NORTH ATLANTIC TREATY ORGANISATION

RESEARCH AND TECHNOLOGY ORGANISATION

RTO PUBLICATION **SET-114/RTG-65**

Basic Guide to Advanced Navigation

(Principes de la navigation avancée)

2nd Edition

Published February 2010

www.rto.nato.int

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Preface

The purpose of this document is to give an overview of various forms of navigation technologies currently or soon to be available, that have particular suitability in environments where traditional satellite navigation signals (such as GPS) may not be available, or where traditional inertial navigation systems (INS) may not be feasible due to physical or economical constraints. These can include urban, indoor, subterranean and other difficult and complex environments in which our forces are asked to operate.

A previous RTO handbook, published in 2004 and entitled *"Basic Guide to Advanced Navigation,"* focused on inertial and satellite navigation systems. While these are the common forms of navigation technology available today, and are expected to remain so in the foreseeable future, there are applications for which traditional INS/GPS systems are not well suited. This handbook reviews GPS and inertial navigation but, unlike the previous handbook, also highlights other technologies such as lesser known radio navigation aids, non-traditional sensors like pedometers and television signal receivers, and innovative bio-inspired navigation concepts.

This handbook was prepared as part of the NATO Research Technology Organisation (RTO) Sensors and Electronics Technology (SET) Panel, Task Group 65 – "Urban, Indoor and Subterranean Navigation Sensors and Systems".

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List of Acronyms

Acronym	*Definition*
CSAC	Chip Scale Atomic Clock
DGPS	Differential GPS
DME	Distance Measuring Equipment
DR	Dead Reckoning
DVL	Doppler Velocity Log
EGNOS	European Geostationary Navigation Overlay System
EKF	Extended Kalman Filter
EM	Electromagnetic
FOG	Fiber Optic Gyro
GMT	Greenwich Mean Time
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
KF	Kalman Filter
LAAS	Local Area Augmentation System
LOP	Line Of Position
LORAN	Long Range Navigation
LOS	Line of Sight
MEMS	Micro Electro-Mechanical Sensor
MMAE	Multiple Model Adaptive Estimation
MOEMS	Micro Optical-Electro-Mechanical Sensor
NAVWAR	Navigation Warfare
NCO	Numerically Controlled Oscillator
ns	nanosecond
PNT	Positioning, Navigation, and Timing
RF	Radio Frequency
RFID	Radio Frequency Identification

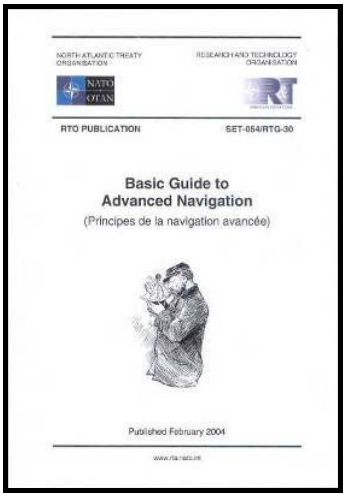
Acronym	*Definition*
RLG	Ring Laser Gyro
RTO	Research and Technology Organisation
SET	Sensors & Electronics Technology
SLAM	Simultaneous Localization And Mapping
SoOp	Signal of Opportunity
SPKF	Sigma Point Kalman Filter
STANAG	Standardization Agreement
SV	Space (Satellite) Vehicle
TACAN	Tactical Air Navigation
TAI	Time Atomic International
TDOA	Time Difference Of Arrival
TOA	Time Of Arrival
TRN	Terrain Referenced Navigation
UHF	Ultra High Frequency
UKF	Unscented Kalman Filter
UTC	Universal Time Coordinated
UWB	Ultra Wideband
VMS	Vehicle Motion Sensor
VHF	Very High Frequency
VOR	VHF Omni-directional Radio-ranging
WAAS	Wide Area Augmentation System
ZVU	Zero Velocity Update

Chapter 1 – INTRODUCTION

The purpose of this document is to give a comprehensive overview of various forms of navigation sensors and technologies currently or soon to be available. Many of these technologies are applicable to difficult and complex environments such as urban, indoor and subterranean environments in which our forces are increasingly forced to operate. In such environments navigation using modern satellite navigation systems is often not possible.

Satellite navigation does not work in all environments (courtesy of G. Duckworth, QinetiQ, 2007)

A previous RTO handbook focused on inertial navigation and satellite navigation systems and was printed by NATO RTO and distributed in 2004. The purpose of that handbook was to familiarise decision makers with modern navigation systems, with particular emphasis on INS/GPS (Inertial Navigation Systems / Global Positioning System) technologies.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Previous RTO Navigation Handbook
(RTO-SET-054 / RTG-30) published February 2004

There remain many applications today for which traditional INS/GPS systems are not well suited. This handbook reviews GPS, inertial and other conventional navigation systems but, unlike the previous handbook, also emphasizes many other technologies that may provide, alone or in combination, effective and affordable positioning and navigation solutions.

In addition, we highlight some research that is trying to exploit how animals navigate (bio-inspired). Various combinations of these techniques are used in Integrated Navigation Systems. Timing and time determination are also keys to navigation and are also described in some detail.

1.1 USES OF NAVIGATION SYSTEMS

Modern military systems, including space-based, air, ground, sea, and individual warrior, must have not only the capability to navigate, but also the capability to direct a variety of sensors and weapons. Today's warfare also requires increasingly higher levels of situational awareness which in turn demands higher navigation accuracy within a common time and reference coordinate system. The navigation system aboard or integrated into each of these platforms provides this mission essential information.

Graphically portrayed below are the three principal uses for positioning and navigation:

- **Navigation**: To get from point A to B on a defined route.
- **Pointing**: To orient a weapon or sensor system in the desired direction.
- **Situational Awareness**: To enable shared awareness, among a variety of commanders and team members, of the platform location in the battle space.

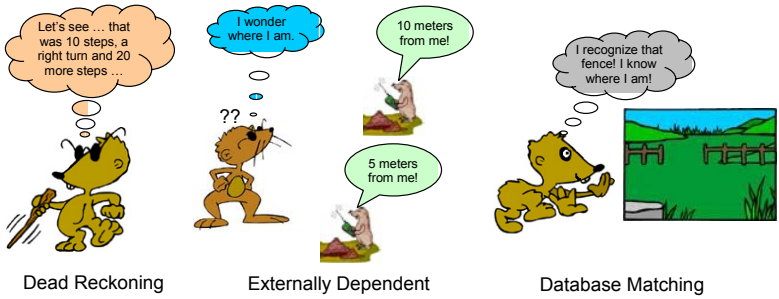
Three Primary Uses of Navigation Information

1.2 METHODS OF NAVIGATION

In this handbook, we have divided navigation sensors and systems in several broad ways, or methods, of navigating:

- **Dead Reckoning** (e.g. inertial navigation);
- **Externally Dependent** (e.g. GPS); and
- **Database Matching** (e.g. celestial navigation).

To envision these methods, imagine being blindfolded and moving to some unknown area. If you kept track of your turns and distance travelled while moving, you would be dead reckoning. If, while blindfolded, you shouted out, "Where am I?" and waited for bystanders to answer, you would be externally dependent. If you took your blindfold off and looked around, you might be able to determine your location by recognizing various landmarks and matching them to images in your memory (database).



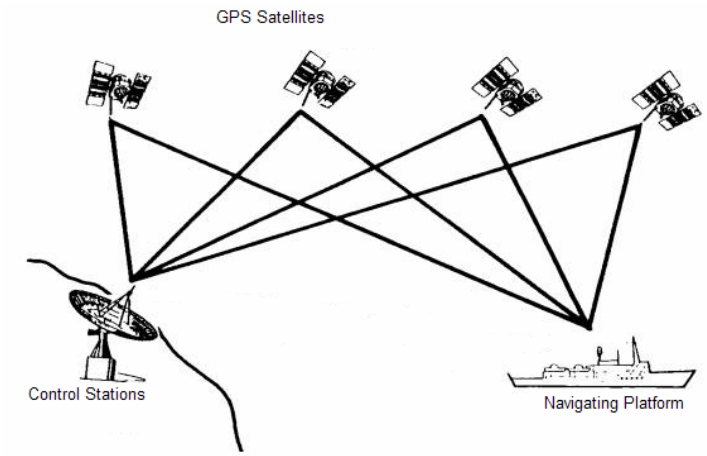
Methods of Navigation

1.3 NAVIGATION REFERENCE FRAMES

Position, velocity and attitude information can be expressed either in *absolute* or *relative* reference frames. Depending on the operation, mission, or scenario at hand, there may be times when one is more appropriate than the other.

1.3.1 Absolute Navigation

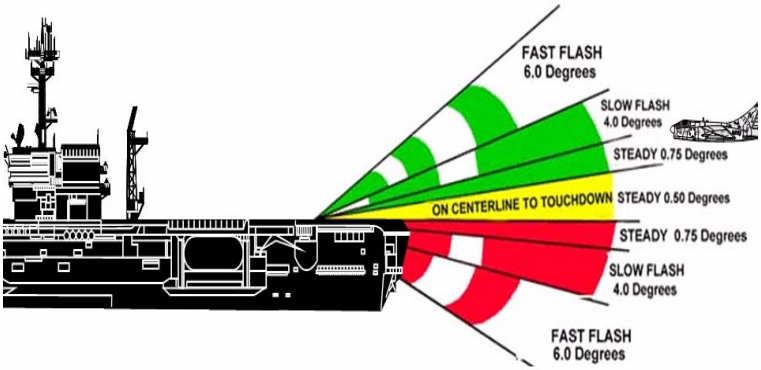
In this approach the user's location is determined in an absolute reference frame using a set of distance and/or bearing measurements from external points whose locations in the environment are absolutely known (e.g. stars, radio navigation systems, satellite navigation). The user then can navigate to other known points in the same frame. In a multi-user environment, it is **essential** that every operator use the same common reference frame.



Absolute Navigation

1.3.2 Relative Navigation

These techniques measure the relative distance, velocity or acceleration and the direction of travel from the current position to a target or other reference position. This information is used to estimate position, velocity or attitude with respect to the target or reference point without knowledge of either in an absolute coordinate frame (e.g. aircraft landing on aircraft carrier only requires relative information for a successful landing).



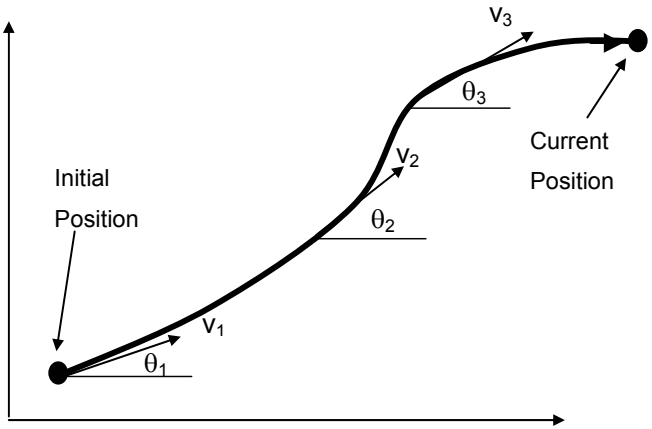
Relative Navigation

Chapter 2 – DEAD RECKONING TECHNIQUES

Dead reckoning is a self-contained method of navigation that does not rely on any external infrastructure. The use of one or more of the following techniques is the most common way of implementing a dead reckoning navigation system. These techniques are particularly useful in urban, indoor, and subterranean environments when the use of outside infrastructure is often not feasible:

- Inertial Acceleration/Rotation;
- Velocity Measurement;
- Heading Determination;
- Distance Travelled; and
- Altitude or Depth Determination.

A dead reckoning system uses a platform's initial position and velocity and then updates its new position based on measured or estimated velocity, heading and elapsed time.



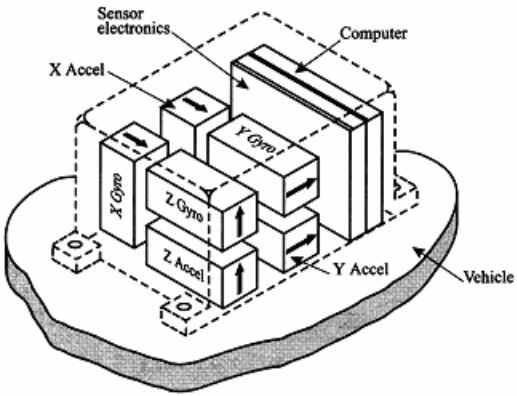
Dead Reckoning Evolution of a Platform's Position Based on Velocity and Heading Measurements

2.1 INERTIAL NAVIGATION SENSORS AND SYSTEMS

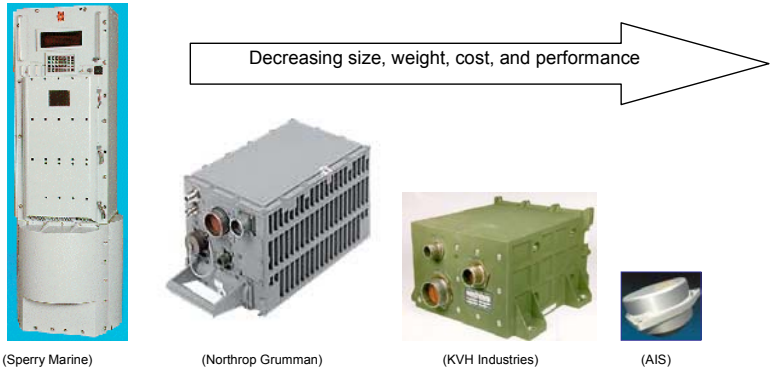
Among dead reckoning systems, Inertial Navigation Systems (INS) are the most complete and also the most complex. They consist of multiple accelerometers and gyroscopes which continuously measure both linear acceleration and angular rotation rate in three dimensions. Starting from a given initial position, the INS updates the path followed by the user based on the motions sensed by the gyroscopes and accelerometers. During this process the velocity and attitude of the vehicle are also computed.

A more detailed description of inertial sensors and technologies is given in the previous handbook.

Inertial Navigation Systems have several advantages. They are self-contained in that no external infrastructure (such as a radio transmitter network) is required; they provide continuous information; the output is available anywhere (under foliage cover, underwater, inside buildings); and they are unaffected by any outside interference or jamming. However the accuracy of a standalone INS degrades with time (unbounded error) due to sensor errors, and it needs to be provided with its initial position. Accurate systems can be expensive, large and heavy; although this is changing as the technology improves.



Components of an Inertial Navigation System



Examples of Military Inertial Navigation Systems used in (left to right) Ships, Aircraft, Armoured Vehicles, and Guided Munitions

2.1.1 Inertial Sensor Technologies

The basic sensors within an Inertial Navigation System are accelerometers (to measure linear motions) and gyroscopes (to measure rotational motion).

Accelerometers fall into two main categories:

- Pendulous rebalanced accelerometers; and
- Vibrating beam accelerometers.

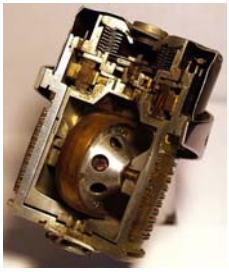
Gyroscopes are more diverse:

- Earlier designs consisted of metal wheels spinning in ball or gas bearings.
- Optical gyros have counter-rotating laser beams either in an evacuated cavity (RLG: Ring Laser Gyro) or in an optical fibre (FOG: Fibre Optic Gyro).
- Other designs use resonators (vibrating elements) of different shapes (e.g. bars, cylinders, rings and hemispheres) and are known under the generic name of Coriolis vibrating gyros.

Both accelerometers and gyros are generally moving from older construction methods consisting of assembling large numbers of mechanical parts, to modern automatic mass production techniques. One such technique uses Micro-Electro-Mechanical Systems (MEMS) technology, micro-machined from silicon or quartz, which enables true solid state sensors. MEMS or Optical MEMS (MOEMS) technologies offer a complete sensor and supporting electronics on a single integrated circuit chip.

Active research in new technologies is continuing; future designs exploiting the properties of individual atoms may provide breakthroughs in inertial sensing performance.

SAGEM



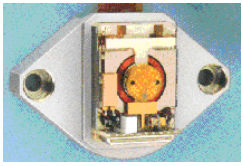
Northrop Grumman

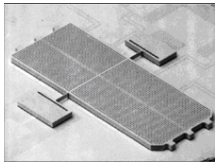
Draper/ Honeywell

Systron Donner

Gyroscope Types (clockwise from top left): Spinning Mass, Ring Laser Gyro, Tuning Fork Resonator, MEMS Vibratory Gyro

BAE Systems





Draper

Accelerometer Types (left to right): Pendulous Rebalanced, MEMS Vibratory Accelerometers

2.2 VELOCITY AND DISTANCE TRAVELLED SENSORS

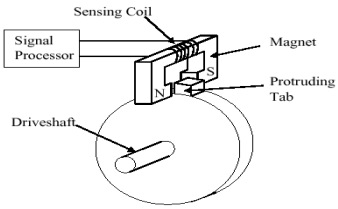
There are a number of sensors available to measure speed, velocity and distance travelled to varying degrees of accuracy. When coupled with other sensors such as heading determination systems, they can form a dead reckoning navigation system. When used as an aid to an inertial navigation system they provide error growth control.

Examples of such devices include odometers, pedometers, Doppler velocity sensors, air speed sensors, water speed logs, visual odometry systems, zero-velocity updates, etc. Some of these, such as pedometers, are especially applicable to urban, indoor and subterranean environments.

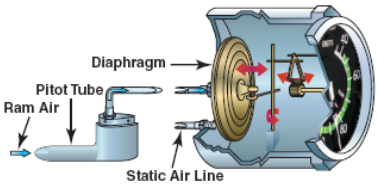
2.2.1 Speed Sensors

Land, air and water speed sensors, although mechanically different, all provide similar information: the speed of the user relative to the surrounding environment. These sensors tend to be very reliable and inexpensive, however their measurement errors are environmentally dependent and must be calibrated for accurate applications.

In land vehicles, odometers, often called vehicle motion sensors (VMS), measure the number of wheel, engine or transmission rotations. The number of rotations multiplied by the wheel circumference provides the distance travelled, and the rotation rate provides the speed. An air speed indicator uses a pitot tube to measure the difference between the static pressure and the total pressure. This difference is related to the speed of the air vehicle with respect to the air.



Odometer



Air Speed Indicator

Water speeds can be measured with an Electromagnetic (EM) speed log. An EM log generates an electromagnetic flux that changes with the speed of water flowing over it providing the relative speed of the vehicle with respect to the water. Water speed can also be measured with a mechanical speed log: the flow of water over a propeller causes it to rotate. The number of revolutions of the propeller per unit time is proportional to the speed of the vehicle with respect to the water.

2.2.2 Pedometers

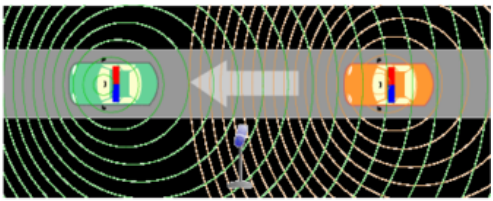
A pedometer is a small device, usually containing a simple accelerometer, which counts the steps a user makes to determine distance travelled. Pedometers are inexpensive, lightweight, passive, self contained and readily available. However, because of variations in the length of a stride, errors are typically on the order of 10% of the distance travelled. As part of an integrated system, the calibration of the user's stride length can be done when more accurate independent sensors are available (e.g. GPS).

Pedometers work well for uniform-stride pedestrian navigation systems, but may not perform so well for soldier movements such as crawling, sidestepping and walking backwards

2.2.3 Doppler Velocity Sensor

A Doppler radar velocity sensor is a device that transmits and receives a low power radio signal, and deduces its velocity based on the shift in frequency of the returned signal as it reflects from nearby objects. This shift in frequency is known as the Doppler effect, and is directly related to the velocity (speed and direction) of the sensor.

Doppler radar systems are available commercially for automotive and traffic enforcement applications and are being adapted to personal navigation systems. These sensors provide very accurate user velocity; however they are not covert and the measured velocity is sensitive to user orientation.



The Doppler Effect: The velocity of a moving transmitter is directly related to the shift in frequency observed

The DRS1000 Doppler Radar Speed Sensor from GMH Engineering

For marine vehicles, a Doppler Velocity Log (DVL) sends acoustic beams and uses the Doppler effect to measure the speed of the vehicle with respect to sea floor. However, this system is limited to about 200 m depths and suitably reflective sea floor conditions.

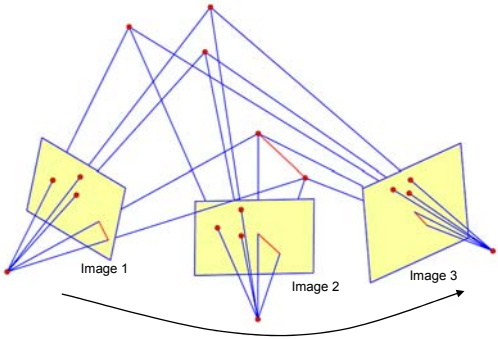
2.2.4 Zero Velocity Update

Zero velocity updates (ZVU), or measurements of velocity = 0, are most often used to control the error growth in inertial navigation systems (INS). A ZVU can be made whenever a user, such as a land vehicle or a dismounted soldier, is known to be stationary. The concept is simple: when the INS is stationary, its known velocity (zero) can be used as a measurement to update the navigation processing filter. ZVUs can be processed continually as long as the INS is stationary. They may be scheduled, requiring the operator to hold stationary for a short length of time. Additionally, periods of zero motion can be automatically detected by software and a ZVU executed.

ZVUs can be performed when vehicles are stopped, when soldiers are relatively stationary, or even on every footfall of a foot-mounted sensor

2.2.5 Visual Odometry

Visual odometry refers to the estimation of relative platform motion from visual data. The determination of motion parameters starts with establishing feature correspondences between consecutive image frames, either by feature tracking or feature matching. Distinctive image points and straight line segments are examples of commonly used image features. Assuming a static scene, motion parameters, such as velocity or distance travelled, can be accurately estimated through the application of geometrical constraints.



Estimating Camera Motion by the 3D Mapping of Points and Line Segments from Multiple Images of an Image Sequence

Features extracted from sequences of images can be used to provide position and attitude updates to an INS through an extended Kalman filter (Section 8). This is referred to as Image-Aided inertial navigation. In addition to the navigation solution, the visual approach offers the opportunity to construct a sparse map of the environment. This exploration technique is closely related to what is known in the robotics community as *simultaneous localization and mapping* (SLAM). These maps can potentially be used for map-matching (Section 5.1).

Image processing algorithms can be applied to estimate absolute position coordinates if a geo-referenced image database is available for matching (as described ahead in Section 5.2). Similar techniques can be used with other sensors such as RADAR, laser radar (LIDAR/LADAR) or thermal imaging cameras.

2.3 HEADING SENSORS

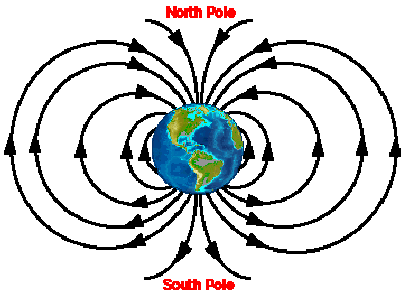
This section presents the common sensors used to indicate a platform's heading with respect to North (azimuth). They are commonly found on ships and airplanes and, when integrated properly, provide information for navigation, pointing or precise target localization.

2.3.1 Magnetic Compass

Magnetic sensors determine heading by sensing the intensity and inclination of the Earth's magnetic field. However, local disturbances in the Earth's magnetic field caused by nearby permanent magnets, electric currents, or large iron bodies can dramatically affect the derived azimuth, or even prevent their use. The azimuth angles from magnetic compasses must be corrected for magnetic declination if they are to refer to true north. Magnetic declination, or the difference between magnetic north and true north, varies with position and time.

The sensors are passive, self-contained, of very small size, low cost, and lightweight. The accuracy of derived azimuths from magnetic compasses depends heavily on the degree to which the local magnetic field is being disturbed. When properly calibrated, heading accuracy can be on the order of 1 degree.

A Digital Magnetic Compass from KVH Industries



Earth's Magnetic Field

2.3.2 Gyrocompass

Gyrocompasses use gyroscopic technologies, as described earlier in Section 2.1.1, to determine the direction of the Earth's rotational axis, i.e. true north.

Gyrocompasses measure the Earth's rotation rate (15 degrees/hour) in the horizontal plane. A measurement of zero indicates east while the maximum measurement (Earth's rotation rate times cosine (latitude)) indicates north.

They have two main advantages over magnetic compasses: they find true north, i.e. the direction of Earth's rotational axis (as opposed to magnetic north), and they are not susceptible to external magnetic fields.

For applications such as artillery pointing (which generally requires pointing accuracies of 1/1000 of a radian), gyrocompasses need to be able to sense rotations to accuracies on the order of 1/1000 of the horizontal component of Earth's rotation rate (0.01 deg/hr at 45 degrees latitude).

In the case of a gyrocompass using medium performance class fiber optic gyros, the heading accuracy is better than 0.5 degrees and can be used as a ship's main navigation instrument.

Cutaway of an Early Anschütz Gyrocompass (Wikipedia Commons Image)

A Modern Fibre Optic Gyrocompass (IXSEA OCTANS)

2.4 ALTITUDE/DEPTH SENSORS

Many navigation systems do not provide very good indications of height or depth. Inertial systems are unstable in the vertical axis and if unaided will provide no useful height information. Dead reckoning by compass and distance travelled provides no height information at all. In difficult urban, subterranean, or underwater environments, the knowledge of height (or depth) is often critical to mission success. A few applicable sensor technologies that measure height/depth are outlined below.

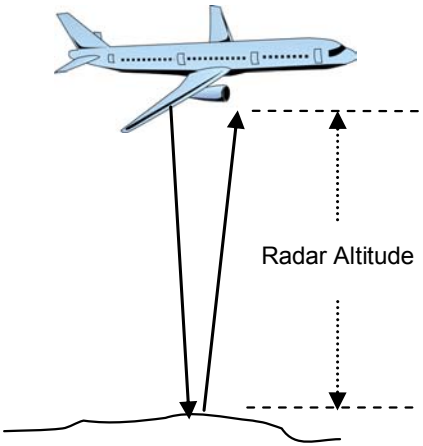
2.4.1 Barometric Altimeter

Barometric altimeters provide a measure of altitude based on the measure of static atmospheric pressure. This pressure measurement is directly related to the height above mean sea level. Like many speed sensors, they tend to be very reliable and inexpensive. However, the pressure readings vary with weather conditions and must be corrected on a regular basis with a reference barometric altimeter at a known height and nearby location for long duration applications.

Druck Barometric Altimeters

2.4.2 Radar Altimeter

For airborne applications, radar altimeters can be used to provide a very accurate measure of the height of the platform above the ground level. A low power radio signal is transmitted towards the ground, and the time required for the signal to reflect from the surface and return to the altimeter provides a direct measure of height above ground. Miniature radar altimeters that would be of use in micro air vehicle applications are available that can measure the height above the ground to a few centimetres.



Radar Altimeter Concept

2.4.3 Water Depth

Used in underwater vehicles, depth sensors typically measure water pressure. A precision quartz crystal resonator whose frequency of oscillation varies with pressure-induced stress is thermally compensated to calculate depth and can achieve high accuracy over a broad range of temperatures. Accuracies on the order of 0.01% can be achieved.

Depth Sensors from Digiquartz Technologies

Chapter 3 – EXTERNALLY DEPENDENT SYSTEMS

The next method of navigation to be addressed is the very broad class called "Externally Dependent Systems." By this we mean a system which navigates using a pre-installed infrastructure. Typically the system would receive radio signals from the infrastructure, and based on any number of techniques, determine its position.

We further divide these radio navigation systems into a number of sub-classes:

- Time of Arrival / Time Difference of Arrival (Range Determination);
- Angle Determination;
- Signal Strength; and
- Signals of Opportunity and other combinations.

Satellite navigation systems (based on range determination) are the predominant form of radio navigation systems today and will remain so in the foreseeable future. Satellite navigation will be listed among the range determination systems and, because of its predominance, Chapter 4 will also be devoted to it.

There are numerous other radio navigation aids that are not based in space. Terrestrial systems are based on a radio receiver using signals from transmitters at known locations on the earth's surface to determine horizontal position. Due to transmitters typically being located on the ground, terrestrial radio navigation systems are generally unable to generate accurate height information.

3.1 TIME OF ARRIVAL / TIME DIFFERENCE OF ARRIVAL (RANGE DETERMINATION)

The use of radio waves to obtain a navigation solution relies on the propagation speed of light. Given the known speed of light, the range between a radio transmitter and receiver can be calculated given the time taken for the signals to travel between them. Propagation uncertainties can significantly affect achievable ranging accuracies.

In a Time of Arrival (TOA) system, position is derived by computing the distance from the receiver to each transmitter, by measuring the time taken for a signal to travel from the known transmitter's location to the receiver. The receiver requires a clock synchronised with the transmitters.

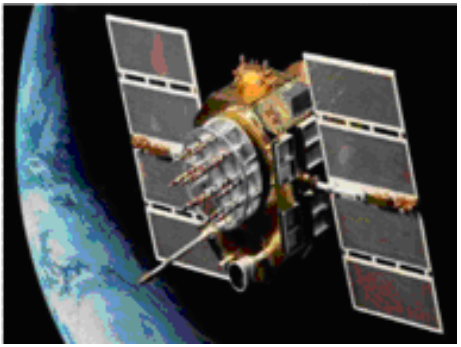
In a time difference of arrival (TDOA) system, pairs of stations transmit simultaneous pulses which arrive at the user's location with a small time difference. A single time difference represents a hyperbolic line of position (LOP). The intersection of two or more hyperbolic LOPs defines the receiver's position. The receiver does not require a clock in this case.

3.1.1 Global Navigation Satellite System (GNSS)

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 locations.

There are four GNSS currently operating or in development: the US Global Positioning System (GPS), the Russian Global Navigation System (GLONASS), the European Union GALILEO, and the Chinese COMPASS system. These systems are designed to give three-dimensional position, velocity and time data anywhere in the world with an accuracy of a few meters.

For a more detailed description of the operation of GNSS see Chapter 4.



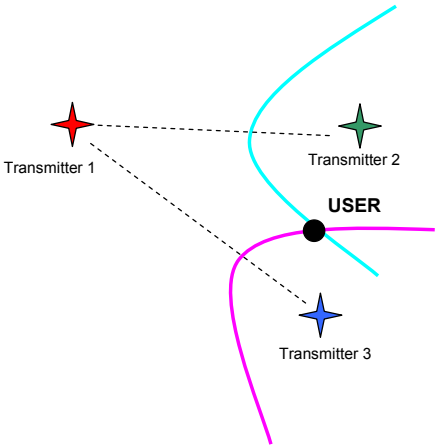
A GPS Satellite

3.1.2 Loran-C

Loran-C (LOng RAnge Navigation) is a time difference of arrival (TDOA), low-frequency navigation and timing system originally designed for ship and aircraft navigation.

A Loran receiver measures the time difference of arrival between pulses from pairs of stations. This time difference measurement places the receiver somewhere along a hyperbolic line of position (LOP). The intersection of two or more hyperbolic LOPs, provided by two or more time difference measurements, defines the receiver's position. Accuracies of 150 to 300 m are typical.

Loran-C has a number of advantages: it uses a very strong transmitted signal which is difficult to jam, it can sometimes be an independent backup to GPS, it provides for high accuracy time dissemination, and the low frequency signal penetrates indoors much better than GPS. However, the positioning accuracy of Loran-C alone is not sufficient for urban/indoor use. There is no global coverage, and the system as a whole has an uncertain future.



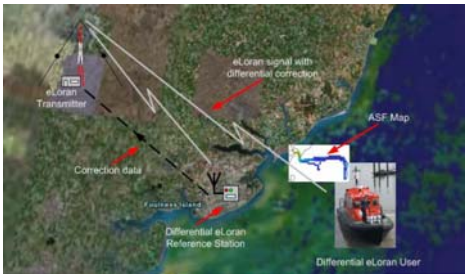
A Loran-C user position is at the intersection of hyperbolic lines of position which result from the time difference of arrival of pulses from pairs of transmitter stations (1&2 and 1&3)

3.1.3 eLoran

Enhanced Loran, or eLoran, is an international initiative underway to upgrade the traditional Loran-C system for modern applications. The infrastructure is now being installed in the US, and a variation of eLoran is already operational in northwest Europe.

eLoran receivers employ time of arrival (TOA) positioning techniques, similar to those used in satellite navigation systems. They track the signals of many Loran stations at the same time and use them to make accurate and reliable position and timing measurements. It is now possible to obtain absolute accuracies of 8 – 20 m and recover time to 50 ns with new low-cost receivers in areas served by eLoran.

Also significant is the addition of a data channel which allows eLoran to meet the accuracy and integrity requirements of ship harbour entrance and aircraft non-precision approach. The data channel broadcasts differential corrections, warnings, and signal integrity information to the user's receiver.

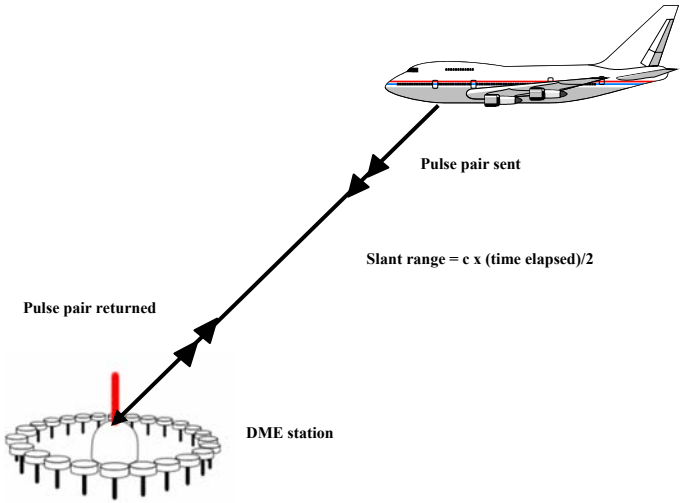


Top – A Combined GPS/eLoran Receiver and Antenna from Reelektronika; Bottom – The Differential eLoran Concept (G. Offermans, 2007)

3.1.4 Distance Measuring Equipment (DME)

Distance Measuring Equipment (DME) stations for aircraft navigation were developed in the late 1950's and are still in world-wide use as a primary navigation aid. The DME ground station receives a signal from the user and transmits it back. The user's receiving equipment measures the total round trip time for the interrogation/reply sequence, which is then halved and converted into a slant range between the user aircraft and the DME station.

There are no plans to improve the DME network, though it is forecast to remain in service for many years. Over time the system will be relegated to a secondary role as a backup to GNSS-based navigation.



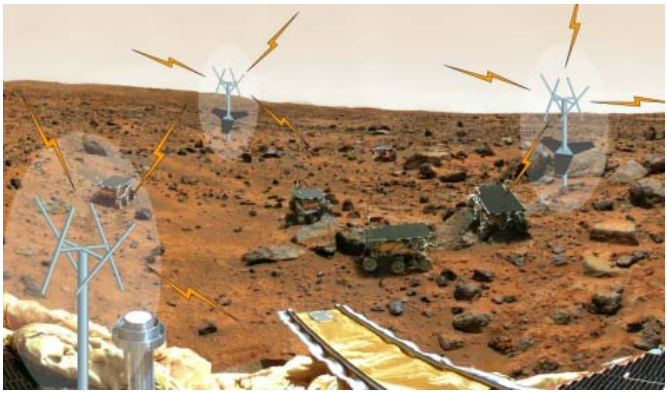
Aircraft DME (Distance Measuring Equipment) Range Determination System

3.1.5 Pseudolites

A pseudolite (pseudo-satellite) is a ground-based transmitter that is capable of transmitting navigation signals that mimic satellite navigation systems. They can be used to augment GNSS satellite signals where there may be significant satellite shading effects, such as indoors.

In order to utilize pseudolites with a GNSS, the signals must be time synchronized with GNSS time, the location of the pseudolites must be known, and the transmitted signals must be of compatible power levels.

If one assumes that the receiver uses **only** pseudolite signals, the transmitted signal power can be changed at will to penetrate difficult environments. For best performance, the pseudolites should be placed around the area of interest to provide good geometry, and therefore good accuracy.



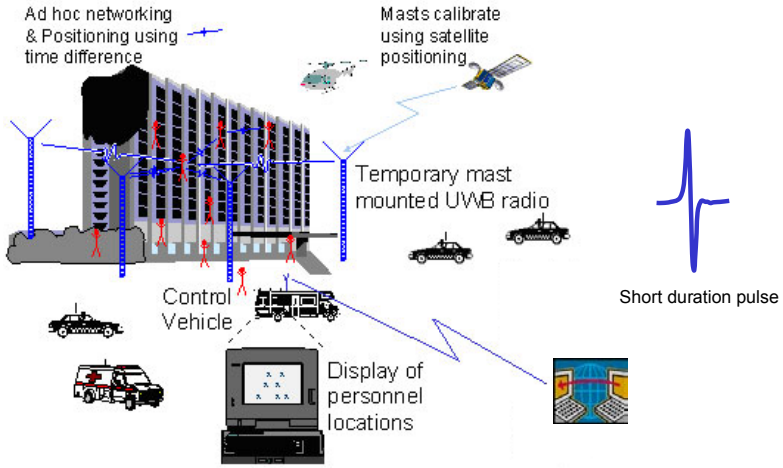
Ground Based Pseudolites Deployed for a Conceptual Mars Mission (LeMaster 2001)

3.1.6 Ultra Wideband

Ultra wideband (UWB) signals are produced by generating and transmitting short pulses of RF energy (on the order of nanoseconds and less). Such short pulse durations in the time domain result in a very wide bandwidth in the frequency domain. Because of this short pulse duration, very high range resolution is possible.

Positioning with UWB technology is accomplished by measuring the Time of Arrival (TOA) or Time Difference of Arrival (TDOA) of the UWB signals. For example, a number of beacons at known positions transmit pulses synchronously and the receiver computes its position by TOA (similar to GPS) or TDOA (similar to Loran-C).

A number of UWB systems have demonstrated indoor positioning with errors of less than 1 m. However, positioning accuracy will depend on the geometry of the beacons and the obstacles between the transmitter and receiver.



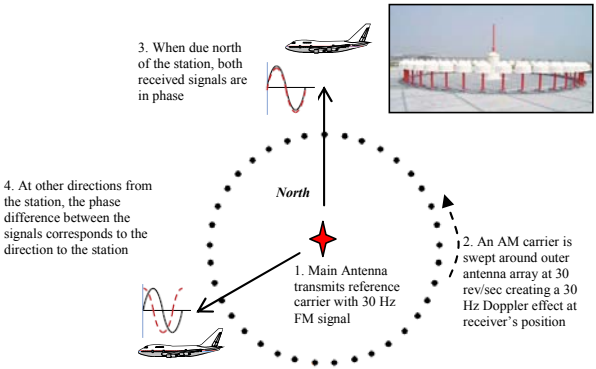
UWB Positioning Concept of Europcom (Emergency Ultra Wideband Radio for Positioning and Communications, Delft University of Technology, et al.)

3.2 ANGLE (BEARING DETERMINATION)

A few radio navigation aids are based on angle or bearing determination from the user's receiver to a reference location. If angle observations to a sufficient number of geographically dispersed sites are made, the user's position can be triangulated. If there are insufficient observations for a position fix, such systems are still useful as heading determination or homing systems, or can be used in a larger integrated system coupled with information from other sensors. Examples of such systems for aircraft include VOR (VHF Omni Directional Radio-range) and TACAN (Tactical Air Navigation).

3.2.1 VHF Omni Directional Radio-Range (VOR) System

The VHF Omni directional Radio-range (VOR) system is comprised of a series of ground-based beacons operating in the VHF band (108 to 118 MHz). A VOR station transmits a reference carrier frequency modulated (FM) with a 30 Hz signal from the main antenna. An amplitude modulated (AM) carrier is electrically swept around several smaller antennas surrounding the main antenna. This rotating pattern creates a 30 Hz Doppler effect on the receiver. The phase difference of the two 30 Hz signals gives the user's azimuth with respect to the North from the VOR site. The bearing measurement accuracy of a VOR system is typically on the order of 2 degrees, with a range that extends from 25 to 130 miles.

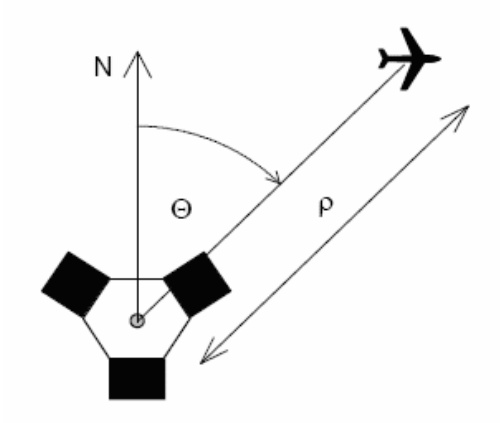


Determining Bearing to a VOR Station

3.2.2 TACAN

TACAN (Tactical Air Navigation) is an enhanced VOR/DME system designed for military applications. The VOR component of TACAN, which operates in the UHF spectrum, makes use of a two-frequency principle, enabling higher bearing accuracies. The DME (Section 3.1.4) component of TACAN operates with the same specifications as civil DME.

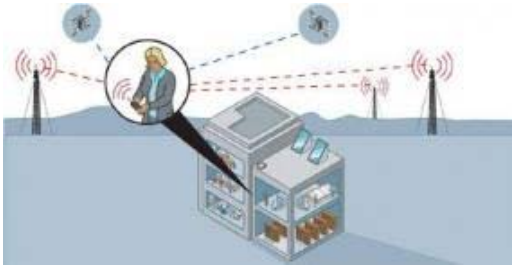
The accuracy of the azimuth component is about ±1 degree, while the accuracy of the DME portion is ±0.1 nautical miles. For military usage a primary drawback is the lack of radio silence caused by aircraft DME transmissions.



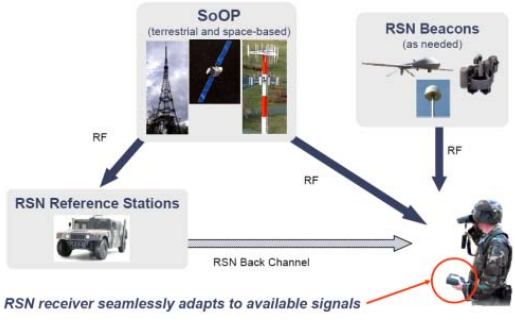
TACAN is the Military Enhancement of VOR/DME

3.3 SIGNALS OF OPPORTUNITY

Recent research efforts are seeking ways to develop technology capable of determining one's position on the Earth based on any or all available "signals of opportunity" (cell phone towers, TV transmitters, etc.). By measuring the time it takes the signal to travel from the transmitter to the receiver, a range to the transmitter can be estimated. However, since signals of opportunity are not usually designed for navigation, a reference station is usually required to provide additional timing and reference data.



(Boeing)



(Argon ST)

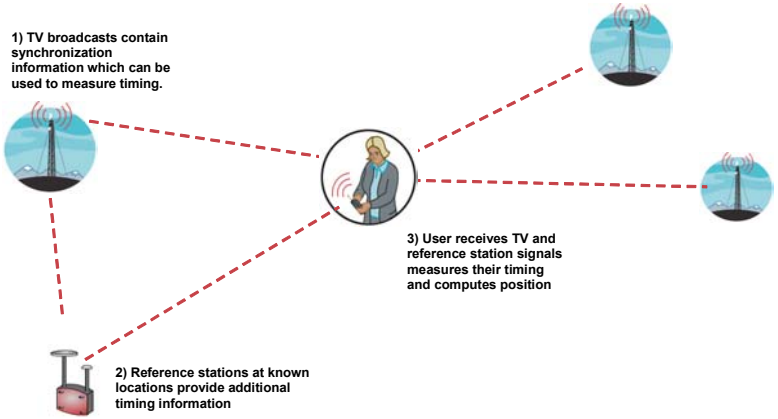
The Robust Surface Navigation (RSN) program, being led by teams from Boeing and Argon ST, is currently studying the exploitation of such signals of opportunity (SoOP)

3.3.1 Radio/TV Broadcast Signals

The use of radio or TV broadcast signals can be used to provide a user's position. By measuring differences in the times at which the broadcast signals arrive at a user's location and at a second receiver at a known fixed location, an estimate of the ranges between the user and the transmitters can be determined.

The exploitation of such signals comes with several advantages. No deployment of a transmitter network is required (it is already available), and the high power, relatively low frequency signals penetrate buildings well and are less susceptible to multipath. However, the concept can only be employed in areas in which there are known operating TV or radio broadcast stations.

For outdoor receivers, position accuracies of a few meters over baselines of several hundreds of meters have been demonstrated. However, positioning accuracy will depend on the geometric distribution of the broadcast stations with respect to the user's position.



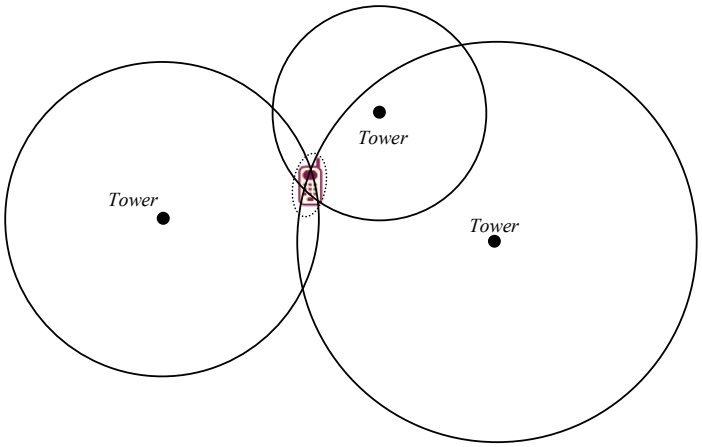
TV and radio station transmitters can be used for positioning (G. Duckworth, QinetiQ)

3.3.2 Mobile Telephone Positioning

Positioning information can be obtained from mobile telephone systems. Either the Time Difference of Arrival (TDOA) or Time of Arrival (TOA) of signals transmitted between the wireless handset and the network can be used. Position may then be estimated by intersections of lines of position. Positioning accuracies better than 50 m have been shown, given a proper geometry between the user's mobile handset and the transmit towers.

The main advantage of such systems is that a special transmitter for positioning purposes is not required. The mobile handset is a relatively low cost and ubiquitous commercial device.

The main disadvantage of telephone positioning systems is that the geometry of the base stations is optimized for communications, not positioning. As a result, the geometry may be very poor resulting in degraded accuracies on the order of 100 – 200 m. Also additional software/hardware may be required in the mobile phone network and/or handset.



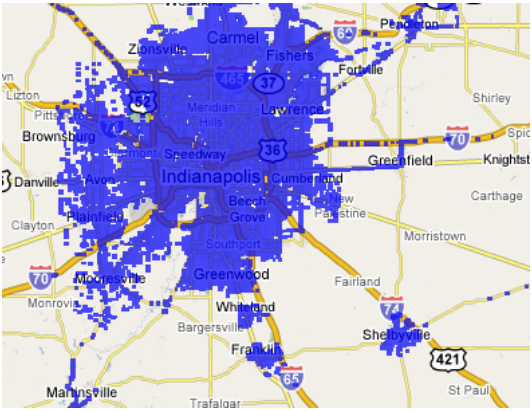
Mobile Phone Positioning Based on the Time of Arrival of Signals from Cell Towers

3.3.3 Signal Strength

Another method of determining position involves the measurement of received signal strength. Such measurements can provide an approximate range between the user's device and the reference stations. A common approach is proximity detection – this approach uses a mobile receiver travelling through an area with a number of fixed transmitters at known locations which measures the power level received from each transmitter. The accuracy of this approach is correlated to the number and geometry of transmitters used and propagation paths between them. If the measured power levels are recorded and catalogued for later use, positioning accuracies should improve.

Examples of positioning systems based on received signal strength are some mobile phone positioning systems, RFID (Radio Frequency Identification) tag readers, or systems that use the known locations of Internet Wi-Fi hotspots to determine approximate location.

These approaches can work very well in indoor and urban environments in developed areas that have been mapped in advance (for first responders in domestic operations, for example), but are less likely to be available to military forces in actual operations.



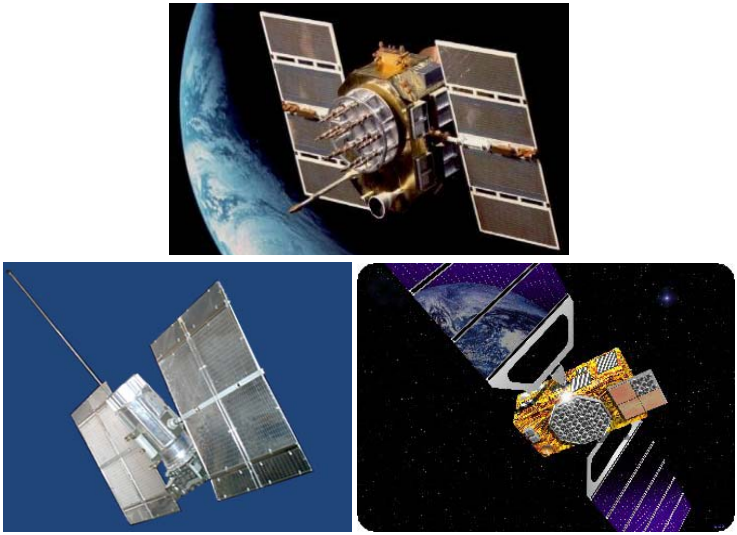
Known Internet Wi-Fi hotspot locations near Indianapolis are exploited by the Wi-Fi positioning system being developed by Skyhook Wireless Inc.

Chapter 4 – SATELLITE NAVIGATION SYSTEMS

Four satellite navigation systems have been designed to give three-dimensional position, velocity and time data almost anywhere in the world with an accuracy of a few meters:

- The Global Positioning System, GPS (USA);
- The Global Navigation Satellite System, GLONASS (Russia);
- GALILEO (European Union); and
- COMPASS (China).

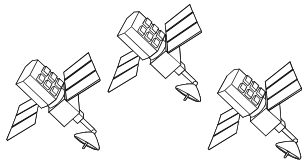
These are all examples of Time of Arrival (range determination) radio navigation systems.



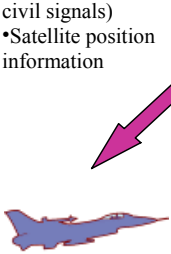
Satellites of the GPS, GLONASS and GALILEO Systems

Space Segment:
Constellation of nominal 24 satellites in six orbital planes around the earth (20200km altitude, each plane inclined at 55°). Each satellite is equipped with very precise atomic clocks.

Downlink Data:
•Time tagged coded range signal (there are currently both military and civil signals)
•Satellite position information



Uplink Data:
•Clock corrections
•Satellite position information (ephemeris data)



User Segment:
GPS receivers detect, decode, and process the GPS satellite signals to calculate position.

Control Segment:
The ground control segment consists of antenna stations that track and monitor the GPS satellites. It computes and uploads corrections to the satellite constellation.

Primary Elements of the Global Positioning System

4.1 SATELLITE NAVIGATION – PRINCIPLE OF OPERATION

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 coordinates (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.

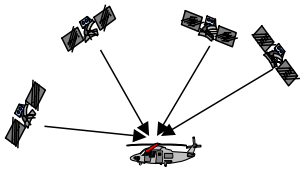
Satellite navigation provides a great number of advantages: It provides global coverage, at all times of the day and in all weather; it is very accurate (positions to a few meters, velocity to 0.1 m/s, time to a few microseconds or better); there is no error growth with time; and the user requires only a small, low-cost receiver.

However, there are some significant limitations as well: it is dependent on external signals which may be jammed or blocked by buildings, terrain and foliage; there may be position shifts due to changing satellite visibility; and there may be no signal validation or real time integrity monitoring.

2. Satellites broadcast their exact positions from data sent to them from the system controllers.

1. Each satellite has very accurate atomic clocks.

3. Each satellite transmits its position and time signal.



4. The signals travel to the receiver delayed by the distance travelled from the satellite to the user recever.

6. For 3-D position and time data the receiver needs to track a minimum of four satellites.

5. The receiver calculates the range to each satellite (from the time signal) and then calculates its own position.

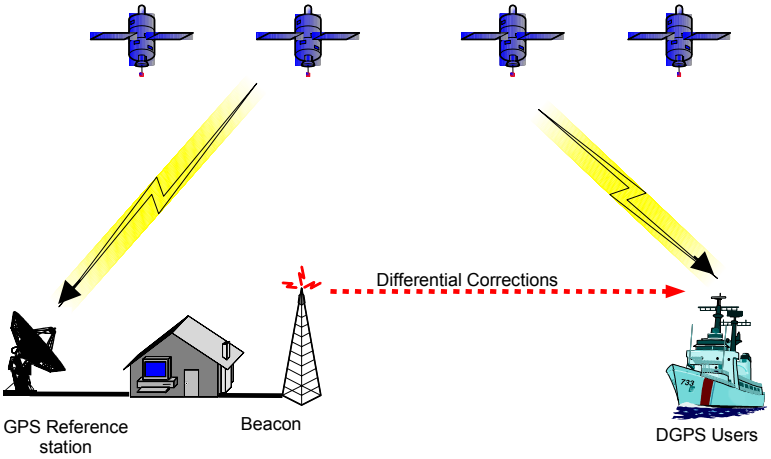
Satellite Navigation is a Time of Arrival, Range Determination System

4.2 GPS AUGMENTATIONS

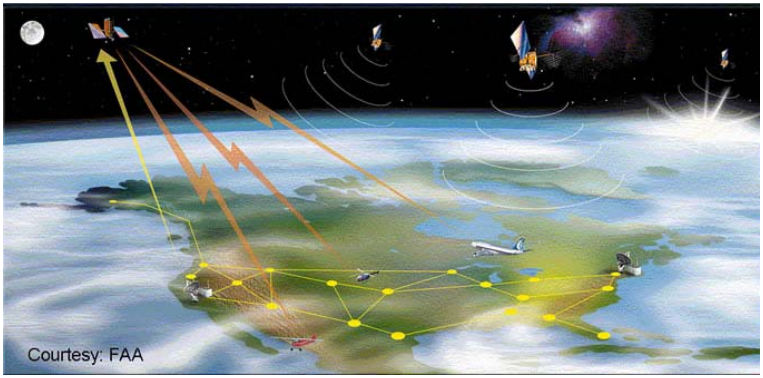
To increase the accuracy of GPS and provide a measure of its integrity, a number of augmentation techniques and systems have been developed. These are based on differential (DGPS) techniques in which one or more high accuracy GPS reference receivers are installed at known locations and the differences between the measured and known ranges to the satellites are broadcast to other GPS users in the vicinity. This removes much of the ranging errors caused by atmospheric conditions (locally), and satellite orbit and clock errors (globally).

Examples of differential GPS augmentation systems include:

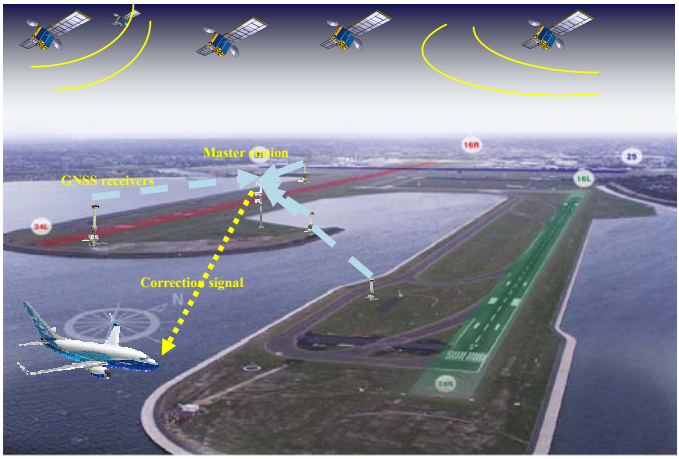
- Maritime DGPS operated by several national authorities for coastal approaches. Corrections are broadcast from shore-based 300 kHz (approximate) beacons.
- Wide Area Augmentation System (WAAS), European Geostationary Navigation Overlay System (EGNOS), and other similar systems broadcast corrections and GPS integrity information on the GPS frequencies from geo-stationary satellites.
- Local Area Augmentation System (LAAS) is being installed at some airports to provide high accuracy position and integrity data to support automated GPS-based aircraft landing.
- Assisted GPS receivers, which use information provided by alternate communication channels to aid them in acquiring weakened GPS signals.
- High precision GPS-based surveying systems, employing local differential corrections.



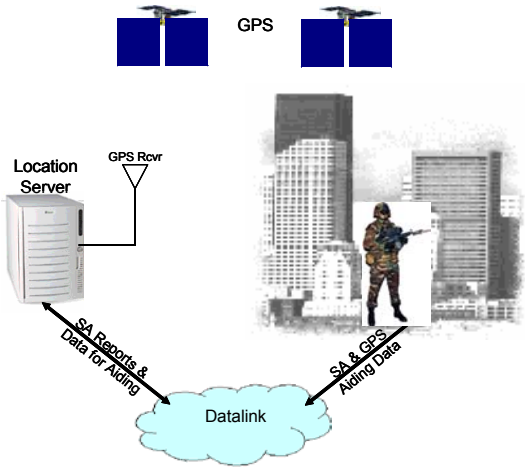
Concept of the Marine DGPS System



The Wide Area Augmentation System (WAAS)



The Local Area Augmentation System (LAAS)



Assisted GPS – Time, Satellite Data, and Approximate Position Transmitted via Alternate Means to Assist a GPS Receiver in Finding and Maintaining Lock on GPS Signals

4.3 INTERFERENCE TO GPS

Interference to the reception of GPS signals can be caused by telecommunication devices, local interference from signals or oscillators on the same platform, or possibly radar signals in nearby frequency bands. Attenuation of the GPS signal can be caused by obstructions or antenna orientation and can result in reduced signal/noise ratios. This decrease can result in loss of signal even without intentional jamming or interference.

In April of 2001, GPS was jammed in much of Moss Landing Harbor in Monterey Bay, California and about 1 km out to sea. The source turned out to be a defective preamplifier in a VHF/UHF television antenna on a pleasure boat docked in the harbor. Due partly to the intermittent use of the TV system on the boat, it took several days to find this low power emitter.

GPS receivers are also at risk due to intentional jamming. The effects of jammers can be reduced by improved anti-jam technologies within the receiver, improved antennas, or by integration with another navigation technology, such as an INS.

It took several days to find this unintentional jammer in Monterey Bay in 2001

4.4 NAVIGATION WARFARE

NATO military forces must be prepared for GPS and other navigation systems electronic warfare environments in future conflicts. Such Navigation Warfare (or NAVWAR) concepts as Electronic Attack, Electronic Protection, and Electronic Support have been defined in NATO STANAG 4621 ("Navigation Warfare Definition") and NATO STANAG 4665 ("Navigation Warfare Operational Planning and Management").

Navigation Warfare is defined in STANAG 4621 as "… preventing the hostile use of PNT (Positioning, Navigation, and Timing) information while protecting the unimpeded use of the information by NATO forces and preserving peaceful use of this information outside the area of operations." The aim of STANAG 4665 is "to promote interoperability for the exchange of data and information among NATO nations for NAVWAR awareness … NATO should develop and implement a procedure that ensures consistency for operating in a NAVWAR environment." STANAG 4665 details:

a) NAVWAR modeling and simulation;

b) Tests, trials and demonstration standardization; and

c) A NAVWAR operational assessment methodology.

NAVWAR Concepts: Protect NATO Use, Prevent Hostile Use, but Preserve Peaceful Use

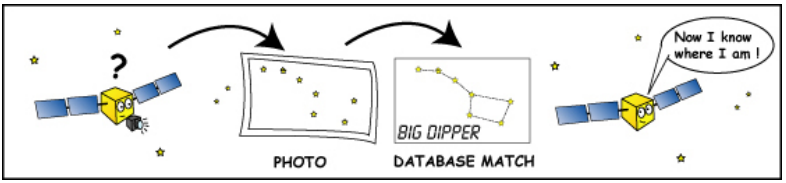
Chapter 5 – DATABASE MATCHING

The next major method of navigation is called Database Matching. This technique involves sensing the surrounding environment, comparing this to a pre-stored representation of that environment, and deducing a sensor location and orientation from that comparison.

Examples of database matching techniques include:

- Map Matching;
- Image Matching;
- Terrain Referenced Navigation;
- Celestial Navigation; and
- Gravimetry.

Some of these are highlighted in upcoming sections.



Database Matching

5.1 MAP MATCHING

Maps are considered one of the most common aids to navigation. They can be used as a sole means of navigation with users determining their location by feature matching. Alternatively, distinctive map features such as streets, for example, can be used to generate lines-of-position, or otherwise complement or constrain the position generated by other navigation sensors.

The accuracy of map-matched systems is comparable to that of the underlying maps, and the existence of map databases is the key requirement to automating this process.

Matching your surroundings to a map is a classical navigation method

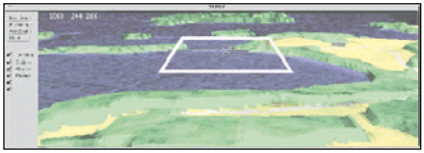
5.2 IMAGE MATCHING

Humans use visual images to avoid obstacles and navigate through their surroundings every day. If points in their images are known to them, they can determine their position.

Computerized image based navigation systems can be organized in two methods: 1) **Image Matching**: Given a textured up-to-date surface model of the environment, the position and orientation of the camera can be estimated from a single frame by maximizing the correlation between the observed image and an image database; and 2) **Spatial Resectioning**: Given only a sparse 3D point or line model database of the area, this method determines the current camera position and attitude from several known points/lines. Other image-based navigation techniques were discussed in Section 2.2.5.

Most recent work in image-based navigation, mainly autonomous robot navigation, has been done in structured indoor environments, which are very easy to model since all the objects are of relatively simple geometry. Error sources are mainly related to the sensor errors and the accuracy with which the image coordinate of the known points can be identified and measured. The limitations to implementing image-based navigation in outdoor environments are due to the difficulties in developing smart algorithms that model such complex environments.

Seeker Image

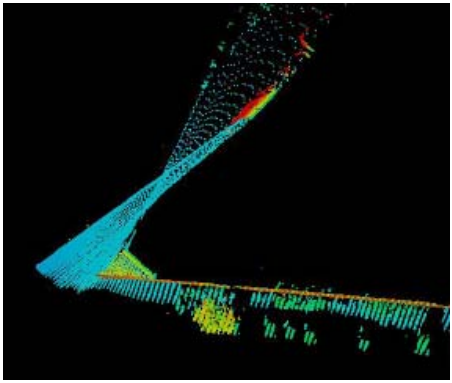


Database

Database Matching in an Optical Image Based Navigation System

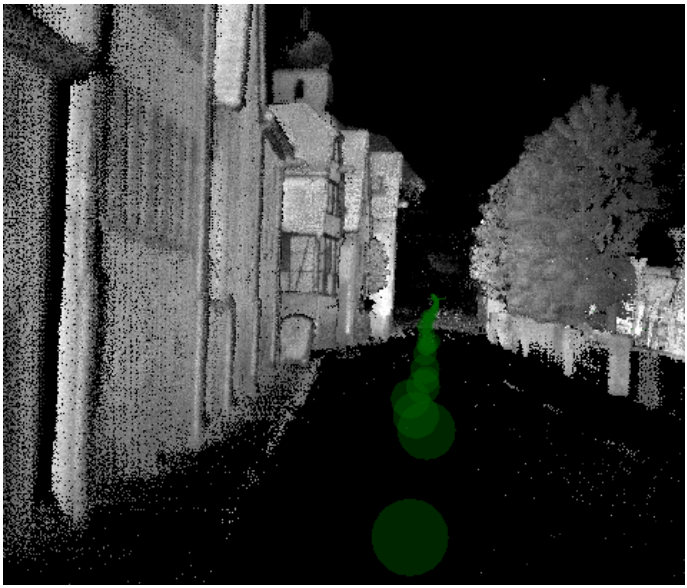
5.3 LASER IMAGING

A Laser imaging system traditionally uses a scanning laser diode to measure the ranges to all nearby reflecting surfaces. The resulting laser point cloud is an 'image' of the surrounding area. Position information can be derived if the image can be matched to an existing database. Range measurements from laser imaging systems are very precise: typically better than 0.1 m at 50 m distance and 1 – 5 m at 3000 m.



Representation of a Wall Ahead of a Scanning Laser (Image courtesy Applanix Corp)

New flash laser imaging systems are an emerging technology that capture multiple point clouds with a staring array at a frame rate similar to that of a video camera. Data processing algorithms can be applied to estimate the motion parameters (see Visual Odometry described in Section 2.2.5) or absolute position coordinates if a database is available for matching.



Reconstructed Scene and Camera Path for a Forward Motion through a Village – the green dots indicate the estimated projection centers (Data by the Air Force Research Lab; result by W. von Hansen, FGAN-FOM)

5.4 TERRAIN REFERENCED NAVIGATION

Terrain Referenced Navigation (TRN) is the name for a group of techniques using sensed terrain height (or depth) information and a terrain database to generate position measurements.

Sequences of terrain measurements are taken and an algorithm then searches the terrain database for a good match with the sensed values. When a good match is found, the approximate route and position of the platform can be inferred.

Typically, INS position and attitude data is used to compute the platform's position from where the terrain sensor measurements are taken. This allows an optimized search of the database. The result of the match is used to improve the current best estimate of position, using a Kalman filter or other data fusion algorithm.

In general, TRN systems are attractive in times of GPS data unavailability because they are virtually impossible to jam, they 'navigate' (relatively) in the coordinate system of the terrain/environment, and they operate autonomously (i.e. they do not rely on external systems).

Terrain Referenced Navigation by Radar (left) and Sonar (right)

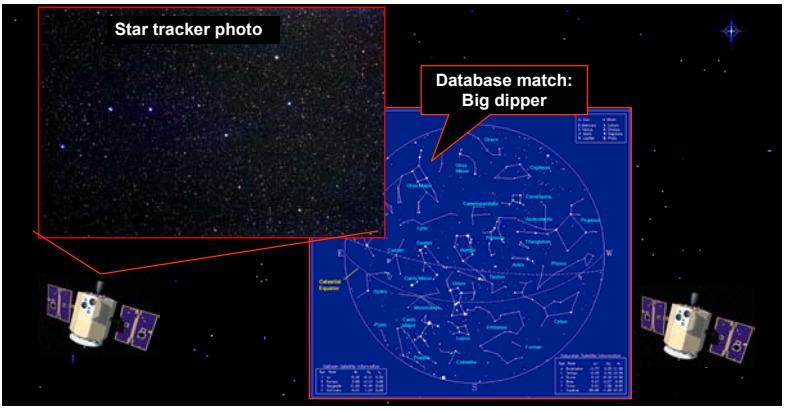
5.5 CELESTIAL NAVIGATION

Celestial navigation is the process of finding one's geographic latitude and longitude by means of astronomical observations to celestial bodies, with knowledge of the correct time.

A star tracker combines a telescope and a photo sensor to convert celestial light energy into an electric signal. A sensor is then used to determine where in the field of view the celestial body is, thus providing an output of azimuth. The star tracker is often integrated with an inertial system by a Kalman filter.

Modern celestial navigation systems are able to simultaneously track many stars, thus allowing constellation matching (using an appropriate embedded star catalogue database) which, in turn, improves the accuracy, continuity and robustness of the navigation solution.

Celestial navigation systems are self-contained, provide worldwide operation, and cannot be jammed. They do have potential utility in certain urban navigation applications. However, cloud cover and other obstructions of the sky may preclude their use. Angle measurements on the order of 1 to 2 arc seconds are achievable which corresponds to a positioning accuracy of about 50 to 100 m.



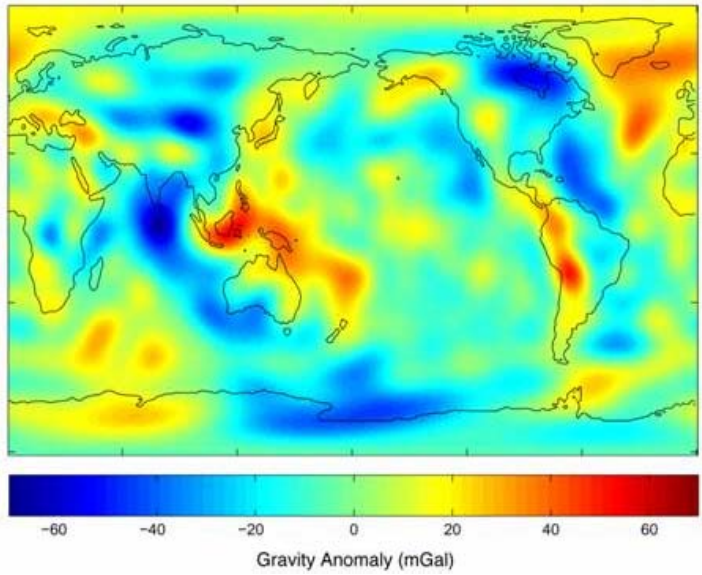
Database Matching Used in Celestial Navigation Systems

5.6 GRAVIMETRY

A gravity gradiometer measures the gradient of gravity, i.e. the variation of gravity with distance. By comparing the measured gravity gradient with a database, the location of the gradiometer can be inferred.

Gradiometer navigation has the tactical advantage of being a passive system and is thus stealthy. Unlike established terrain referenced navigation systems, it may also be used over sea and flat featureless terrain. However the granularity of available global gravity maps is coarse and the results are not especially accurate. Local gravity maps may be much better.

Exploitation of measured gravity gradients may be useful in subterranean applications.



A Representation of the Earth's Gravity Field

Chapter 6 – TIME

Time is critical for navigation. Time was required by the early navigators to determine longitude and is required in all dead reckoning systems. Accurate time measurement is also the principle by which a modern radio navigation system, such as GPS, is able to function. Since radio signals travel about 30 centimetres in one nanosecond (ns), time accuracy must be on the order of 1 ns to maintain overall system accuracy to a few meters. Each GPS satellite contains four highly accurate atomic clocks which are monitored continuously by ground control stations.

GPS time is a composite of the time scales maintained by atomic clocks on the ground and on the satellites. Relativistic effects are removed and synchronization with ground clocks is performed via periodic corrections to the on-board clocks.

Each GPS satellite includes in its navigation message an estimate of the difference between its internal clock and GPS time and the difference between GPS time and UTC (Universal Time Coordinated). The exact difference between UTC and GPS time is given by two constants which are refreshed periodically: one giving the time difference and the second the rate of time difference. These predictions are updated on the ground every 15 minutes, but each satellite's broadcast information is updated approx. once per day.

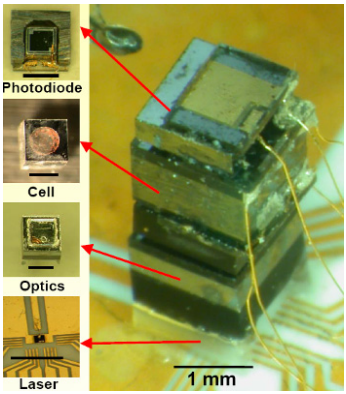
Portable Cesium Atomic Clock

GPS time was set to zero (week 0, day 0) and synchronised with 00:00:00 UTC on January 6, 1980 and since it is not perturbed by leap seconds, GPS is now ahead of UTC, popularly known as GMT (Greenwich Mean Time),

or *Zulu* time, by 14 seconds. With the exception of the integer number of leap seconds, GPS time is steered within one microsecond of UTC with the difference reported in the GPS navigation message to a precision of 90 nanoseconds.

All GPS receivers contain an inexpensive, but less accurate, oscillator/clock that is calibrated continuously by the GPS system while signals are being received. When the receiver is not tracking satellites, the clock can drift significantly, making subsequent signal reacquisition harder.

Advanced research is ongoing to develop a "Chip Scale Atomic Clock" for many applications, including GPS receivers, which would allow rapid signal acquisition and navigation with less than four satellites, which is especially useful in urban and indoor environments. When mature and deployed in future military GPS receivers, it can improve signal tracking in a high-jamming environment, signal reacquisition capability, and position solution accuracy.



A Prototype Chip Scale Atomic Clock (CSAC), from the National Institute of Standards and Technology

GPS is the main source used to disseminate accurate time world wide. The GPS prediction of UTC time has an average accuracy of 1 ns. This has enabled many applications ranging from digital communications, energy control and transfer, banking transactions, and much more. The number of users of GPS time far outweighs the number of users of GPS position.

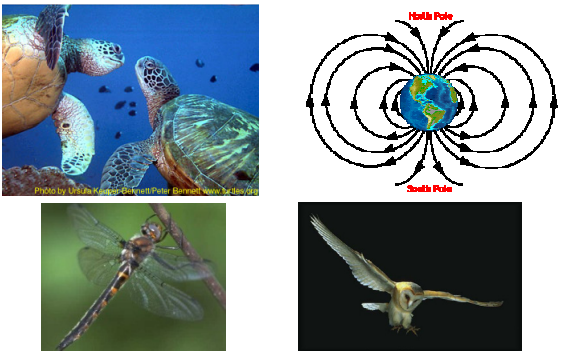
Chapter 7 – BIO-INSPIRED NAVIGATION

Bio-inspired navigation relates to navigation sensors and techniques motivated by nature. Natural systems such as birds and insects rely on navigation sensors and techniques to ensure their survival. For example, birds use vision (landmark navigation), sense of smell (olfactory), and magnetic and sun compasses to navigate during migration, food foraging, and mating. Examples of bio-inspired navigation techniques include:

- Light Polarization;
- Landmark;
- Magnetic;
- Echo-Location; and
- Olfactory.

Many animals use combinations of several of these techniques and seem to naturally adjust the use of these methods based on their current situations.

Several of these methods are currently being studied with the goal of developing robust integrated navigation systems that will work in difficult environments. Some of these are highlighted in upcoming sections.

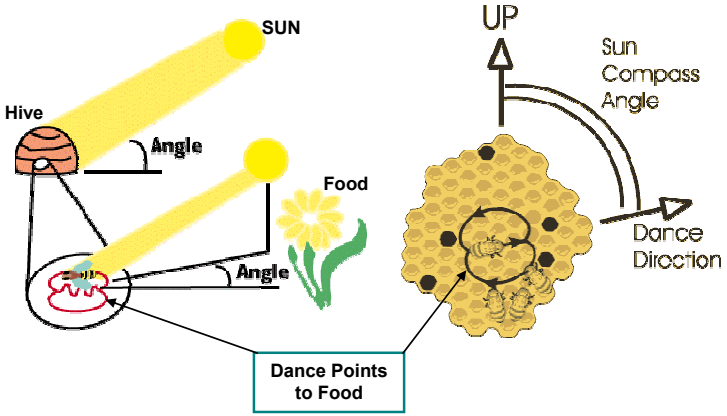


Many animals have natural abilities to use various navigation methods

7.1 LIGHT POLARIZATION

Sunlight is scattered by atmospheric molecules and a pattern of polarized light is set up in the sky. This occurs when there are clear or partially clear skies (including partial tree cover and urban canyons), but not when the sky is overcast or at night. For a given sky direction, the sun's polarization will change as the sun moves through the sky, thus providing the basis for a polarization compass and clock.

It is speculated that several biological species, such as bees and ants, have the ability to perceive the polarization of light and use this information for navigational purposes.

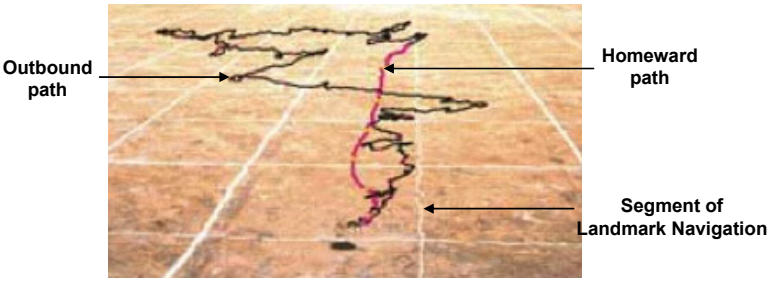


Bees can communicate directions with respect to polarized light using various flight patterns

7.2 LANDMARK

Homing pigeons are known to use landmarks as a navigational aid when returning to a previously established home site. Ants also exhibit a great ability to selectively retrieve and follow landmark-defined routes through various environments. This gives them a powerful method for navigation away from and back to their home site.

Landmark-based navigation is probably the oldest form of navigation used by humans. This navigation technique simply requires the memorization of unique stationary features which serve as navigational reference points. Early aviators completely relied upon landmark navigation during their air travel. Examples of landmarks include buildings, road intersections and natural landmarks. Other examples of landmark navigation often used by humans were discussed in Chapter 5. They included map matching, image matching, and terrain referenced navigation systems.



The navigation skills of desert ants has been extensively studied by R. Wehner, University of Zürich

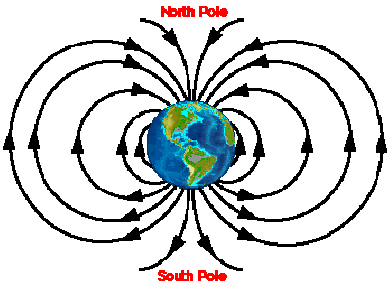
7.3 MAGNETIC

Research indicates that many animal species can naturally sense the Earth's magnetic field and use it to successfully navigate great distances. As an example, sea turtles perceive both the inclination angle and the intensity of the Earth's magnetic field. They use this information both for determining their own geographic location and their desired direction of travel.

The inclination, the angle at which the magnetic field lines intersect the surface of the earth, ranges from 0 degrees at the equator to 90 degrees at the poles. The intensity of the magnetic field also varies in strength over the earth's surface, being strongest at the poles and weakest at the equator.

Older sea turtles use magnetic information in a classical navigational map, allowing them to assess their position relative to their internal magnetic map. This may provide an interesting conceptual design for low-resolution positioning systems.

The concepts described here are the same as used in the Magnetic compass sensor described in Section 2.3.1.

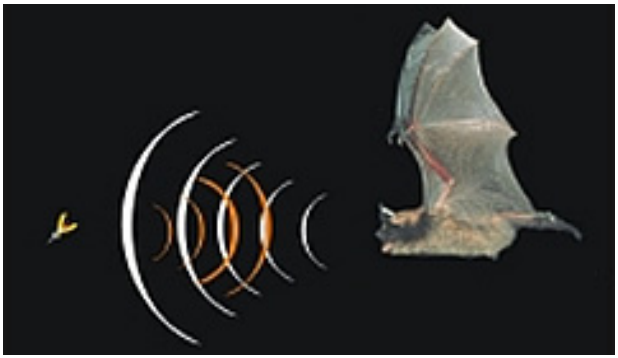


The navigation skills of sea turtles has been extensively studied by K. Lohmann, University of North Carolina

7.4 ECHO

Echolocation, also called acoustic location or biosonar, is the biological sonar used by several mammals such as dolphins, shrews, and many bats and whales. Echolocating animals emit calls out to the environment, and listen to the echoes of those calls that return from various objects in the environment. The echoes are used to locate, orientate, range, and identify objects. The animal determines the range by measuring the time delay between the sound emission and the returning echoes. Echolocating animals generally have two ears positioned slightly apart as shown in the bat picture. The echoes returning to the two ears arrive at different times and at different loudness levels, depending on the position of the object generating the echoes. The time and loudness differences are used by the animals to "see" where it is going; determine an object's size and type; and also determine an object's features.

Currently, sonar is used in submersibles and surface ships to determine the distance to an underwater object (e.g. sea floor) as was discussed in Section 5.4.



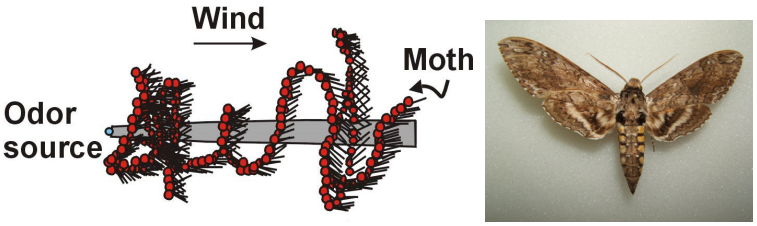
Echolocating is commonly used by many bats
(Lake Mead NRA Echolocation Photo)

7.5 OLFACTORY

Olfaction refers to an animal's sense of smell. Specialized sensors are required to detect the odour and determine the direction of the wind (air flow) carrying the odour. Animals steer into the wind and move upstream trying to stay in contact with the odour until they reach its source.

As an example, the figure below depicts a moth's flight track as it tracks an odour upwind to its source. In this image the moth's position is marked with a dot and the orientation of the moth's body is represented by the stick attached to the dot. Of note:

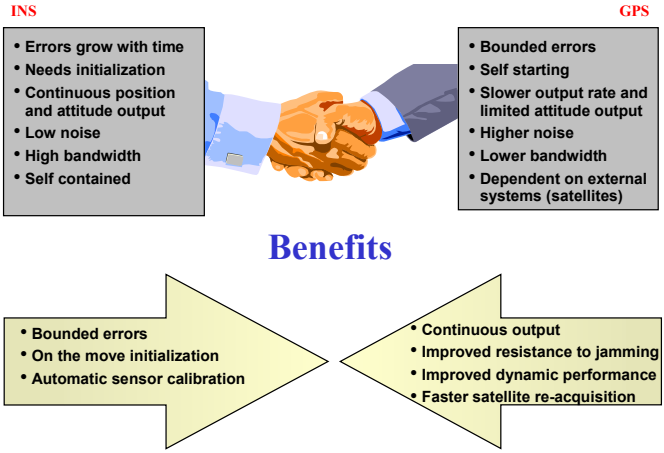
- The moth regularly alters its direction back-and-forth across the wind as it tracks the plume upwind.
- As the moth gets closer to the odour source it narrows its flight track by slowing down and turning more frequently, effectively homing in on the source.



The navigation skills of moths as studied by M. Willis, Case Western Reserve University

Chapter 8 – NAVIGATION MULTI-SENSOR INTEGRATION

The concept of an integrated navigation system is to combine the outputs of different types of sensors. Navigation sensors, like anything else, have strengths and weaknesses. For example, GPS has exceptional accuracy, but it is subject to outages due to the loss of satellite signals. Inertial sensors rely only on gravity and platform dynamics, which cannot be jammed, but they exhibit time growing errors that eventually become unacceptable. Through the careful design of the integrated system, the limitations of individual sensor technologies can be greatly mitigated and improved accuracy and robustness can be achieved.

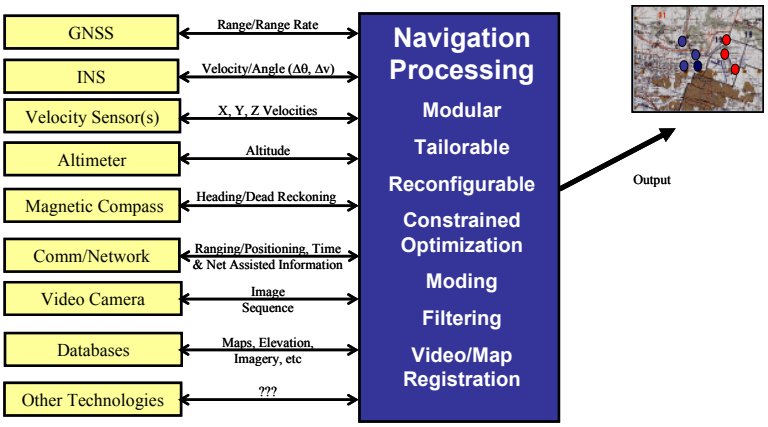


The Benefits of Integrating INS and GPS Systems

The classical method of integrating navigation sensors is called Kalman filtering, following the algorithms developed by R. Kalman in the 1960's. Navigation Kalman filter design requires a careful error analysis and model development for each sensor to be integrated. The Kalman filter will produce the optimal estimate of all the errors in the system given all available sensor data.

Three different architectures are in use today: *loosely coupled*, *tightly coupled*, and *deeply integrated* (or *ultra-tightly coupled*) systems. These are described in **Annex A**, along with some new and innovative alternatives to the Kalman filter, such as particle and sigma-point filtering.

In challenging complex environments, it is quite possible that no one set of sensors will be applicable to all environments. This implies that the ultimate solution will be a modular system in which a suite of sensors can be selected for a given situation and a high level Integration scheme will adaptively integrate those sensors in an optimal fashion.



Modular, adaptive, multi-sensor integrated systems provide a possible solution to providing robust navigation in complex environments

Chapter 9 – A LOOK TO THE FUTURE

Advances in navigation sensor and integration technologies have allowed us to equip a wide variety of platforms with an integrated navigation capability that has not been cost effective in the past. The modern commander demands precise location information of operational assets, be they aircraft, ships, spacecraft, ground vehicles (both manned and robotic) as well as individual soldiers. This capability will enhance situational awareness and command and control, increase speed of manoeuvre, improve weapon effectiveness, and simplify communications and logistics requirements.

Navigation systems will continue to get progressively smaller and more affordable. Technological advances, improved mass production techniques and further cost reductions are forecast for the foreseeable future for both inertial sensors and satellite systems. Integrated navigation systems, such as INS/GPS, will continue to be the standard and applicable to almost any platform or application. These systems will provide accurate position, attitude, velocity and extremely accurate time information to the user continuously. New sensor technologies, innovative methods for exploiting signals of opportunity, bio-inspired navigation concepts, and improved data integration algorithms are all actively being pursued to handle the difficult case of navigating when satellite navigation is not always available. This will be particularly useful for ground forces operating in complex urban, indoor and subterranean environments.

Some of the new and emerging military applications of future integrated navigation systems will include:

- Networking of sensor platforms to create new and highly effective integrated network sensor systems.
- Robotic assets that use precise navigation systems to allow autonomous manoeuvre, alone or in concert with others.
- Guided munitions (e.g. artillery shells) that can attack a given coordinate precisely, independent of aiming accuracy.
- Accurate positioning of all platforms even when operating in GNSS denied environments.
- Other innovative applications that we have not yet imagined.

Chapter 10 – SUMMARY

The previous NATO handbook (Basic Guide to Advanced Navigation) focussed on both inertial navigation and satellite navigation systems as a way to provide accurate position, attitude, velocity and time information to the user continuously. Advances at both the high and low ends of the cost/ performance spectrum have allowed a wide variety of platforms to be fitted with an integrated navigation capability that has not been cost effective in the past. However, systems employing satellite navigation may not be the best approach when operating in challenging environments where traditional satellite navigation signals may not be available.

In this new booklet we have set out to highlight other areas of technology that, when combined with an inertial navigation system, may be more applicable to these challenging environments. Areas of technology ranging from dead reckoning techniques (such as velocity and distance travelled sensors, heading sensors and altitude/depth sensors) to externally dependent systems such as pseudolites and signals of opportunity have been covered. Database matching systems, such as terrain referencing, are also discussed. Imaging sensors such as visual, thermal and laser-based are advancing rapidly and navigations systems exploiting these devices are also covered in this booklet.

One area that has future potential is bio-inspired navigation, where humans are trying to exploit some of the mysterious techniques that birds, animals and insects use to navigate. From bees returning to their hive to birds migrating half-way around the globe, nature has an inbuilt capability to navigate with remarkable accuracy and repeatability.

A final section covers various approaches that can be used to integrate all these forms of navigation to generate a robust navigation solution.

The navigation systems of the future, which will undoubtedly be based on advances in traditional integrated inertial and satellite navigation systems, need to employ a range of other techniques to help provide an accurate navigation solution capable of operating in all environments.

Chapter 11 – FOR FURTHER READING

G. Schmidt, et al., *Low-Cost Navigation Sensors and Integration Technology,* NATO RTA Lecture Series SET-116, October 2008.

Special Issue on Bio-Navigation, Journal of the Institute of Navigation, Volume 55, Number 2, Summer 2008.

Orientation and Navigation in Birds, Humans, and Other Animals, Royal Institute of Navigation Conference Proceedings, University of Reading, UK, April 2008.

P. Groves, *Principles of GNSS, Inertial, and Multi-Sensor Integrated Navigation Systems,* Artech House, 2008.

Military Capabilities Enabled by Advances in Navigation Sensors, NATO RTO Symposium Proceedings MP-SET-104, Antalya, Turkey, October 2007.

M. Veth, and J. Raquet, *Fusion of Low-Cost Imaging and Inertial Sensors for Navigation,* NAVIGATION – Journal of the Institute of Navigation Vol. 54, No. 1, Spring 2007.

Basic Guide to Advanced Navigation (Principes de la navigation avancée), RTO Handbook Publication SET-054/RTG-30 February, 2004.

D. Titterton and T.L. Weston, *Strapdown Inertial Navigation Technology, 2nd Edition,* IEE, 2004.

D. Nistér, O. Naroditsky and J. Bergen, *Visual Odometry*, Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition, Vol. 1, 2004.

Emerging Military Capabilities Enabled by Advances in Navigation Sensors, NATO RTA Symposium Proceedings MP-093, Istanbul, Turkey, October 2002.

A. Lawrence, *Modern Inertial Technology-Navigation Guidance and Control,* Springer-Verlag, Second Edition, 1998.

NATO documents are available at http://www.rta.nato.int

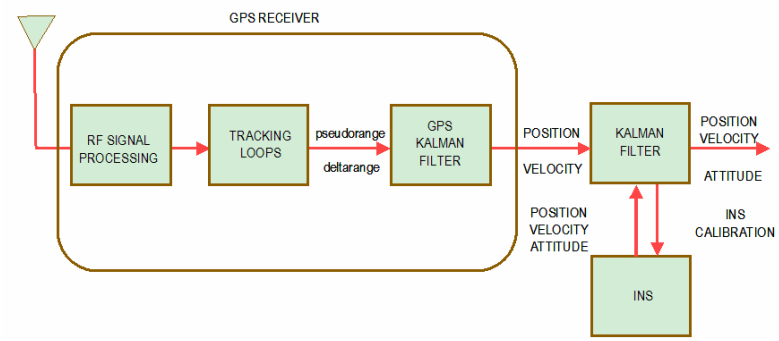
Annex A – INS/GPS KALMAN FILTER INTEGRATION

Kalman filtering is an algorithm that is used to integrate data from multiple navigation sensors. The Kalman filter will produce the optimal estimate of all the errors in the system given all available sensor data. In most cases the sensor errors are modelled as Gaussian sequences propagating through non-linear models, and a linearization step (based on taking the first derivative of the error model) is required. This linearized version is called an Extended Kalman Filter (EKF).

Three different architectures are in use today: *loosely coupled*, *tightly coupled*, and *deeply integrated* (or ultra-tightly coupled) systems.

A.1 LOOSELY COUPLED

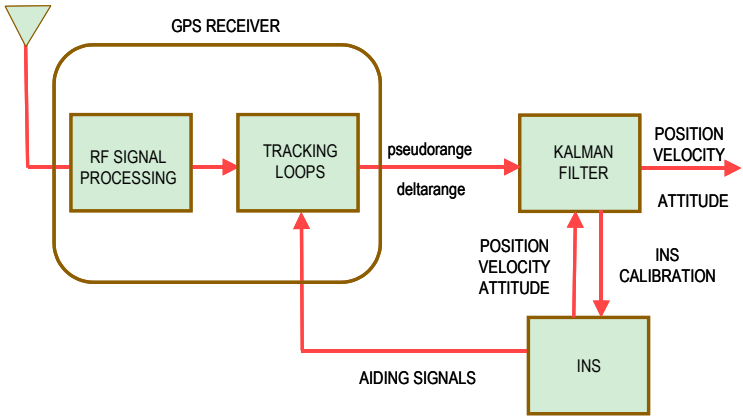
In this implementation, a GPS receiver and an inertial navigation system **independently** provide position and velocity data which are blended together in an external Kalman filter. The GPS receiver may or may not have an internal Kalman filter as well.



The Loosely Coupled Kalman Filter (Schmidt, 2008)

A.2 TIGHTLY COUPLED

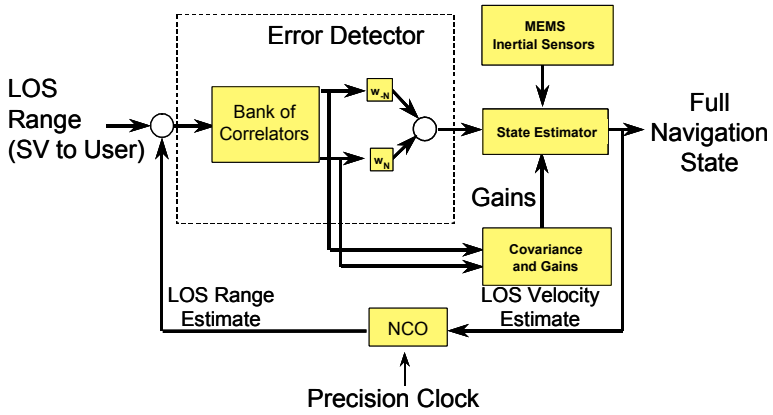
In a tightly coupled system, instead of providing a complete position fix by itself, the GPS receiver provides the raw ranges ("pseudorange" and "delta range") to each individual GPS satellite to the Kalman filter, to be incorporated directly into the navigation estimate with the raw measurements from the inertial system. The INS and GPS modules have been truncated. The GPS receiver now simply provides raw measurements. It does not have its own Kalman filter, but it does still have independent signal tracking loops.



The Tightly Coupled Kalman Filter (Schmidt, 2008)

A.3 DEEPLY INTEGRATED / ULTRA-TIGHTLY COUPLED

In the deeply integrated approach, the notion of separate GPS and INS systems is dropped. The problem is formulated directly as a global optimization in which the best solution is sought for each component of the multidimensional navigation state vector. The solutions that are obtained are not based on the usual notions of tracking loops and operational modes. Measurements from all available satellites (SV) are processed independently, and correlation among the line-of-sight (LOS) distances to all satellites in view is fully accounted for. This integration architecture allows simpler, smaller, cheaper hardware to be employed (at the expense of more complex software), and offers better performance, especially in jamming environments.



The Deeply Integrated Kalman Filter (Schmidt, 2008)

A.4 NOVEL INTEGRATION TECHNIQUES

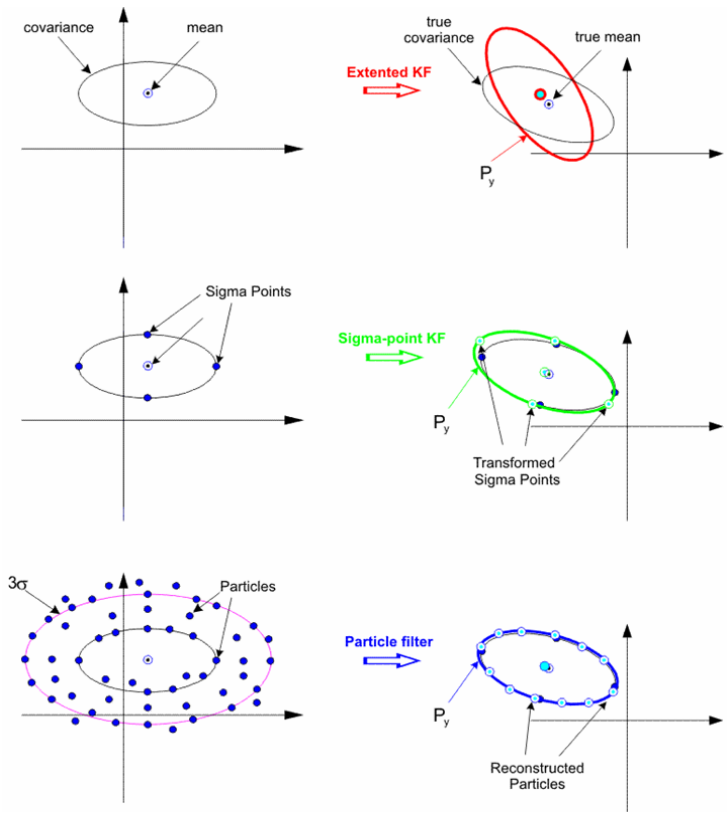
In recent years, there have been new extensions and alternatives to the classical Kalman filter derived for a number of applications and these are finding their way into integrated navigation systems. Three of those, unscented Kalman filters, particle filters and multiple model filters are briefly described here.

A.4.1 Sigma-Point (Unscented) Kalman Filter

The Sigma-Point Kalman Filter (SPKF), or sometimes called the Unscented Kalman Filter (UKF), is a variation of the Extended Kalman Filter for non-linear systems. Instead of the frequent and computationally intensive calculation of the linearization of the error propagation model, an unscented Kalman filter instead maintains the non-linear model and propagates a number of carefully selected data points of the assumed error distribution (called the sigma-points) through the non-linear model to more accurately map the probability distribution than the linearization used in the extended Kalman filter. The SPKF and the EKF have similar performance for systems with small non-linearities, but the SPKF can result in a significant performance improvement when the models are very non-linear.

A.4.2 Particle Filter

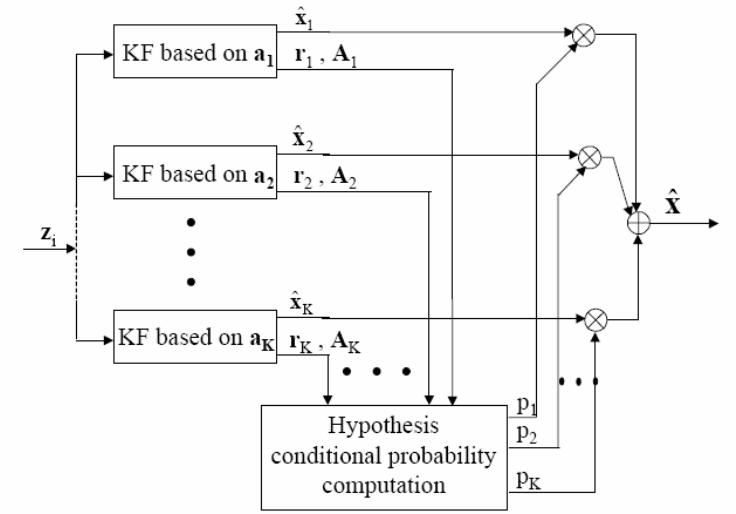
Particle filters approximate the propagation of non-Gaussian probability distributions through non-linear systems with many random samples, named particles. The particles in an integrated navigation system are samples of the state vector. The notion is to track the weighted sum of a number of particles as they evolve through the non-linear system. For practical implementations, a finite number of particles must be used and so there is ongoing research into determining the best choice of particle samples.



Sigma-Point Kalman Filters and Particle Filters.

A.4.3 MMAE – Multi-Model Adaptive Estimation

Multiple Model Adaptive Estimation is an extension of classical Kalman filtering, and in concept is relatively simple. Instead of a single Kalman filter and one set of sensor error models, one can design multiple Kalman filters that operate in parallel. Each filter is based on a slightly different set of error models that better reflect sensor behaviour under specific operating environments. For example, some sensors may have different error characteristics when moving quickly and when stationary, or there may be certain foreseen failure modes that alter the error characteristics significantly and predictably. A separate Kalman filter is designed for each set of models, and their outputs are combined (through a weighted addition, simple voting, or more complex adaptive methods) to derive the final output.



Multiple Kalman Filters, each based on a different set of assumptions, operate on the same sensor data in an MMAE algorithm – their outputs are weighted and combined by a top-level probability computation algorithm (P. Maybeck, US Air Force Institute of Technology)