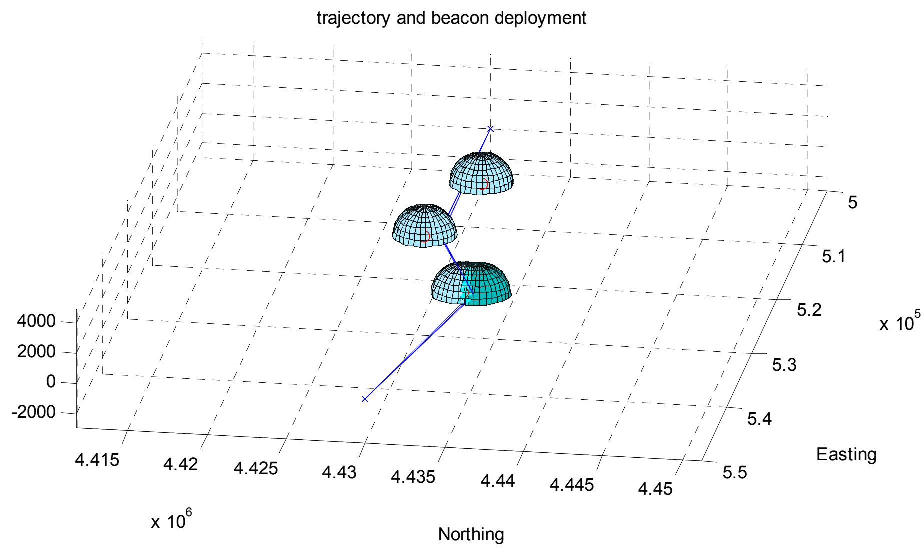


Figure 6-17 Multiple independent GA runs superposed for a case of 6 beacons. (3D view)

6.3.5 Case-5: 6 Beacons - Multiple Observation Windows for Same Beacon

Test case for decision maker to find observation windows for a sharp turn trajectory in which two separate observation windows are possible. The figure is given for a platform with 10 degrees FOV and +/-90 degrees FOR.

Trajectory segments within range of the two beacons are given in *observationpointssorted* matrix and observation windows which satisfy FOV and FOR constraints are given in *observationpointssortedFOVFOR* matrix.

Two beacons are in range between the 272-405th points of trajectory and one beacon is in range between 406-407th points where the first beacon passed out of range but second beacon is still in range. However 2nd beacon can not be used for RI beacouse it is out of FOR. When both beacons are in range decision maker calculates which points throughout the trajectory segment satisfy both FOV and FOR constraints. In this case there are two separate segments that arise due to the sharp maneuver of the missile (Table 6-4).

Table 6-4 Observation points on trajectory and corresponding beacons.

observationpointssorted gives observation possibilities within range and coordinates of beacons in range.								
272	405	2	4430200	520000	4430200	520200	0	0
406	407	1	4430200	520200	0	0	0	0
observatiostart	observationend	number of beacons visible	N	E	N	E	N	E
corresponding observation windows within FOV and FOR constraints								
272	282	2	4430200	520000	4430200	520200	0	0
342	364	2	4430200	520000	4430200	520200	0	0

Figure 6-18 shows decision maker check mechanism for a test condition with sharp turn. Red flight path segments are the observation windows for the missile with 30 degrees FOV and 90 degrees FOR. Decision maker takes into account possible route changes inside the beacon range. There are two observation periods. It is possible to perform 2PR position update in two separate observation windows between 272 and 282 and 342-364.

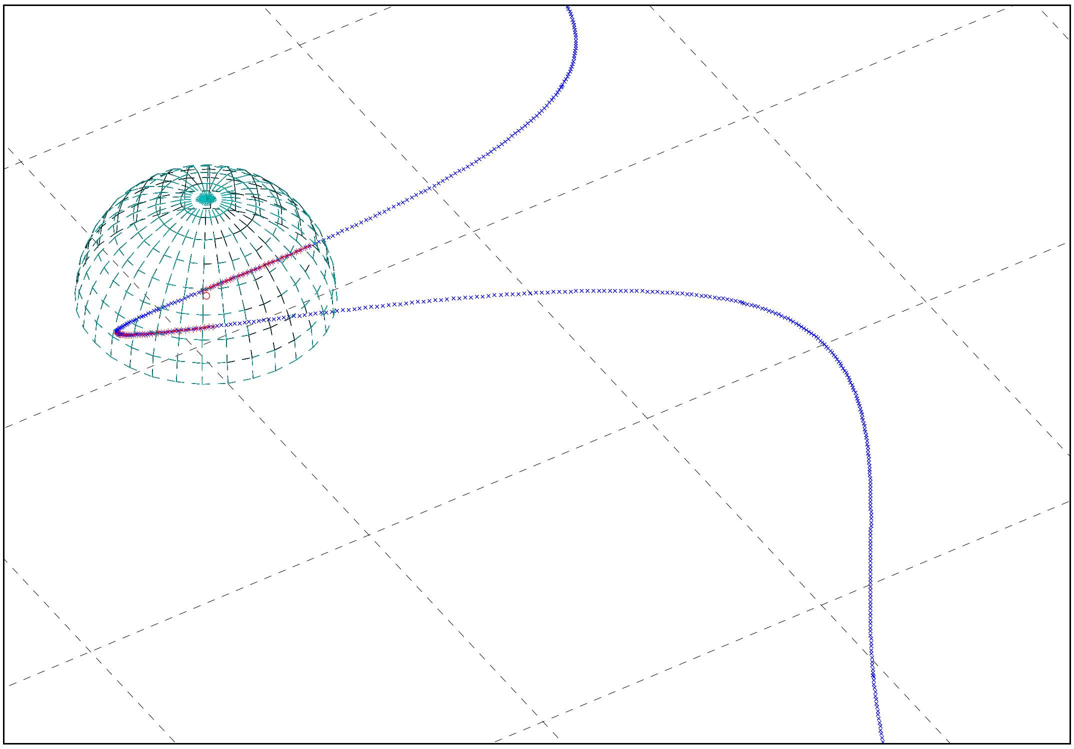


Figure 6-18 Test condition with sharp turn. Red flight path segments are the observation windows for the missile

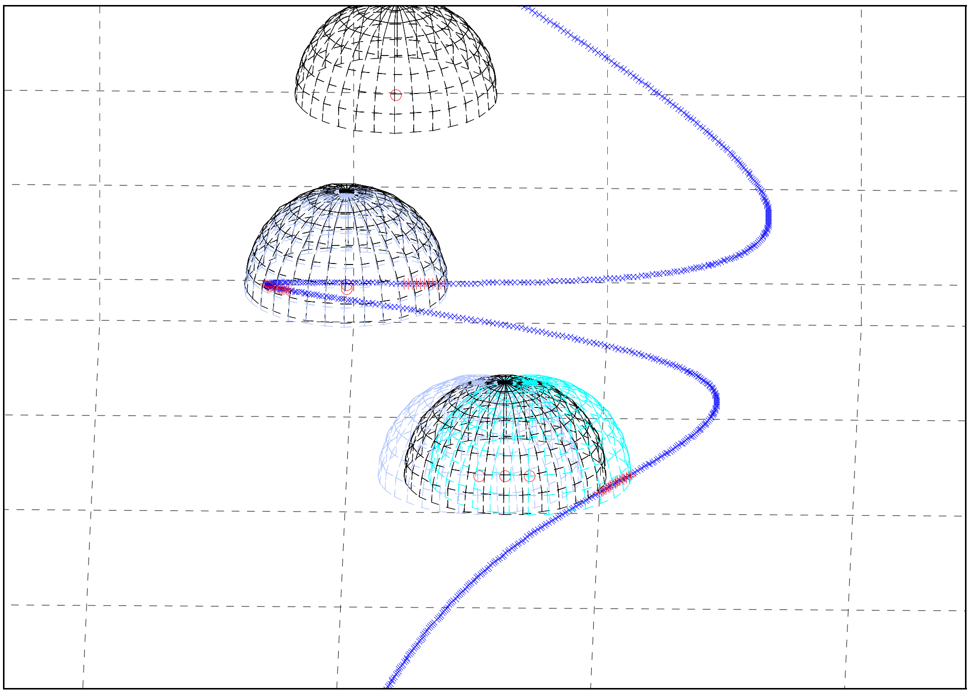


Figure 6-19 Two observation windows (red) for 2PR for the middle two beacon group and RI for the end three beacon group

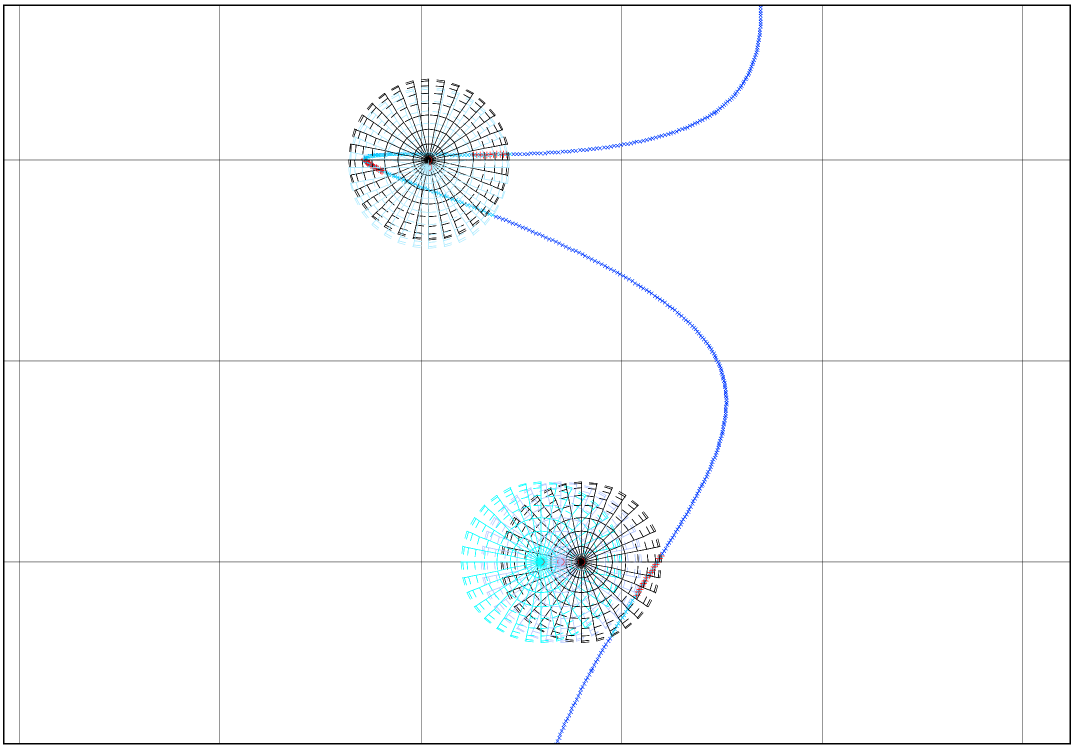


Figure 6-20 Two observation windows (red) for 2PR for the middle two beacon group and RI for the end three beacon group, (Top view)

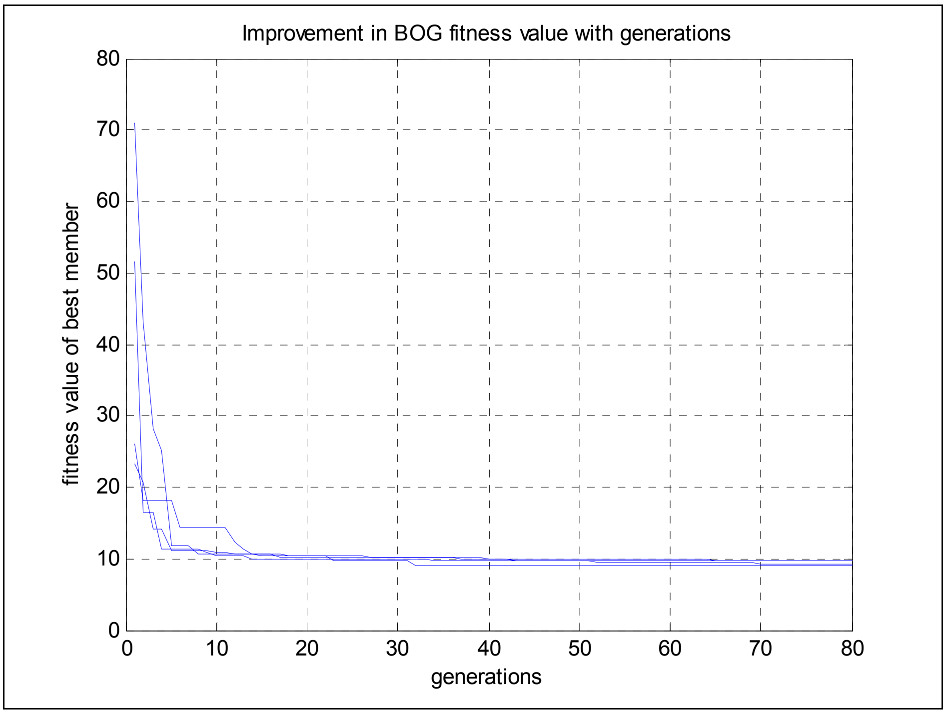


Figure 6-21 Best of generation improvement for 5 different GA runs.

6.3.6 Case-6: Symmetric Beacon Deployment Case

Symmetric deployment cases are also investigated to check if the GA finds the symmetric optimum solutions. Independent runs provided symmetric optimum results and repeatability is also checked.

In order to check the algorithm, a special case is introduced. The fitness function is defined such that the missile tries to avoid beacon ranges. Two sets of beacons, each set having three beacons, are deployed with a 100 meter gap between them in northing. Sets deployed at 10.000 meters from launch point and 10.000 meters away from target in easting coordinates. The fitness function is defined as minimization of (*pathlengthinbeaconrange* + *pathlength*). The expected result is trajectories that pass through the gaps between the beacons. For multiple independent GA runs it is found that the GA can obtain the symmetric two solutions which avoid the beacons as shown in Figure 6-22.

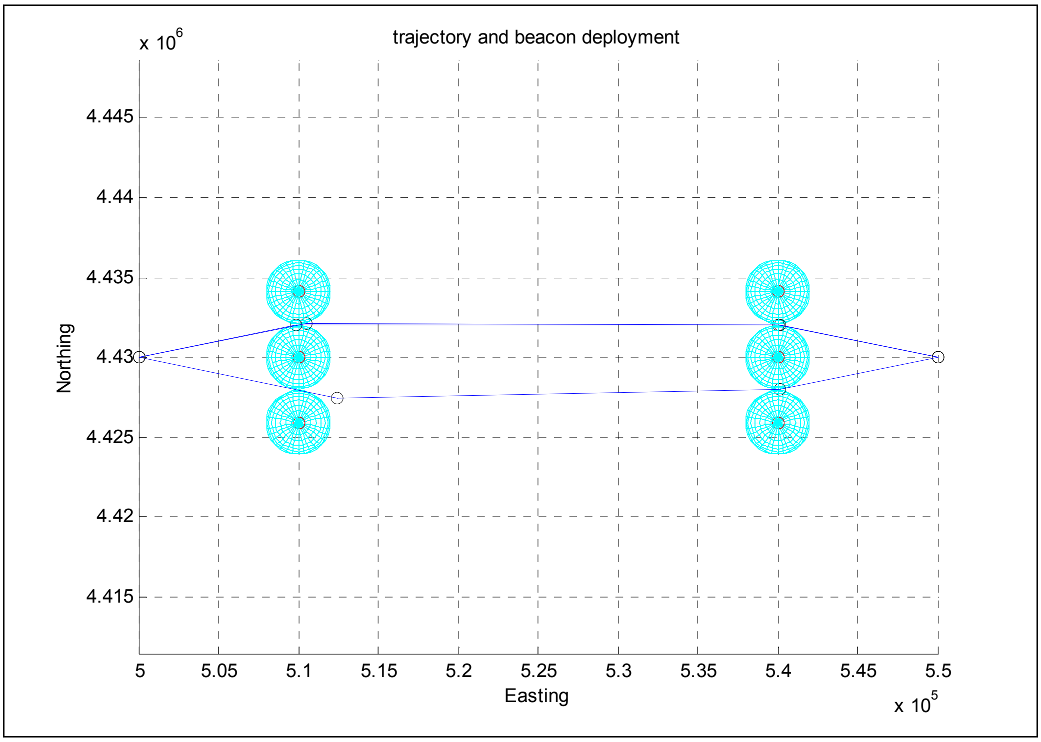


Figure 6-22 Scenario for avoiding beacons. 4 GA runs find the symmetric solutions.

6.3.7 Case-7: Operational Scenario - 6 Beacons - 3 Methods

A sample operational scenario optimization results are given for a test case which is defined as follows.

Operation area is 50 km's by 20 km's wide.

6 beacons are deployed such that the first beacon is left alone to allow RI, while second and third beacons are located near to each other in order to allow 2PR. 4^{th}, 5^{th}, and 6^{th} beacons are deployed to allow 3PR method to be applied. Beacon detection range is set to 2000 meters.

Several constraints are applied, FOV is selected to be 10 degrees and FOR is assumed to be 90 degrees. Heading change constraint between legs of trajectory is set to 30 degrees to avoid sharp turns throughout the trajectory of the missile.

Heading constraint is applied in the form of dynamic penalty function, thus total heading constraint violation throughout the trajectory is found and fitness value is modified by adding a term which is a function of fitness and heading constraint violation.

The objective function is defined to minimize the path length from launch site to target while maximizing the observation windows in beacon ranges. Observation windows are found by applying FOV and FOR constraints to the segments of trajectory inside beacon ranges. In this optimization problem, 3PR is preferred to 2PR and 2PR is preferred to RI. A weighting is used between the methods which favors 3PR to 2PR and 2PR to RI. The fitness function is created in the form of

Minimize *pathlengthtrajectory-weightedpathlength* (in beacon range)

The results of the two independent runs of GA for this particular case is given in Table 6-5 and corresponding trajectories, waypoints and beacon layout are given in Figure 6-28. It is seen that very similar results are obtained.

Table 6-5 Two independent GA run results for a 6 beacon case.

problem	path planning	path planning
objective function	minimize pathlength while maximizing weighted observation windows	
FOR constraint	90 degrees	90 degrees
FOV constraint	10 degrees	10 degrees
heading constraint	30 degrees per leg	30 degrees per leg
waypoints	4	4
populationsize	50	50
generations	150	150
mutation rate	0,40	0,40
expected best fitness	-	-
Generation	BOG	BOG
1	66807,00	66157,00
10	44055,00	42657,00
150	40447,00	40255,00

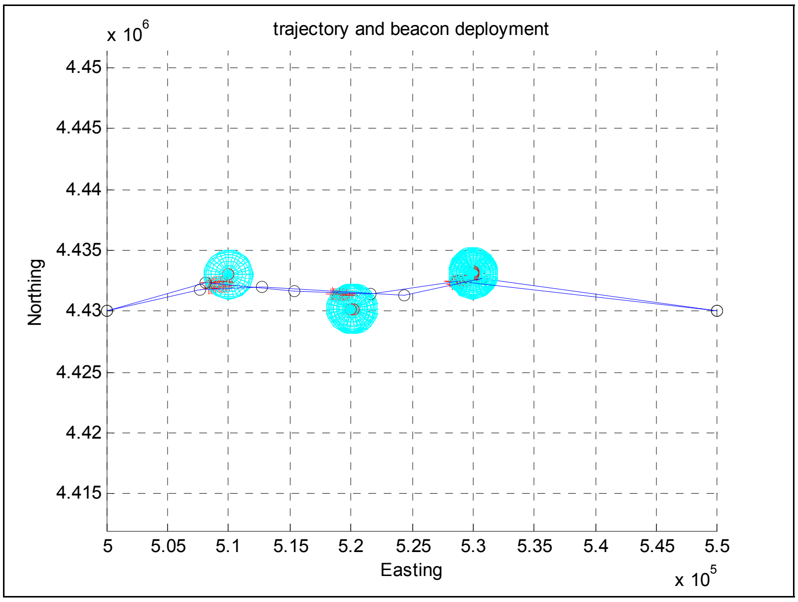


Figure 6-23 Two independent optimization results for 6 beacons located in three groups, with 4 waypoints and FOV, FOR, heading constraints applied.

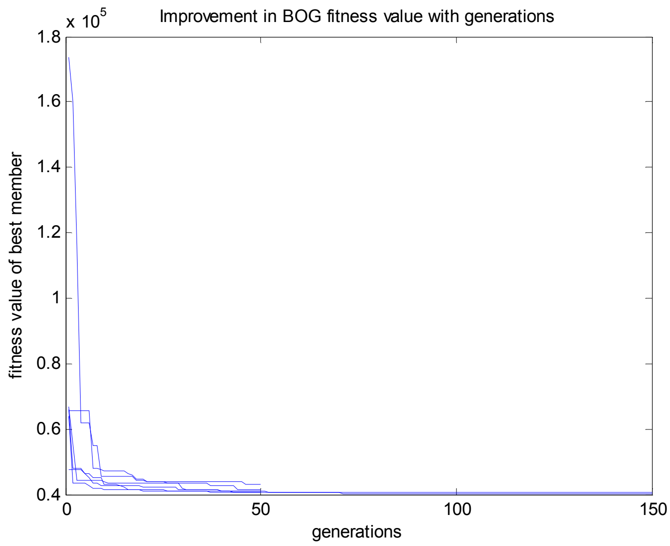


Figure 6-24 Improvement in best of generation value for multiple independent GA runs.

6.3.8 Case-8: Operational Scenario - 7 Beacons - 3 groups

This case is an operational scenario with different missile launch and target coordinates and two groups of three beacon sets, The optimization program is run with the objective function of minimizing path length while maximizing observation window lengths within FOV and FOR constraints. The results are given in Figure 6-25 and Figure 6-26.

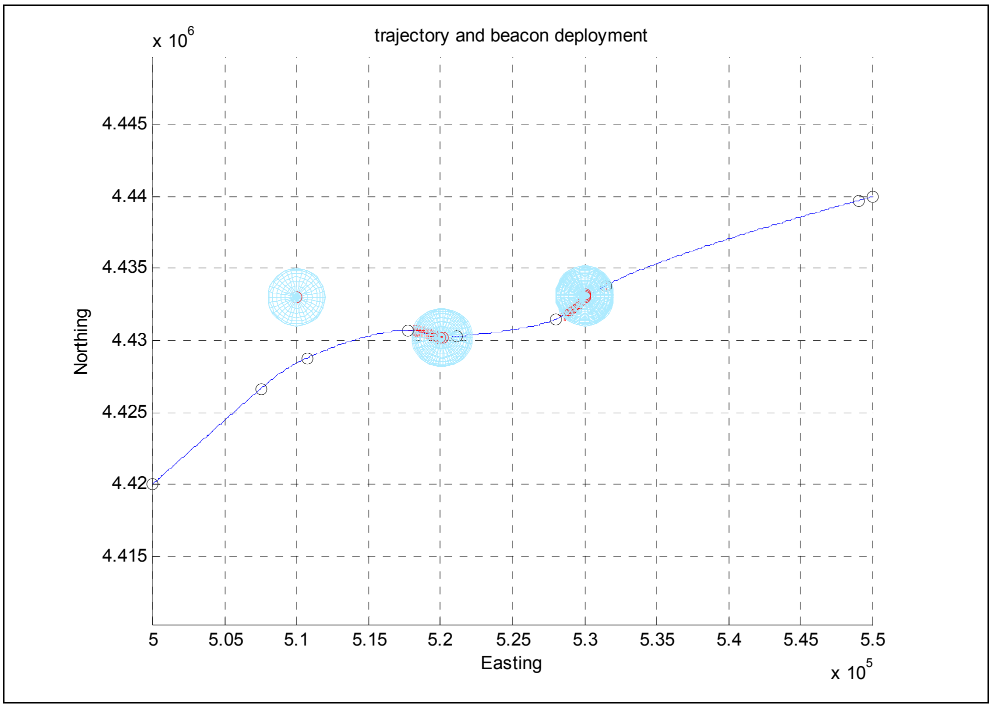


Figure 6-25 Two 3 beacon groups and 3PR method optimization results for minimizing path length while maximizing observation window length under the effect of FOV and FOR.

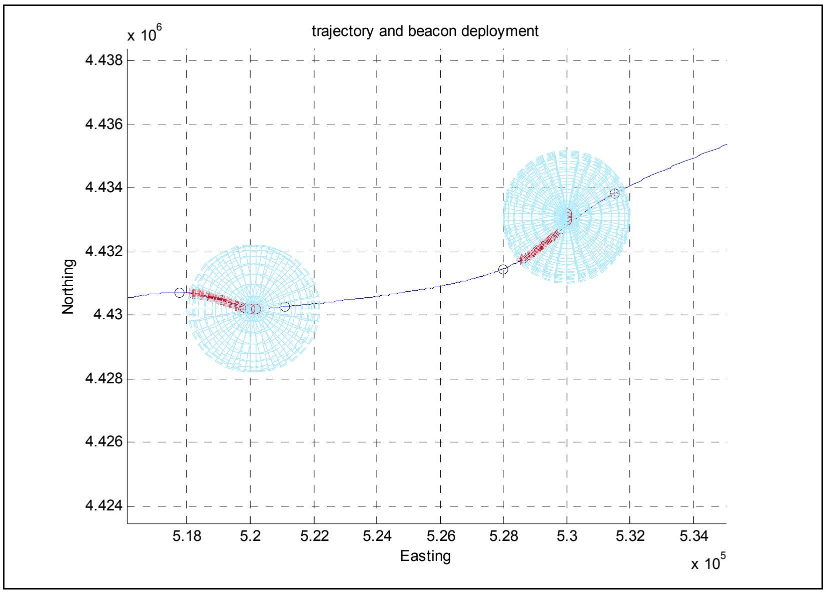


Figure 6-26 Magnified view

6.3.9 Case-9: Operational Scenario - 10 Beacons - 5 groups

A path planning scenario is given in Figure 6-27. 10 beacons are previously deployed to the operation area in groups of 2, 1, 1, 3 and 3 beacons, which allow two point resection, three point resection and, reverse intersection methods to be employed. The aerial platform is launched from south-west corner and heads to north-east corner of the map, defined by UTM coordinates. The objective function aims to minimize the path length while maximizing the observation instants under the constraints with 10 degrees FOV, 50 degrees FOR, 2000 meters detection range, turn rate and method specific geometric constraints to avoid low quality position updates. The GA result is obtained with a population of 20 members, 0.4 mutation rate and 500 generations.

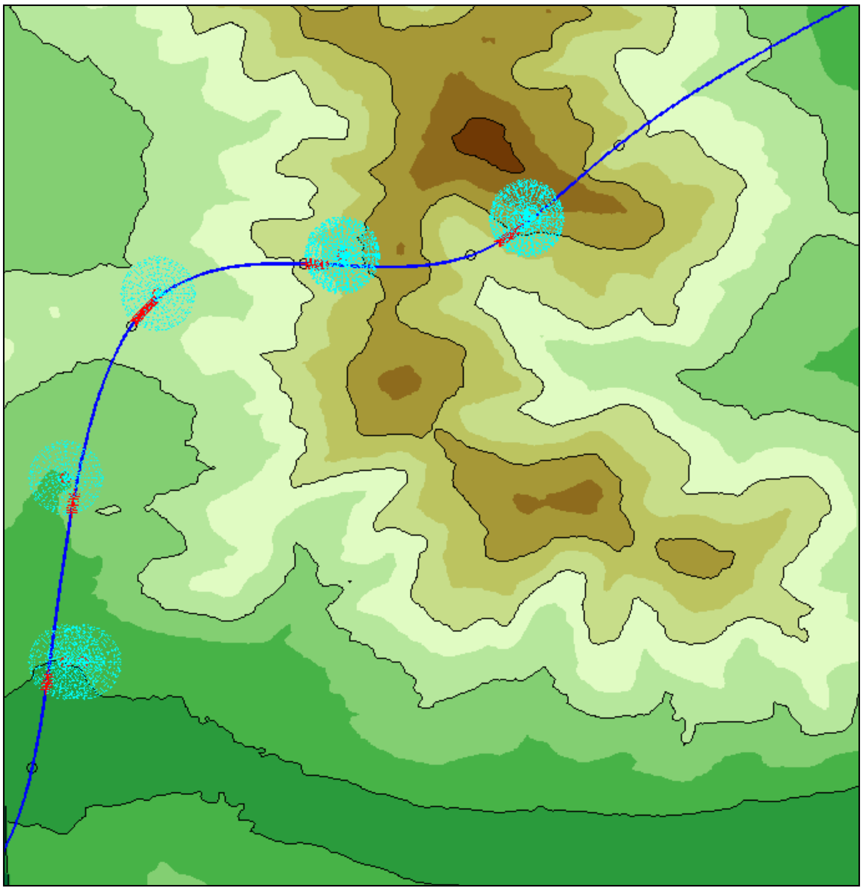


Figure 6-27 Path planning optimization result for 10 beacon case

6.4 Deployment Problem

For the deployment problem, preliminary update trial results are given in the following figures where two RI's and one 3PR are performed without employing FOV and FOR constraints. The results show that position updates can provide noticeable performance increase when compared with the inertial only solution.

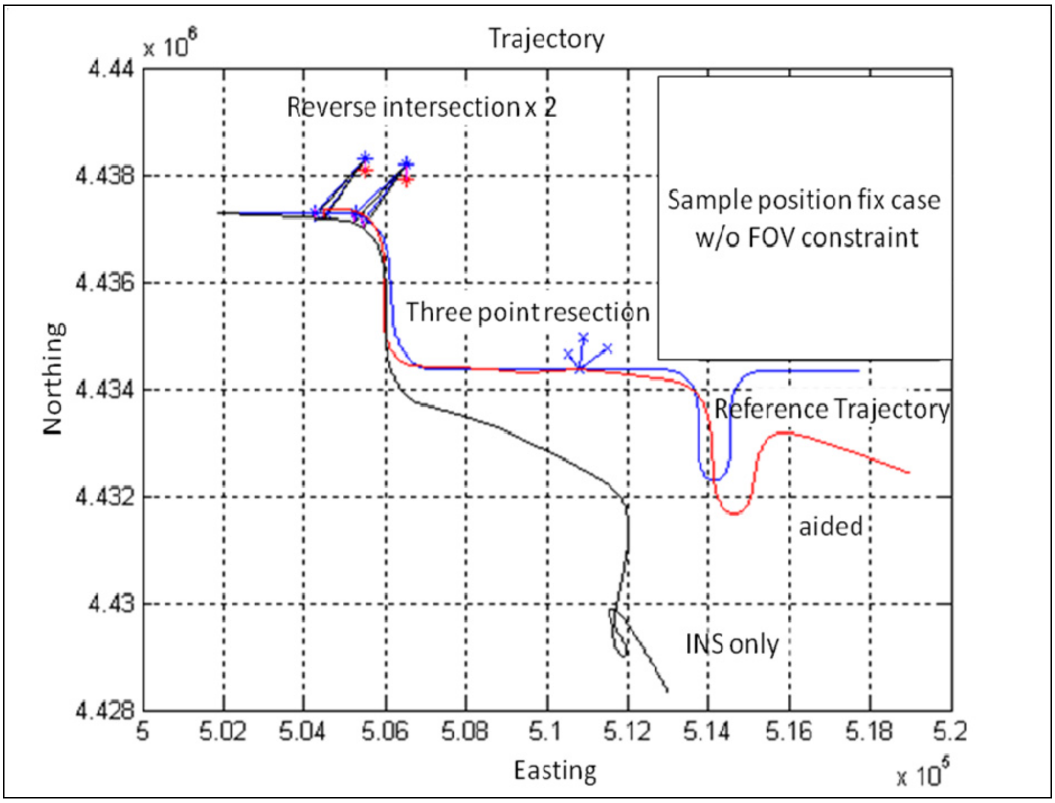


Figure 6-28 A sample position fix scheme with two RI and one 3PR without FOV/FOR constraints.

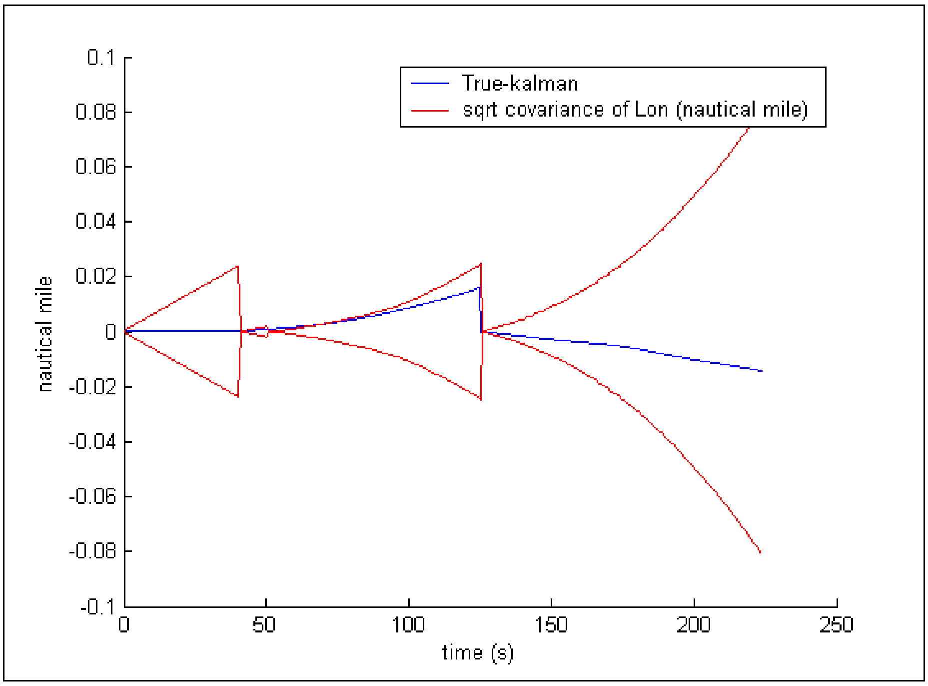


Figure 6-29 Longitude covariance bounds and longitude error for a realization of beacon aided navigation with two RI and one 3PR

6.5 Deployment Problem Optimization Case Studies

6.5.1 Minimization of Position Error VLCGA Results

The deployment problem is based on a reference trajectory which was created to reflect typical maneuvers of an aerial platform, and corresponding accelerometer and gyro readings throughout the trajectory taken at 400 Hz for both reference and inertial only solutions under the effect of gyro and accelerometer errors whose typical magnitudes for a 50 deg/hr IMU were given in Chapter-5.

In this deployment problem case study, Reverse intersection method is used.

Corresponding observation points are given in Table 6-6. 4 observation windows are possible to three beacons. Corresponding trajectories are given in Figure 6-30.

North, east and down velocity histories are given in Figure 6-31, Figure 6-32, Figure 6-33.

Table 6-6 Observation windows, position fix method (1 for RI) and observed beacon coordinates in UTM coordinate system.

26256	26801	1	4434687	507009	0	0	0
39484	40401	1	4434980	507428	0	0	0
42384	46001	1	4434466	510622	0	0	0
52956	56401	1	4434466	510622	0	0	0

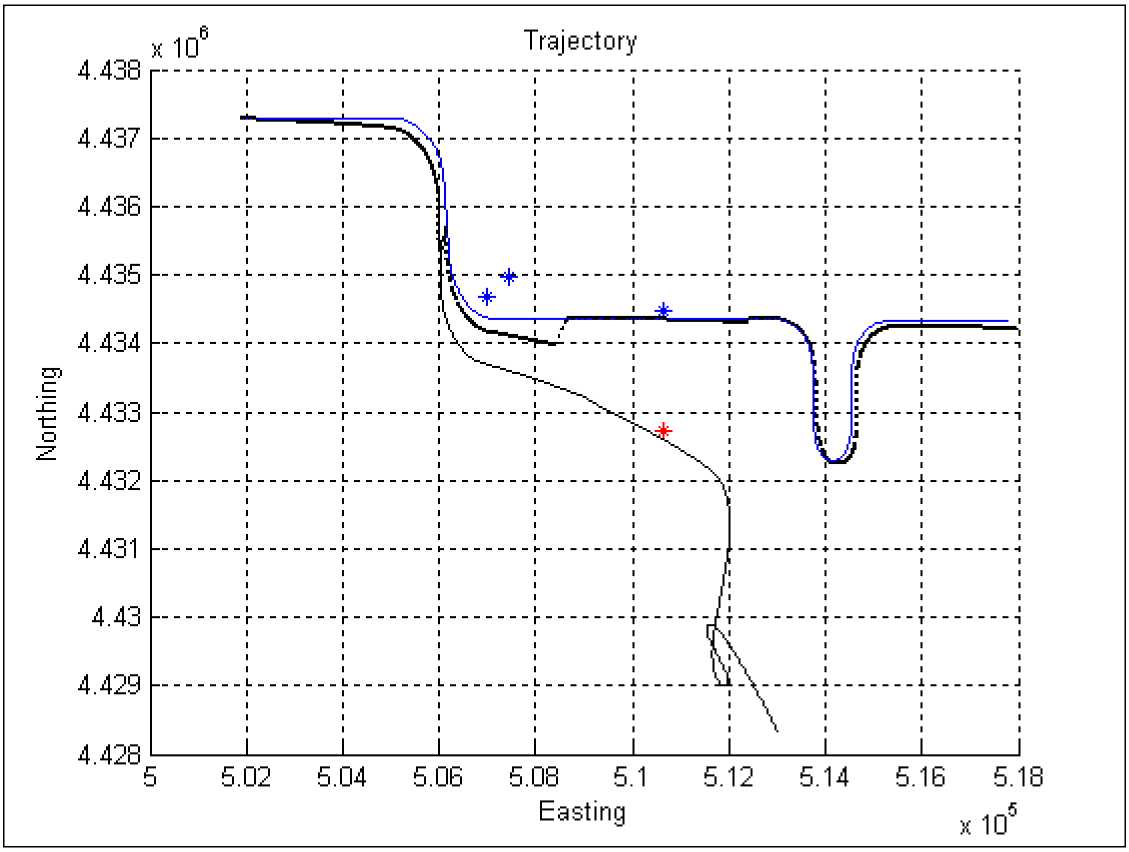


Figure 6-30 An optimal beacon deployment scheme with 4 beacons and its effect.

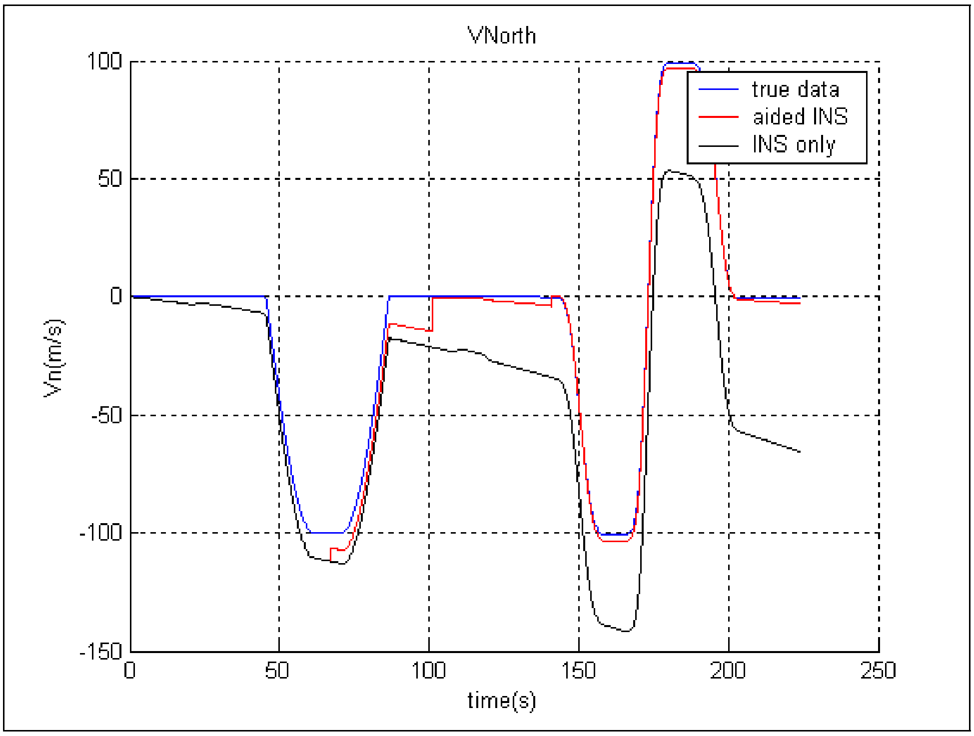


Figure 6-31 North velocity history

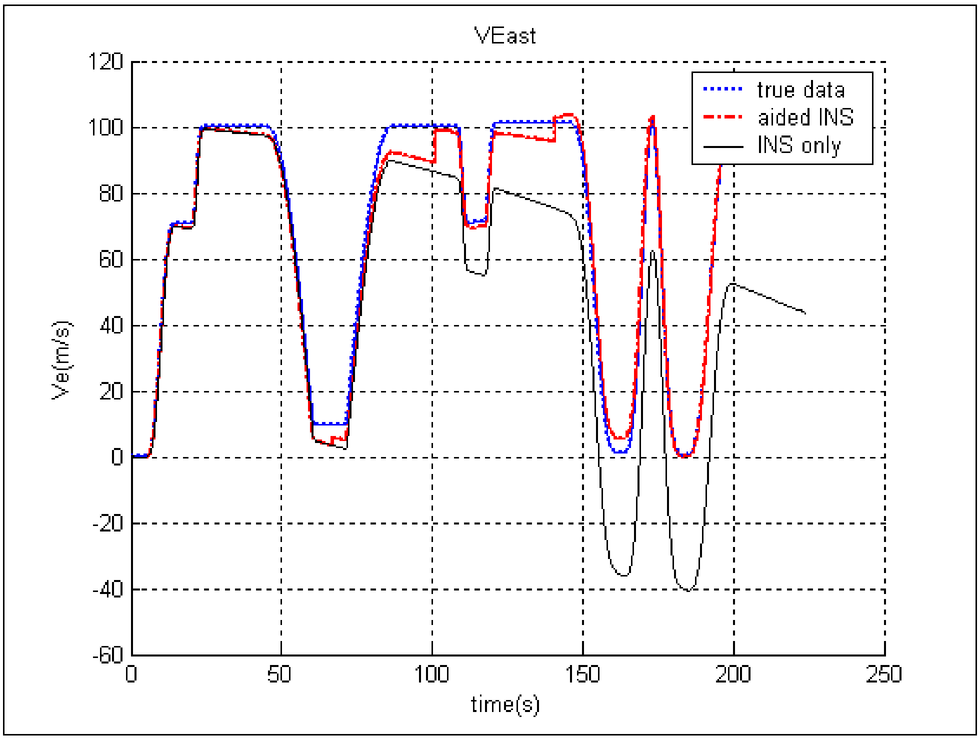


Figure 6-32 East velocity history

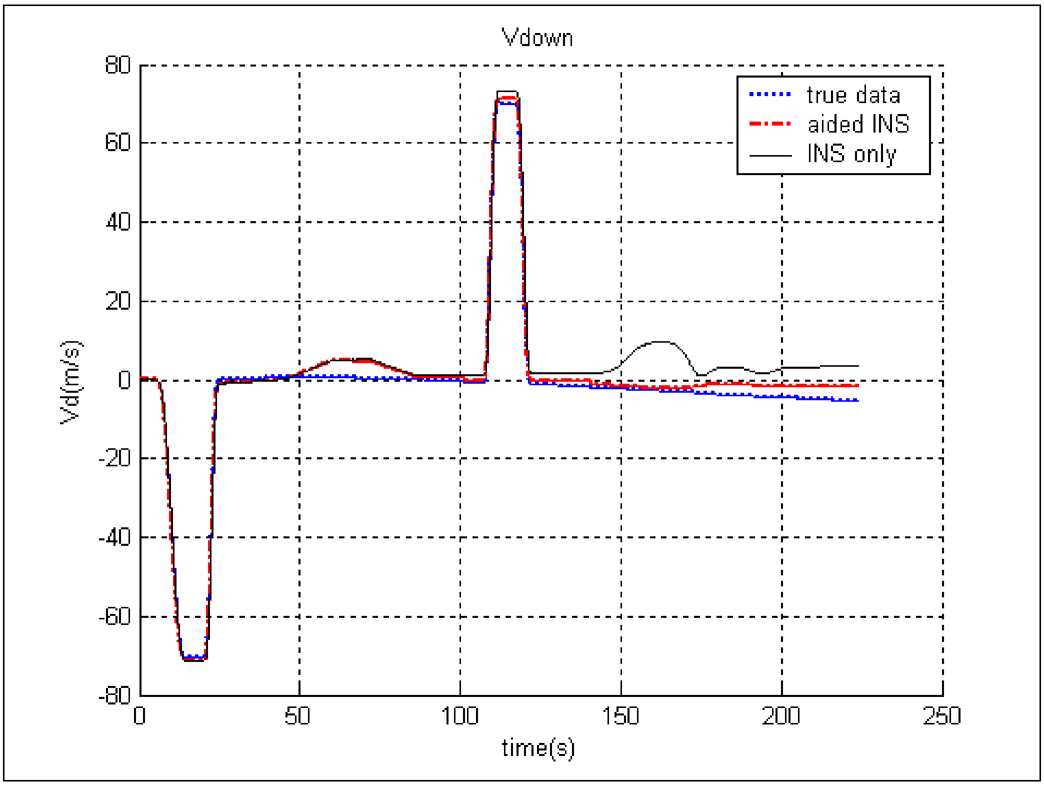


Figure 6-33 Down velocity history

6.5.2 Minimization of Position Error Throughout the Flight (10 generations)

The results are given for a case study with 5 maximum available beacons, optimization results for a VLCGA run with 20 population members and 10 generations Fitness function is defined as the minimization of the maximum error on the way and terminal error. It is observed that 10 generations with 20 members may not be enough for a run. More generation runs are required to obtain better results, but 10 generations also gives a general understanding of the behavior. The best fitness value is 733 meters which is the sum of terminal error and maximum error on the way. Figure 6-34 shows the trajectory with the best of 10 generations. Figure 6-35 gives height history. Velocities are shown in Figure 6-36, and Figure

6-37. Figure 6-38, Covariance bounds in latitude, longitude and height are given in Figure 6-39, Figure 6-40, and Figure 6-41 respectively.

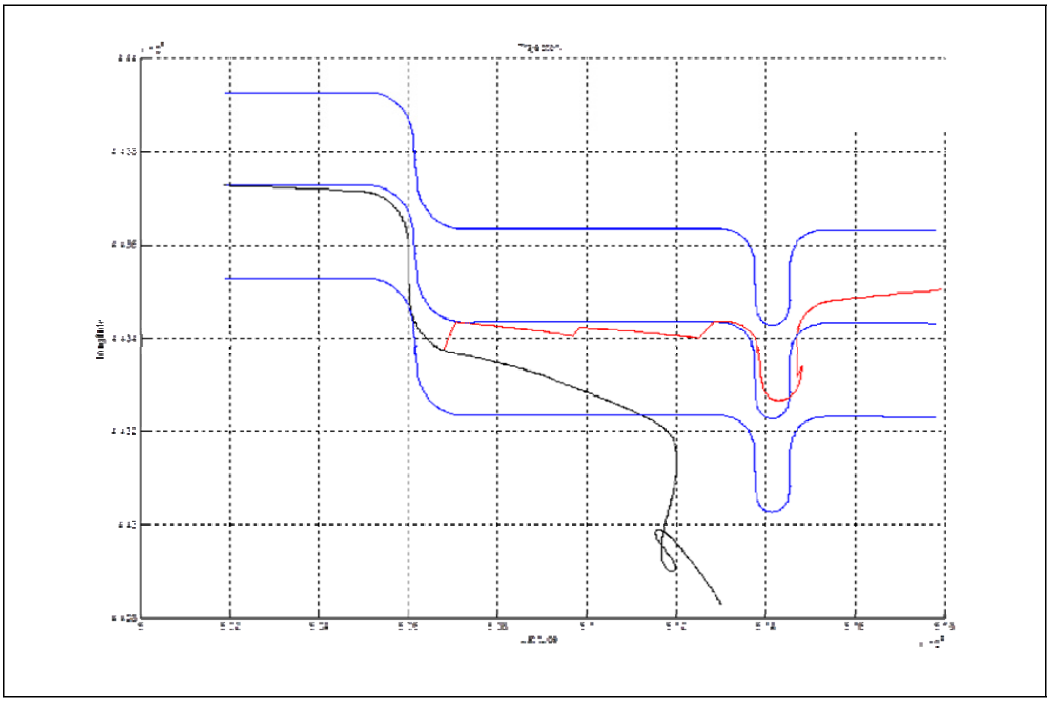


Figure 6-34 Reference (blue), aided (red) INS only (black) trajectories.

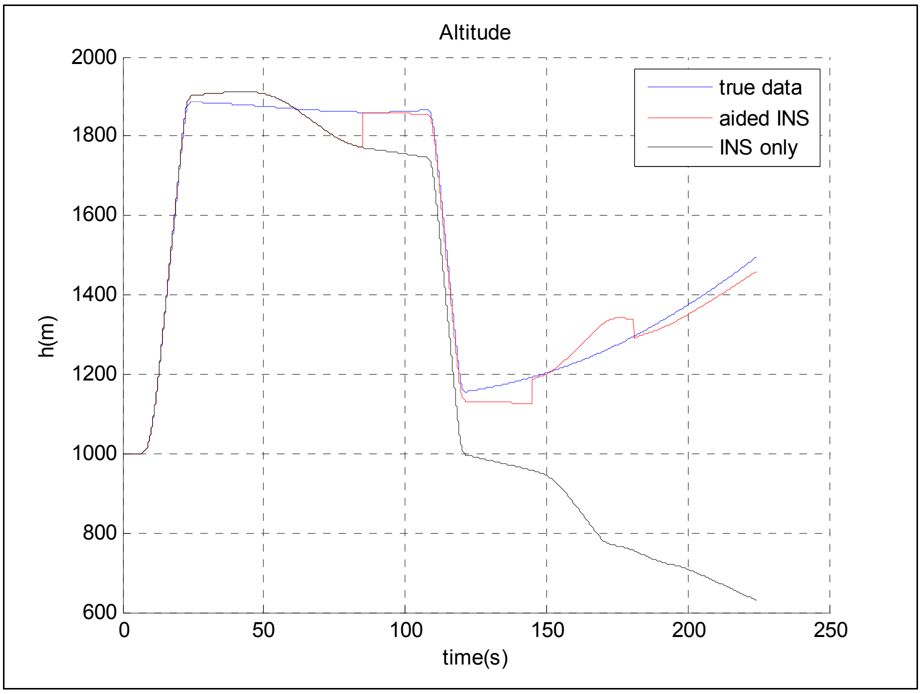


Figure 6-35 Altitude history

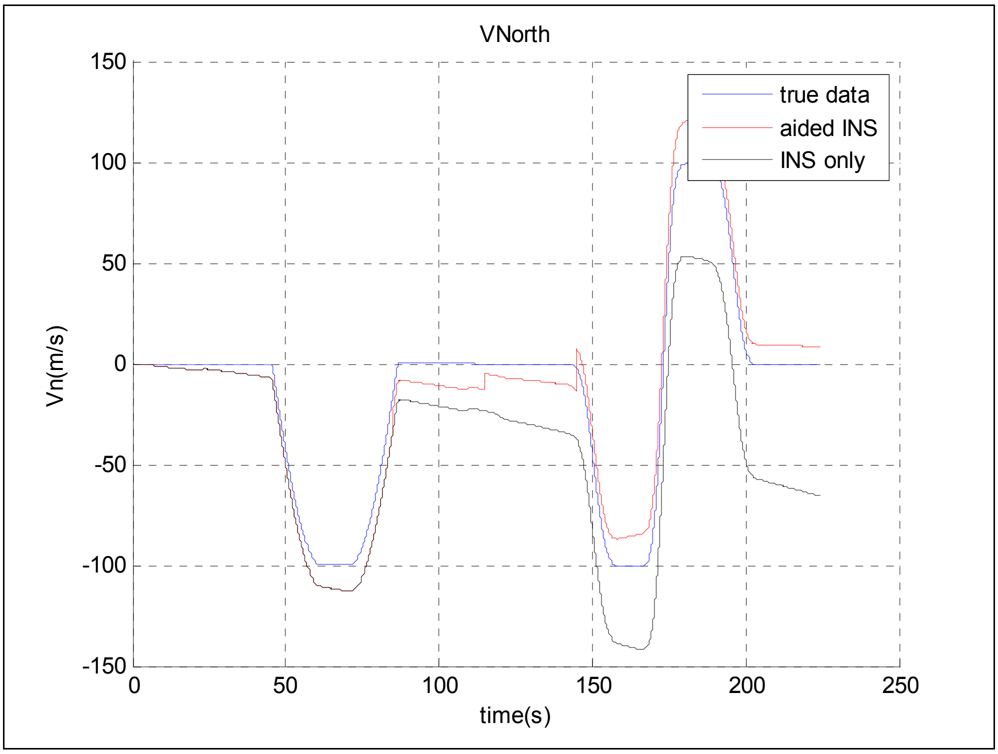


Figure 6-36 North velocity history

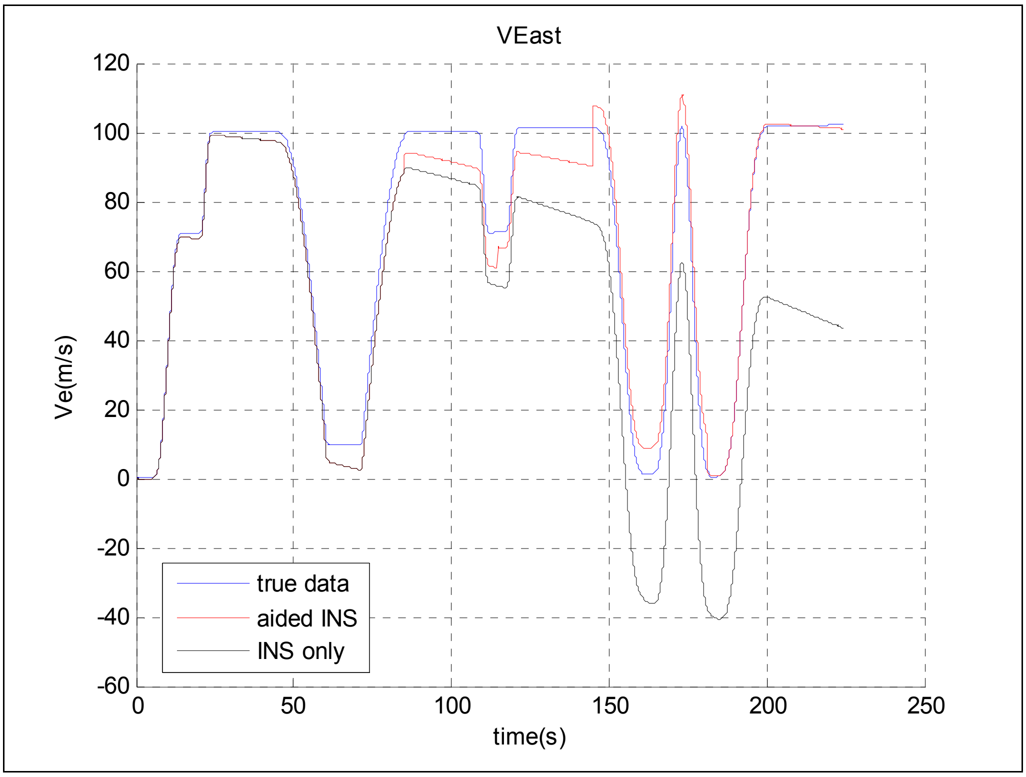


Figure 6-37 East velocity history

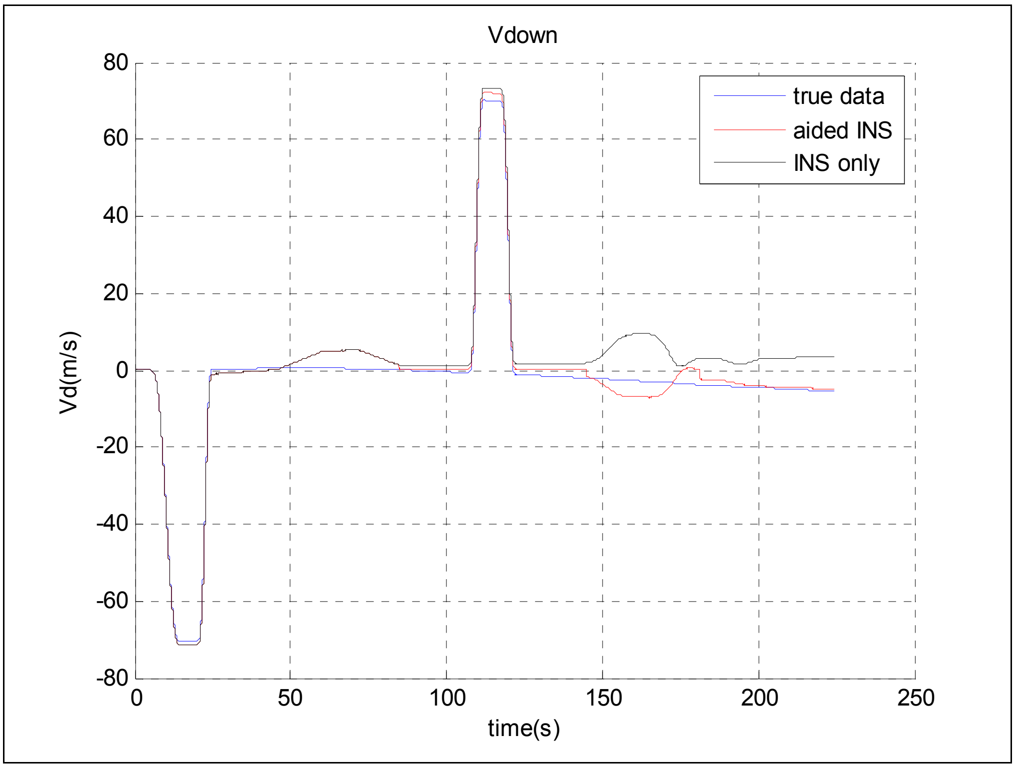


Figure 6-38 Down velocity history

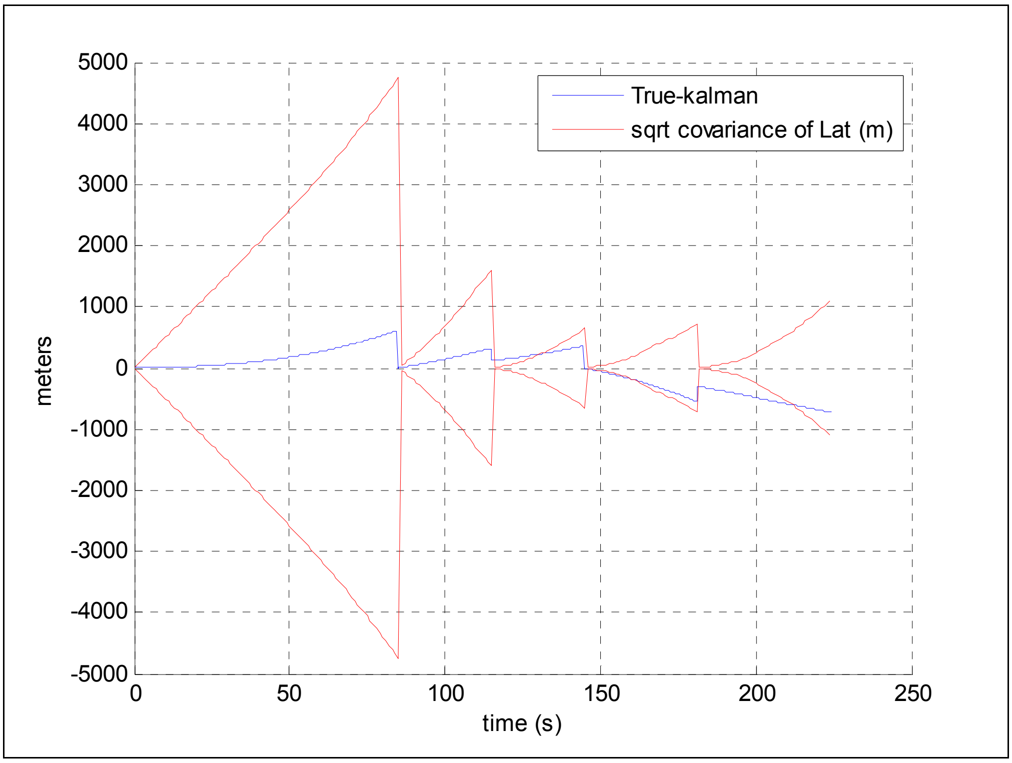


Figure 6-39 Latitude covariance bounds and latitude error history

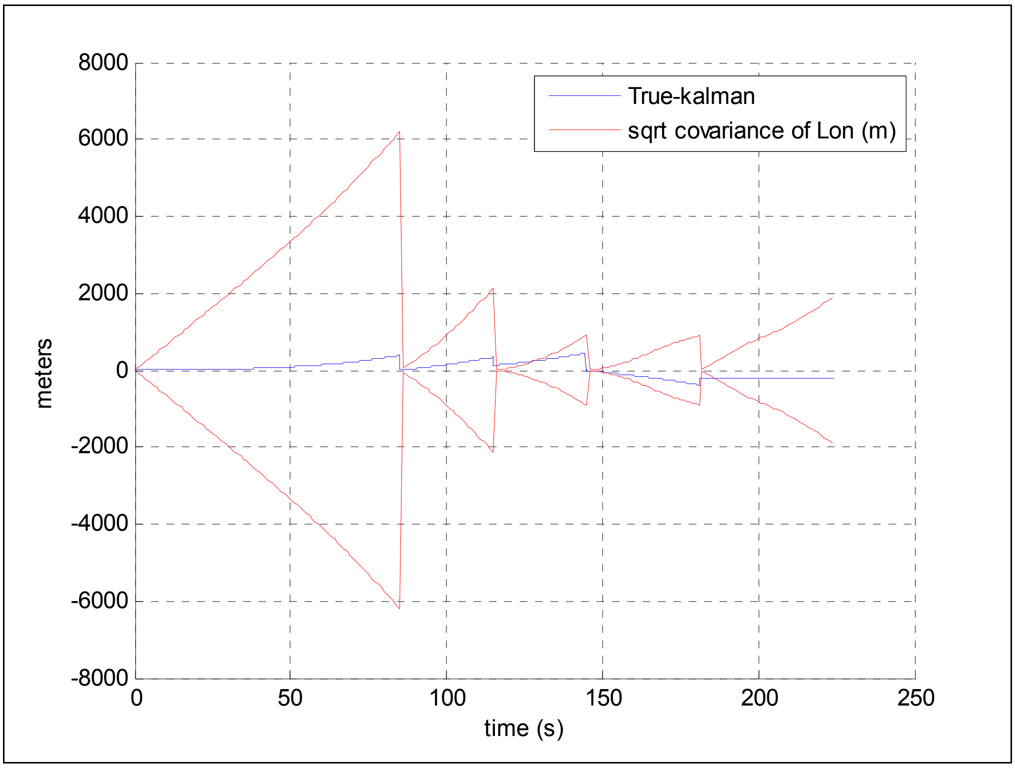


Figure 6-40 Longitude covariance bounds and longitude error history

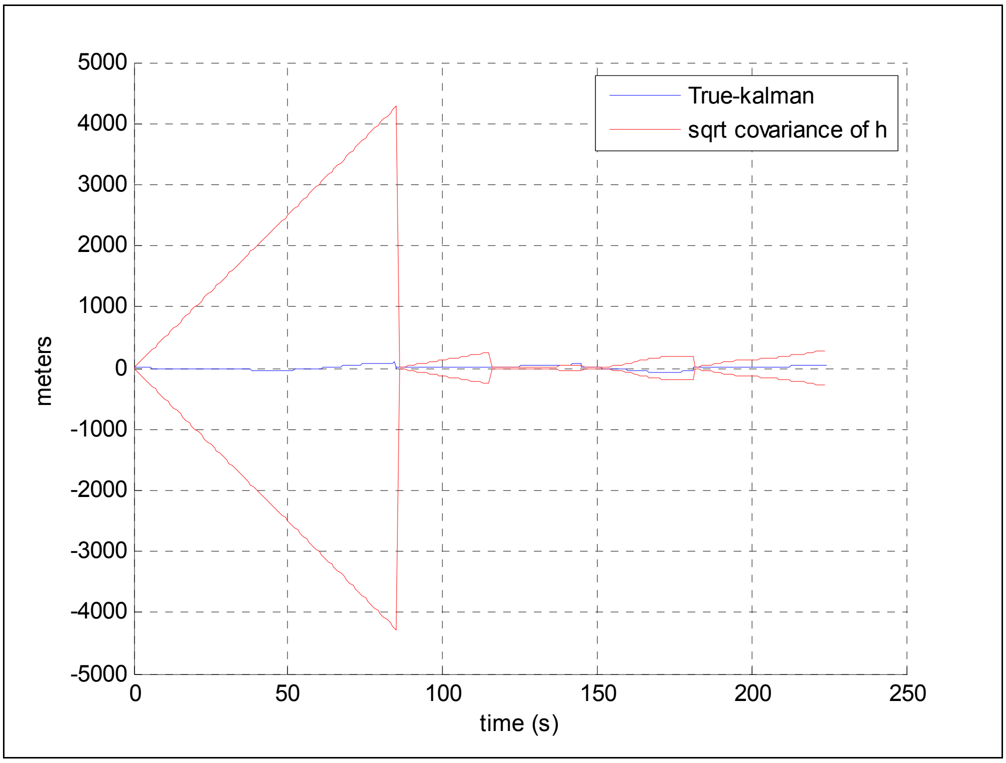


Figure 6-41 Height covariance bounds and height error history

6.5.2.1 Covariance Objective Function VLCGA results

5 VLCGA runs are performed independently with 50 population members and a maximum available beacon number of 5. 50 generations have passed in each GA run.

The best result has a terminal location error of 436 meters and terminal covariance error of 299 meters. The BOG improvement is seen in Figure 6-42. Trajectory and position update instants are seen in Figure 6-43. Height history is given in Figure 6-44. Covariance bounds that are tried to be minimized and a realization of INS error history are seen in Figure 6-45 and Figure 6-46. Velocity histories are given in Figure 6-47, Figure 6-48, Figure 6-49.

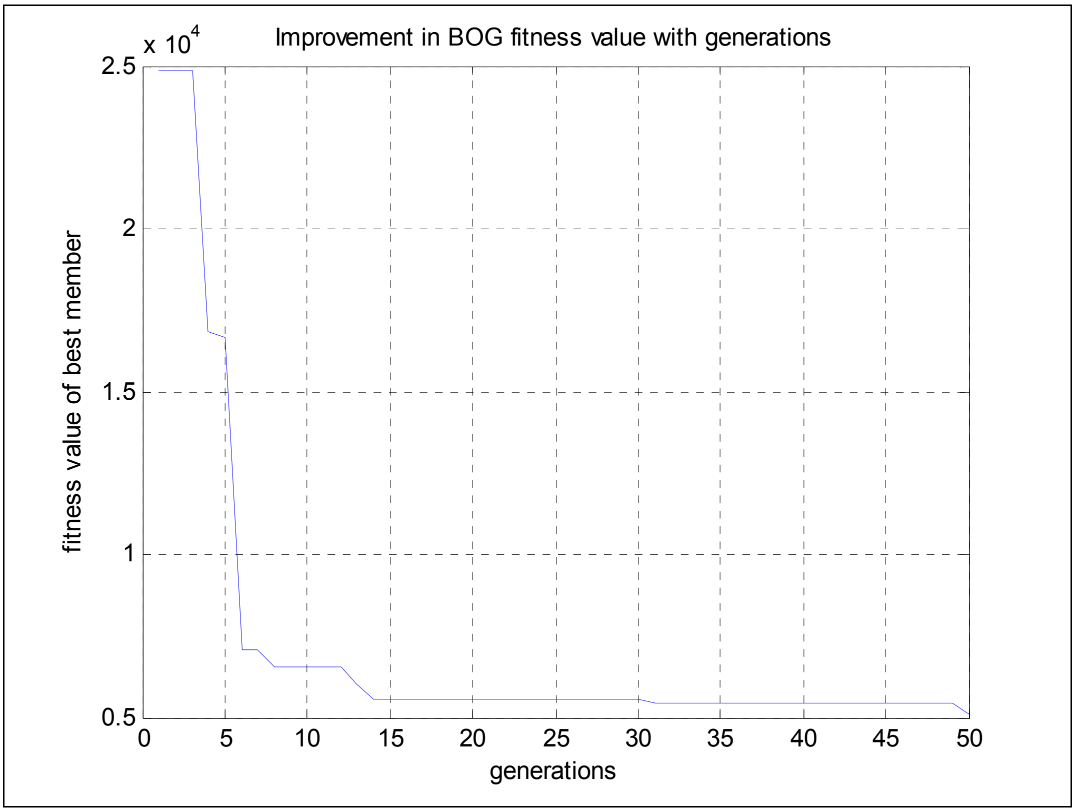


Figure 6-42 Improvement in BOG values with generations.

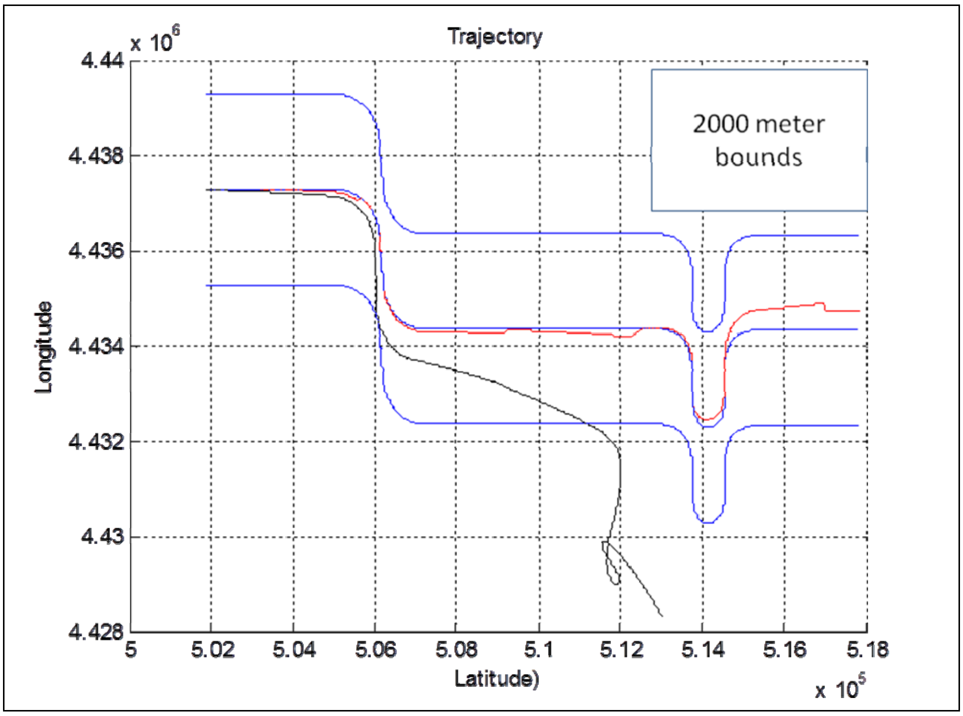


Figure 6-43 Reference (blue), aided (red) INS only (black) trajectories.

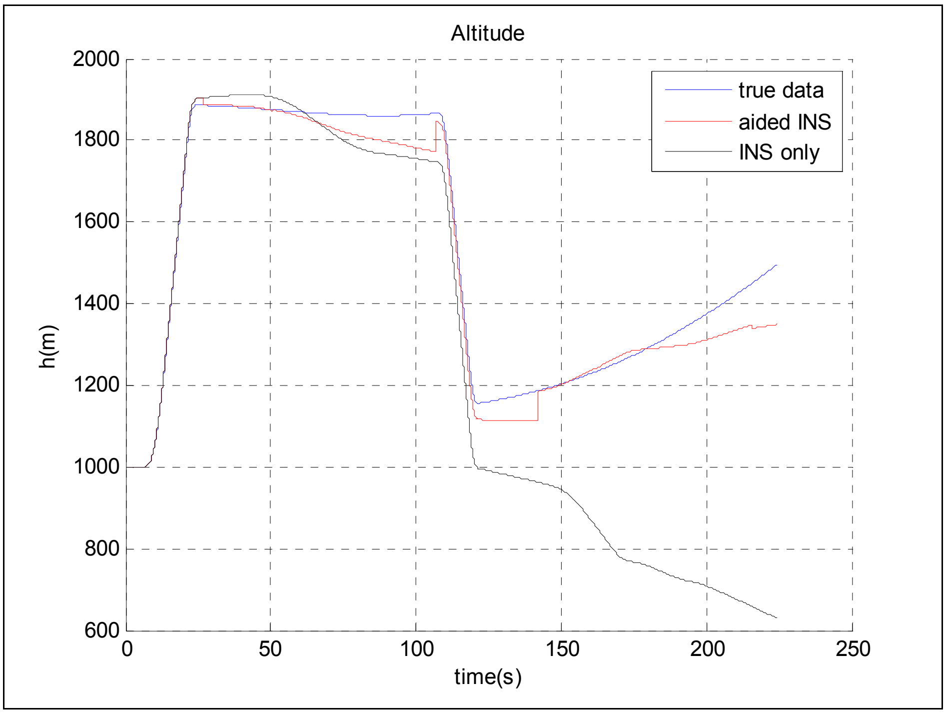


Figure 6-44 Altitude history

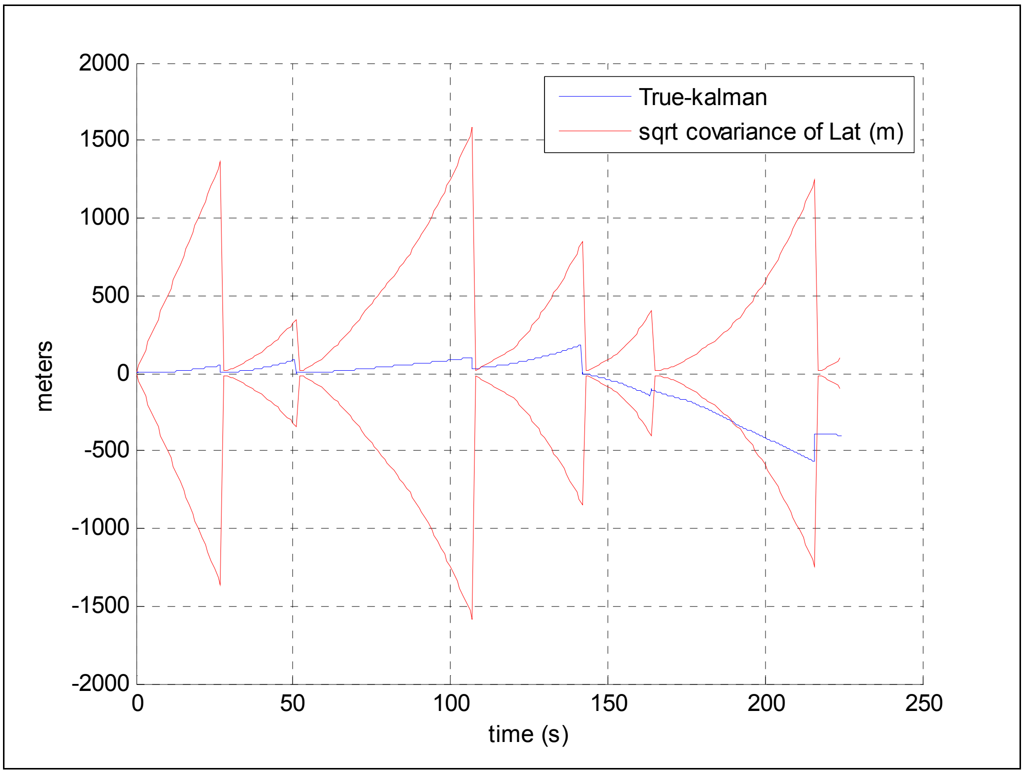


Figure 6-45 Latitude covariance bounds and latitude error history

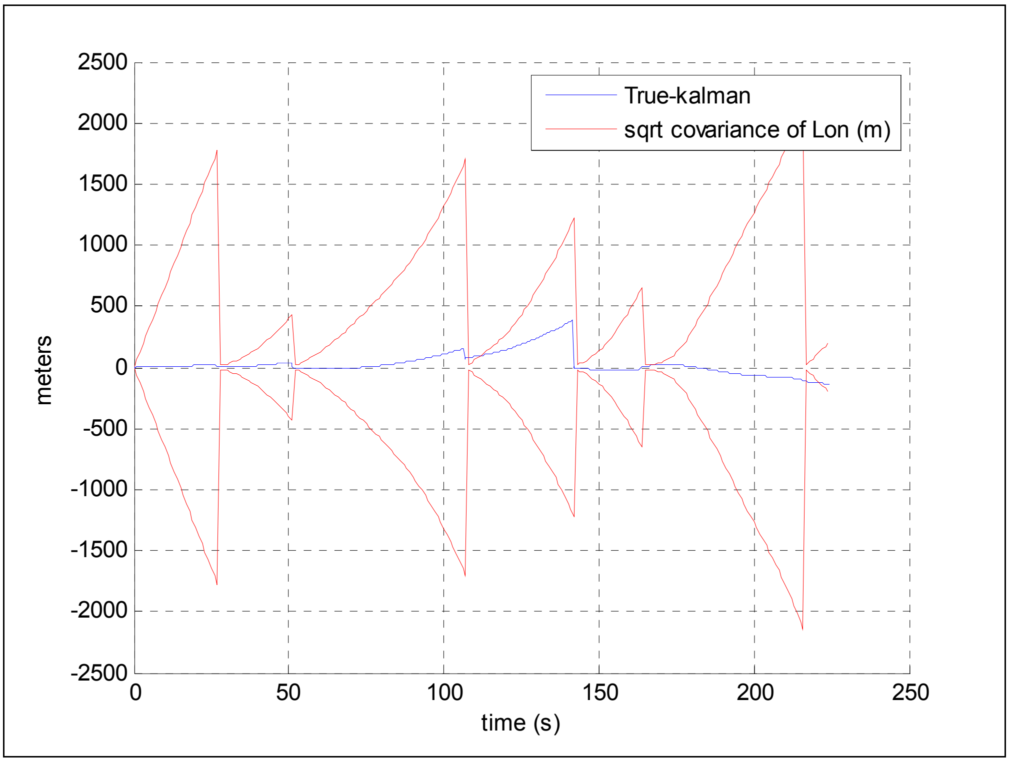


Figure 6-46 Longitude covariance bounds and longitude error history

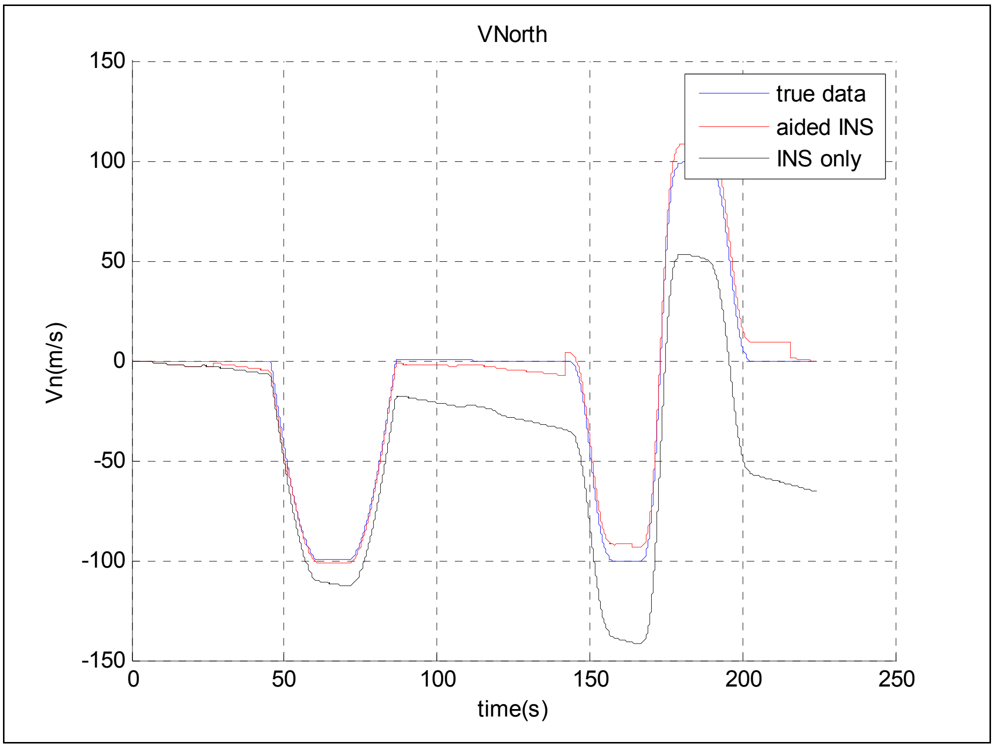


Figure 6-47 North velocity history

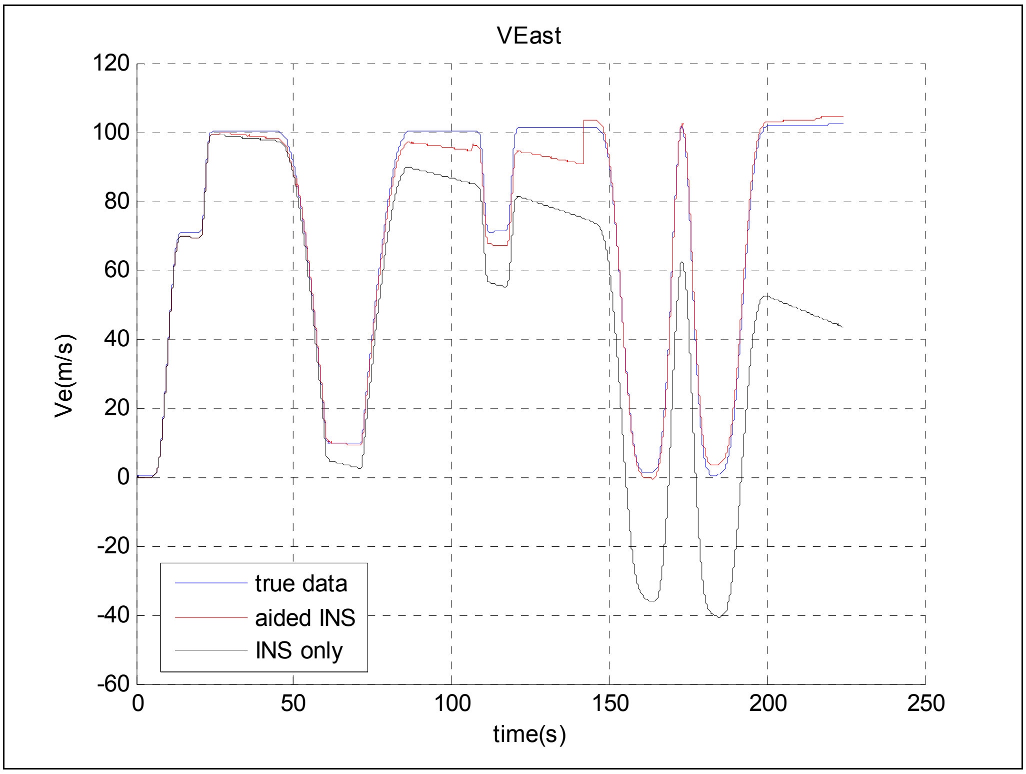


Figure 6-48 East velocity history

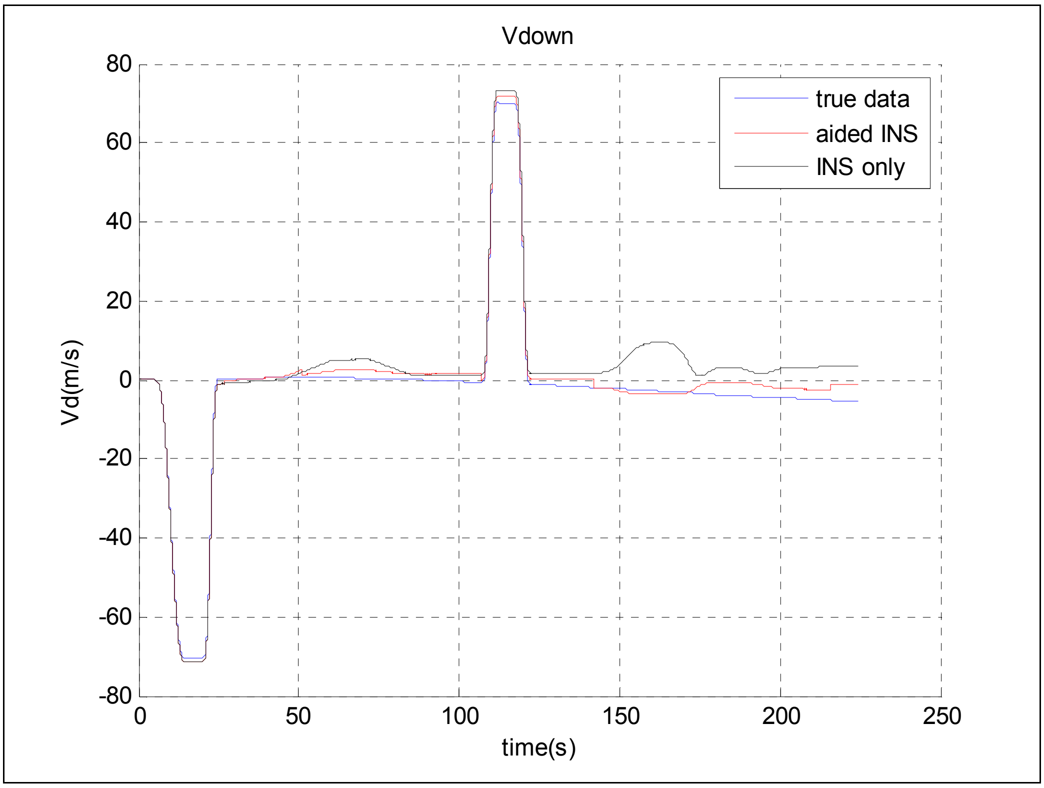


Figure 6-49 Down velocity history

6.6 Remarks about Results

Nominal beacon detection range is an important factor for BNS performance. Detection ranges less than 2000 meters may be problematic for high speed (>1 mach) and low FOV (<5 degrees) platforms since it degrades the capability of using 2PR and 3PR techniques, and the observation window length may be inadequate for locking on.

Increasing FOV and FOR provides longer observation windows as expected. Low FOR systems shall have maneuvers around the beacon without sacrificing the available maneuver potential to hold the beacon in their sight.

Position updates before and/or after (if possible) sharp turn maneuvers with significant heading changes, provides better stability.

Inertial navigation system gyro errors grow with third power of time. Any position update at the end of friendly territory is far better than the free inertial case.

In this work, deviation from the desired trajectory is not wanted for several reasons. Deviation from the desired trajectory is treated with a dynamic penalty function.

When the beacons are deployed near to the missile target line, several variations on the path of the beacons are not affecting the fitness function much as long as the lengths of trajectory segments in the beacon range are not much different.

Reverse intersection updates do not provide a complete error nulling effect since heading error is not updated. So reverse intersection updates shall be made before heading error becomes too large to be effective. This situation does not occur in 2PR and 3PR updates.

CHAPTER VII

SUMMARY AND CONCLUSIONS

7.1 Summary

Navigation techniques can be classified into three main groups, dead reckoning, externally dependent and database matching. All navigation techniques are well-known and have a long history dating back to several thousand years. There is little left in navigation area in terms of methods since all are based on geometry. The increasing dependence on GNSS systems leads to a danger of loss of navigation capability when GNSS is jammed. A ground based aiding solution may lessen the severity of a GNSS jamming scenario if it does not require a strong infrastructure.

In this thesis an alternative navigation scheme for improving the performance of inertial navigation systems onboard guided munitions, missiles and unmanned platforms is investigated, to be used in case of a theater or country-wide GNSS jamming scenario. Previously laid ground based beacon network is used by the aerial platform's EO/IIR seeker for bearing-only measurements and position updates are performed by the use of modified artillery survey algorithms based on triangulation techniques. Three position fixing techniques are offered for position updates, reverse intersection which is a modified intersection method, two point resection and three point resection. Effects of beacon placement geometry are analyzed and a tool for the optimal laying of beacons under several factors, and constraints is developed.

In chapter-1, the proposed solution, namely "Ground based beacon navigation concept" is introduced, reasoning behind beacon navigation, benefits of beacon network, beacon type selection, operation doctrine and possible extensions of the method to various mediums are given.

The reasoning behind beacon navigation system lies behind the *utility* and *cooperative navigation* keywords. The network of beacons can serve a wide variety of systems independent of platform. Network of beacons can serve multiple different kinds of air vehicles in both friendly and hostile territory.

Beacon navigation concept can be applied to all systems with optical /IIR seekers. From missiles to guided munitions, tactical and MALE UAV's that are equipped with seekers/cameras/FLIR's can benefit from the beacon network.

Each beacon is envisioned as a battery powered transportable unit with a solar panel to charge the battery which provides the beacon to be operated within prolonged times, a radio receiver which activates the beacon emission when triggered, and IR (or laser source and a deflector) which generates optical emissions.

The beacon network can be constructed in a region or country wide to allow for operations inside homeland and may provide operation capability in a theater GPS jamming scenario. A typical example of this is UAV surveillance operations inside country's borders.

Cooperative navigation is easier to operate in real world since no huge databases or ambiguities of identification of terrestrial contours or natural landmarks are necessary.

A drawback of a beacon network is that the deployment may require a joint operation between multiple force branches. Missiles and UAV's are operated by Air force and Army, deployment of beacons may require special operation forces, and the planning may be involved with General Command of Mapping. However, considering the other scenario of serious degradation in operational capability, this price may be accepted, especially since successful joint operations are believed to be the key to warfighting success since WWII.

In chapter-2 information about inertial navigation system modeling, Kalman filtering and inertial sensor errors is given. Derivation of error equations in navigation frame is performed. State space equations for an indirect feedback Kalman filter is given obtained to be used in navigation simulation studies.

In chapter-3 position fixing methods are investigated. Position fixing methods may be based on angle measurements, distance measurements or a combination of both. Either trilateration method which relies on measuring distances or triangulation methods are to be employed based on the beacon capabilities and specifications. Optical light emitting beacons are selected as a first candidate for beacon network. The reasoning behind this selection is based on jamming resistance, covertness and no need for an additional hardware requirement. Most missiles and UAV's have readily available cameras/seekers/FLIR systems to engage optical beacons.

Reverse intersection, two point resection and three point resection methods and their solution technique is given. A performance metric that relates the measurements with the states is selected as DOP and derivations of DOP for reverse intersection, two point resection and three point resection are presented.

In Chapter-4 optimal mission planning work is introduced. Two problems are defined related with the beacon navigation concept as "path planning problem" where an optimal trajectory for an air vehicle is sought for a given scheme of previously deployed beacons under FOV, FOR, range, position fix quality constraints and "deployment problem" where an optimal deployment scheme of beacons is sought for a given reference trajectory which minimizes the terminal phase error while not violating the midcourse deviation from the reference trajectory. Evolutionary algorithms class is selected for dealing with optimization problems and a variable length chromosome genetic algorithm (VLCGA) is constructed. Details of the genetic algorithm structure are given. VLCGA structure has a distinct advantage over other optimization methods since it is possible to see the effects of several numbers of deployed beacons in one run and obtain the result of one less beacon deployment. This provides the decision maker (human in this case) to perform a trade of deploying one beacon less to the performance difference. If the performance loss is bearable, one less beacon deployment will also do the mission.

In chapter-5 information about the modeling and simulation structure is given. The implementation and decision maker structure for the three used position fix algorithms is introduced.

For the two problems that are defined in this thesis, a mission planner algorithm that operates in MATLAB is constructed. It uses beacon detection ranges, seeker specifications, IMU specifications, and accepts genetic algorithm design parameters to calculate the beacon deployment scheme for the deployment problem and the path for the path planning problem.

Beacon detection ranges are calculated by modeling laser behavior in the atmosphere analytically, for laser emitting beacons and by using NVTHERM program for infrared wavelength emitting beacons. Optimization is then run regarding the obtained range of detection distances for given visibility, seeker and beacon specifications.

A reference trajectory for the deployment problem is defined taking into account various phases of flight such as climb, heading changes, higher altitude cruise, dive, low altitude maneuvers etc. A 50 deg/hr MEMS IMU's typical error characteristics are used in the simulations. Accelerometer and gyro measurement data is generated for the desired trajectory based on the error specifications of the given IMU. The navigation simulation uses indirect feedback Kalman filter which uses error states. Several case studies are run for both the deployment problem and the path planning problem.

It is shown that lower quality (cheaper-available) inertial sensors can be used in conjunction with the beacon navigation aiding system, to achieve the desired performance levels in case of a GNSS jamming scenario.

Special topics involved in this thesis can be summarized as follows,

1. Positioning algorithms.
    a. 2 point resection.
    b. 3 point resection.
    c. Reverse intersection.
2. Inertial navigation system model.
    a. Nonlinear navigation equations.
    b. Navigation frame mechanization.
    c. Linearization of navigation equations.
    d. Sensor error modeling (typical error levels and their inclusion to model).
3. Kalman filter
    a. Indirect feedback Kalman filter
4. Seeker information.
    a. Realistic parameter forming: Typical FOR, FOV, optics.
    b. Detection range calculations for IIR seeker. Thermal requirements. Requirement drivers for beacon specifications.
    c. Detection range calculations for a hypothetical diffuse beam laser beacon.
5. Optimal mission planning.
    a. Problem definition and classification, Deployment and path planning classes.
    b. Objective function definitions.
    c. Constraint definitions.(FOV, FOR, detection range, turn rate, vehicle range, specific constraints for position fixing methods).
6. Genetic algorithm development.
        i. Variable length chromosome GA code development for both deployment and path planning problems.

7.2 Contributions of the Thesis

Some of the main contributions of the study can be classified as follows;

- A ground based beacon navigation aiding system concept is proposed to form a low cost, high availability aiding system for autonomous air vehicles equipped with EO cameras, seekers or FLIR's, to be used in case of theater GNSS jamming environment. Ground based station systems are used for navigation of manned aircraft such as VOR but there is no system for autonomous aerial vehicles.

- Three distance-free angle-only measurement methods are proposed to be used in the beacon navigation aiding system concept. Distance measurements are avoided for the sake of covertness, and ability to fit multiple autonomous aerial vehicles, especially missiles. These methods are derived from artillery surveying techniques which are used to find high accuracy positioning measurements with static instruments. A method designated reverse intersection which is a modified form of intersection method, two point resection, and three point resection techniques are implemented, to be used in a high speed aerial platform. Position fixing algorithms can be implemented into existing systems with very little modification of software and no modification of hardware.

- It is demonstrated that the proposed method and proposed position fixing techniques can be employed by forming a necessary simulation structure employing a navigation system model, indirect feedback Kalman filtering, and detection range calculations for hypothetical beacons.

- A genetic algorithm based mission planning algorithm is developed that takes into account the unique specialties involved in the beacon navigation concept, and missile specifications (such as position fixing method constraints FOV, FOR, range.) Two main classes of planning problems involved with the beacon navigation concept are identified as path planning and deployment problems. The mission planning tool showed that the proposed method can be used effectively with the proper deployment of beacons to the navigation area.

- It is shown that lower quality (cheaper-available) inertial sensors can be used in conjunction with the beacon navigation aiding system, to achieve the desired performance levels in case of a GNSS jamming scenario. This issue is important by two aspects. A high quality inertial navigation system onboard a missile is destroyed as the mission is accomplished which increases cost per mission kill in a GNSS jamming scenario. The second and more important aspect is that, higher quality INS systems are not generally available due to missile technology control regime regulations, which may cause severe reduction in capabilities of missile systems in jamming.

7.3 Future Work

Experimental demonstration of beacon navigation system with unmanned vehicles may be a future work to identify unforeseen fielding problems and their solutions. This can be achieved by testing on an unmanned helicopter with a camera or FLIR system and heated panels as beacons.

Investigation of effects of random malfunctioning of one or any of the beacons and robustness of the navigation aiding solution by using optimization techniques is regarded as a further research area. Real time implementation of genetic algorithm for path planning problem is also expected to be possible with proper parallel implementation of the algorithm on an FPGA on a flying platform. This can provide on mission re-planning and more elastic operation in case one of the beacons are malfunctioning. The offline GA takes into account the best path for the missile, if at an instant the missile can not detect the beacon due to malfunctioning, it will head to the next beacon in a near optimal manner based on the offline GA solution, but better solutions may also be achieved if the number of available beacons is high, by using an online GA for malfunction cases. Current GA for path planning is suitable to be run for UAV's. For missiles with flight times less than 200 seconds, a course grained solution may be implemented for missiles as is but fine grained solutions require further improvements.

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