GPS Navigation for Outdoor and Indoor Environments

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ABSTRACT

The Global Positioning System (GPS) is an accurate positioning system. The GPS has an accuracy that varies from 4mm up to 11m. This project in lieu of thesis investigates the state of art of the GPS navigation and positioning for outdoor and indoor environments with a particular focus to the outdoor applications. This project includes an overview of GPS system, the GPS segments, the composition of signals from the GPS satellites, and the structure of the GPS data. A comprehensive review of the factors influencing the GPS accuracy such as GPS error sources, and Geometric Dilution of Precision "GDOP" are discussed. The significant up-to-date techniques and methods used for enhancement of the GPS solution such as Differential GPS "DGPS", Carrier phase, Pseudolite, and Wide Area Differential GPS "WADGPS" are thoroughly described.

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1 INTRODUCTION

The Global Positioning System (GPS), originally developed for the military purposes, has demonstrated its benefits and is considered as a precious asset for civilian applications. This paper has been structured to provide the reader with the concept of understanding the different techniques used in GPS to perform navigation and positioning for outdoor and indoor environments.

The GPS is deemed as an outstanding navigational system due to the following: its capability to attain high positioning accuracy (ranging from tens of meters down to millimeters) and its signal availability to users anywhere on the globe (air, ground, and sea applications).

The GPS system architecture consists of three segments: the space segment, the user segment, and the control segment. The GPS technology is based on time of arrival TOA, which is the time interval for the signal to travel from the satellite to the receiver. The time of arrival can easily be converted to a range by multiplying TOA and the speed of light since the signal travels at the speed of light.

The history of development of GPS is recounted in [95] and [47]. A comprehensive treatment of the system, signals, performance, and applications can be found in [96], and [56]. A comprehensive overview of the development of autonomous enabled GPS navigation systems for outdoor vehicle appears in the research of [3], [29], [31], [46], [78], [88], [90], [91], [92], [93], [107], and [108]. Investigations into the use of indoor GPS navigation using different techniques have been performed by [42], [53], [97], [118], and [127].

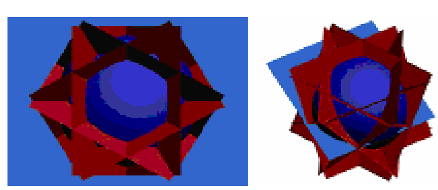
This paper is organized as follows: chapter 2 provides an overview of the GPS system. Chapter 3 provides a comprehensive review of the different up-to-date positioning methods used for enhancing the GPS solution. In chapter 4, factors influencing the GPS accuracy are discussed. In chapter 5, the indoor applications using the high sensitivity GPS receiver is confronted. Chapter 6 summarizes the paper and draws some general some general conclusion.

2 GLOBAL POSITIONING SYSTEM OVERVIEW

The NAVSTAR Global Positioning System (GPS), first launched in 1978, is designed by the U.S. Department of Defense, demonstrates many benefits for positioning requirements. The system is suitable for different type of applications and platforms. The GPS navigation is used everywhere on land, at sea and in the air able to provide service to an unlimited number of users. Many possible GPS receiver implementations are possible and can range from external sensor coupling to a navigation system. The idea behind an integration of GPS with a navigation system (INS, AHRS, or a Doppler Radar Navigation Systems (DRNS)) is the ability of the overall combined system to provide a solution by either GPS receiver, by the host navigation, or by the combination of the two. Thus, the integration avoids the limitations of each system in stand-alone mode.

The GPS is a satellite-based radionavigation system. The system consists of a constellation of at least 24 satellites in 6 orbital planes spaced by 60 degree see Figure 2.1 (4 satellites in each plane) and it is referred as the first segment or “the space segment” (having around 5 to 7 spares ones to improve the system availability). Each satellite orbits 11,000 nautical miles (20,200 kilometers) above Earth’s surface with an inclination angle of 55 degree relative to the equatorial plane in Figure 2.2. One complete orbit is approximately 11 hours and 58 minutes. Each satellite is equipped with an atomic clock and transmits continuous synchronized signals with other satellites to ground stations and receivers. The atomic clock keeps the time within three nanoseconds.

Therefore, these main functions of the satellites can be summarized to following: receive and store data transmitted by the control segment stations, preserve precise time using onboard atomic clocks, and broadcast data and signals to users on two L-band frequencies. The GPS second segment referred as the user segment consists of receivers. The main role and design of these receivers is to receive, decode, and process the GPS satellite ranging codes and navigational data messages.



A Top view B Prespective view

Figure 2.1: The top view (A) and perspective view (B) of the six GPS orbital planes inclined at 55 degree and spaced by 60 degree

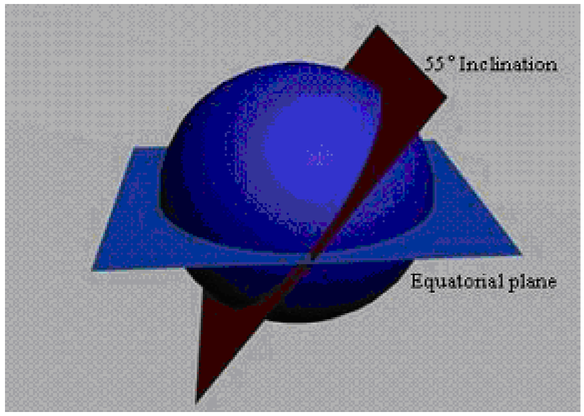


Figure 2.2: The inclination of the GPS orbital planes with the equatorial plane

The third segment referred as the control segment consists of six ground stations located around the world to ensure and monitor the good functioning of the GPS satellites see Figure 2.3. The master ground station located at Schriever Air Force Base in Colorado Springs runs the system as well as transmits corrections back to the satellites themselves. The corrections include the satellite's ephemeris constant and clock offsets.

The idea behind the GPS, as mentioned above, is based on time of arrival TOA, the time interval for the signal to travel from the satellite to the receiver, which then it is converted to a range since the signal travels at the speed of light. In other words the GPS uses satellites in space as reference points. This allow the measuring of the distance between the satellites, which know exactly their positions, and the receiver, which can compute its position, by using the time required for the pseudo-random "noise" bit sequence (PRN code) code to travel from the satellite to the user through an L-band carrier. This time is then transformed to a distance.

The computation of the receiver's position relies on the usage of at least four different pseudorange measurement equations to solve for four unknowns. The pseudorange measurement equation is based on the distance between the satellites and the receiver. The visualization of this concept can be described in the following: with one satellite's distance we can define that the possible receiver's locations lie on the surface of a sphere and that the sphere has the satellite as its center, the second satellite allows the position of the receiver to narrow down to a circle, which is the product of the intersection of the two spheres, then a third distance gives a two-point receiver's position, finally the forth sphere leads to a unique point receiver's position as a product of four spheres intersections centered each on one satellite.

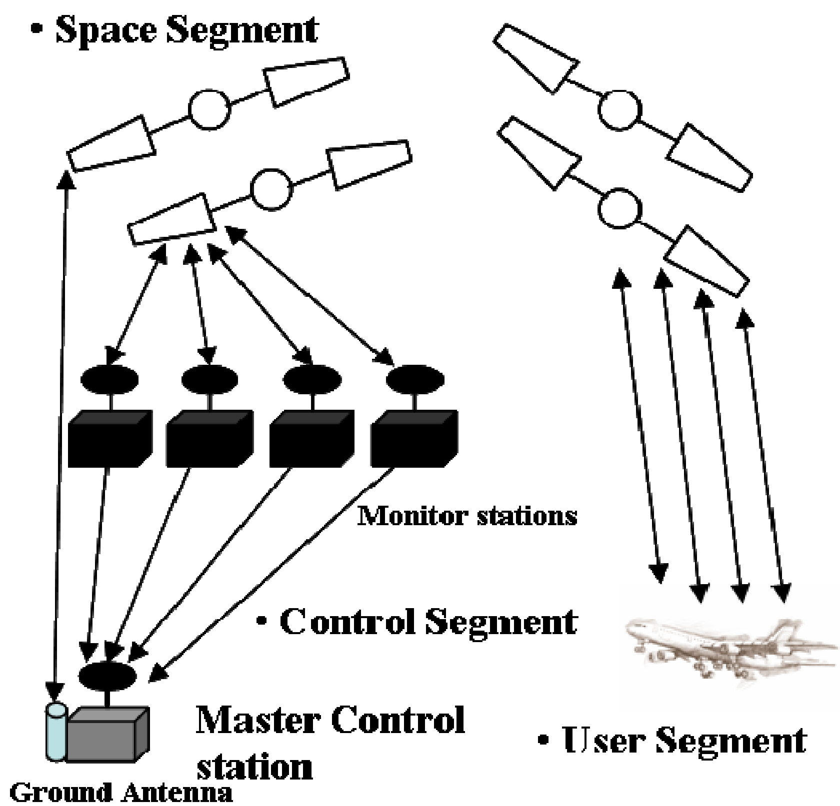


Figure 2.3: The GPS system comprises a control, space, and user segments

The ideal pseudorange for each satellite j, ρ_j is calculated using the following equation:

$$\rho_j = c\left(t_{AU,j} - t_{TS,j}\right)$$

where,
c is the speed of light
$t_{AU,j}$ is the true time of the signal arrival at the user
$t_{TS,j}$ is the true time of the signal transmission from the satellite

The GPS signal consists of three components: carrier wave, ranging codes, and navigation message. see Figure 2.4 The two microwave L-band carrier signals are generated by multiplying the fundamental frequency f_0 (10.23MHz) by 154 and 120. Therefore the frequency of the two waves L1 and L2 are centered at $f_1 = f_0 \cdot 154 = 1575.42MHz$ (wavelength 19.05 cm) and $f_2 = f_0 \cdot 120 = 1227.60MHz$ (wavelength 19.05 cm) respectively. In the global positioning system, the L-band carrier waves are modulated by two codes: the coarse/acquisition or clear/access pseudorandom noise (PRN) code (C/A-code) on L1 carrier phase, the precision or private code (P(Y)-code) on both L1 and L2, and a navigation message.

The carrier waves use the Bi-phase Shift Key Modulation (BPSK) technique to combine the signal components. This BPSK modulation method consists of adding a binary signal to a sine wave carrier, which causes a 180° phase shift in the carrier each time the binary sequence undergoes a transition from "0" to "1", or "1" to "0". The P code plus navigation message is modulated on both the L1 and L2 carriers, while the C/A code plus navigation message is only modulated on the L1 carrier. The ranging codes are composed from a sequence of binary numbers (zeros and ones). Each one of them (zero or one) is called a “chip” instead of the most common used name a “bit” because no data is carried by the signal, and it is characterized by its permanent pattern and length which is repeated indefinitely.

A distinct C/A PRN code is assigned to each GPS satellite and selected from a set of Gold codes [48]. The Gold codes are designed to minimize the cross-correlation, therefore enhancing the receiver recognition of one code for another. The unique PRN associated with each satellite are uncorrelated with respect to each other. This property allows all satellites to broadcast at the same frequency without any time-sharing. This modulation technique is called code division multiple access (CDMA) and used for separating and detecting the GPS signals [61].

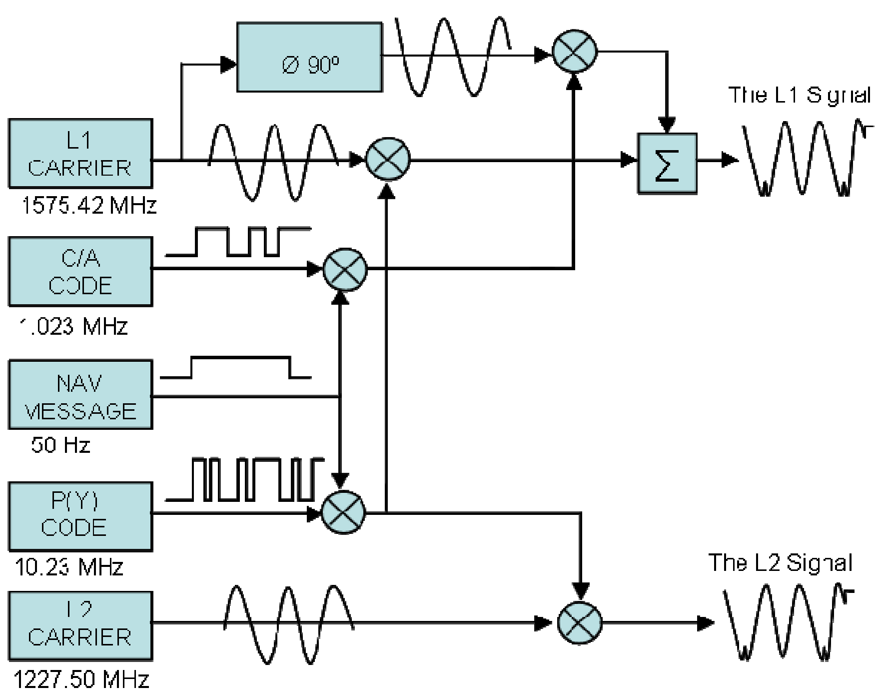


Figure 2.4: Composition of the signals from GPS satellites system adopted from [96]

Both C/A and the P codes are pseudo random noise (PRN) codes and have the characteristics of a random noise. However, they are not random codes, and they are generated by well defined algorithms. These codes are based on a simple Tapped Feedback Shift Register [96]. The length of the C/A code is 1023 chips and it is broadcasted at 1.023 MHz, therefore the C/A code is repeated every each millisecond. Taking into account the speed of light, the length of one ship can be computed to be 293 meters, and the whole C/A code sequence is about 300 km long. The length of the C/A-code is designed to be short hence enabling a receiver to rapidly acquire satellite signals, which helps the receiver transition to the longer P code. The length of the P code is $2.3547.10^{14}$ chip and it is broadcasted at 10.23 MHz, however it would repeat only after 266.4 days, but for practicality of the system only 7 days are being used. The P code is divided into 37 parts (one is designated for each satellite) and the code is restarted every week. The P code has a chip length of 29.3 meters.

The navigational message is a 50 Hz signal and contains satellite orbits data, clock corrections data, and other system information. The data signal consists of 37500 bits with a transmission rate of 50 bit/s which add up to the total time of 12.5 minutes. The 12.5 minutes is considered to be the minimum time required by the GPS receiver to acquire its first position (if no data about the satellites is stored in the receiver) and its complete signal arrival. The data signal is divided into 25 frames. Each frame has a length of 1500 bit (50 bit/s gives a 30 seconds transmission time), and divided into five sub-frame with a 300 bit (6 seconds). Then, each sub-frame is also divided into 10 words (30 bit, 0.6 s) see Figure 2.5. The first word of each sub-frame is the telemetry word noted “TLM”, which contains data about the age of the ephemeris data. The second word is the hand over word noted “HOW”, which contains the time since the last restart of the GPS receiver, therefore it gives the military receivers the ability to access the P-code (transition from the C/A code to P(Y) code tracking). The rest of the words in the first sub-frame contain the status and the accuracy of the transmitting satellite as well as clock correction data. The second and the third sub-frames contain ephemeris parameters. The sub-frames 4 and 5 contain the so-called almanac data which carries information about orbit parameters of all satellites see Figure 2.5. The first three sub-frames are the same for all 25 frames and are the most important information to determine the position. The data signal carries a correction parameter for satellite clocks. Since each satellite has several atomic clocks, the non-synchronization with GPS reference time which makes the correction data for the clocks of each satellite is required. The GPS receiver therefore is able to generate a local replica of the same code sequence. These PRN codes have the attribute to fully correlate with an exact replica of itself only when the two codes are aligned. This correlation can be done with a good correlator implemented in the receiver. A good correlator reaches an accuracy of one percent of the chip length.

There are two main types of measurements that can be made on the GPS signals. The first method is the range based on the PRN codes, referred to as "code range" or "code phase". The use of this method can be used for either the P code or C/A code. However, the accuracy of the P code is around 0.3 meters, and it possesses a better accuracy ten times than that of the C/A code, which is around 3 meters. On the other hand the use of the second method, the carrier phase, is more precise than the range-method measurement; however it has a higher degree of "ambiguity". The carrier phase method has an accuracy of 1% of the wavelength of the carrier. As mentioned earlier the L1 has a wavelength of about 19 cm, and L2 has a wavelength of 24 cm. Therefore, the expected accuracy value for both carriers is 2mm

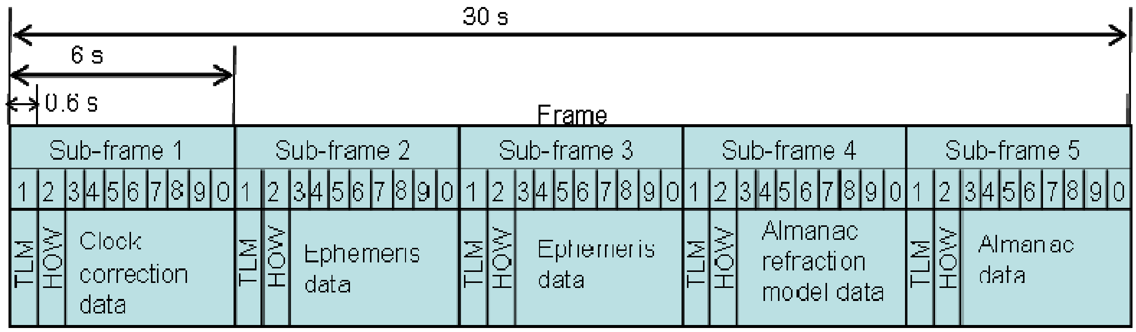


Figure 2.5: Structure of the GPS data of one frame (12.5 minutes before the entire message repeats) adopted from [96]

The correlator checks the received signal for a match against all of the possible PRN codes, generated by the GPS receiver. The matching will only occur if both, the received and the generated signals, are lined up exactly. The matching is not obvious due to the time delay between the broadcast and reception. After a match is made, the GPS receiver recognizes which PRN code, therefore identifies the satellite. The correlation is done in very simple method using a comparison of the received code signal with the locally generated code, and it is done chip by chip. The method counts one match (+1) if both chips are the same (zero or one), and it counts one non-match (-1) if the chips are different. A correlation of +1 is a perfect match for the 1023 out of 1023 chips for the C/A code.

The contact availability between the satellites and the receiver plays a fundamental role in the position determination. The contact availability between the satellites and the receiver generates the following three starts:

- The hot start occurs when the receiver is turned on and located around the same area within 6 hours after its last position determination with up to date almanac and ephemeris data. The hot start takes up to 15 seconds for the first position determination.
- The warm start occurs when the almanac data is available; however the ephemeris data is outdated for more than 6 hours from the last data reception from the satellites in view. The warm start takes up to 45 seconds and can take longer if more new satellites come into view.
- The cold start occurs when the receiver has been switched off for several weeks and stored with no batteries or has traveled more than a couple hundred of kilometers since the last position fix. The cold start takes up to 12.5 minutes.

Figure 2.6 summarizes the steps about the operation of a GPS receiver.

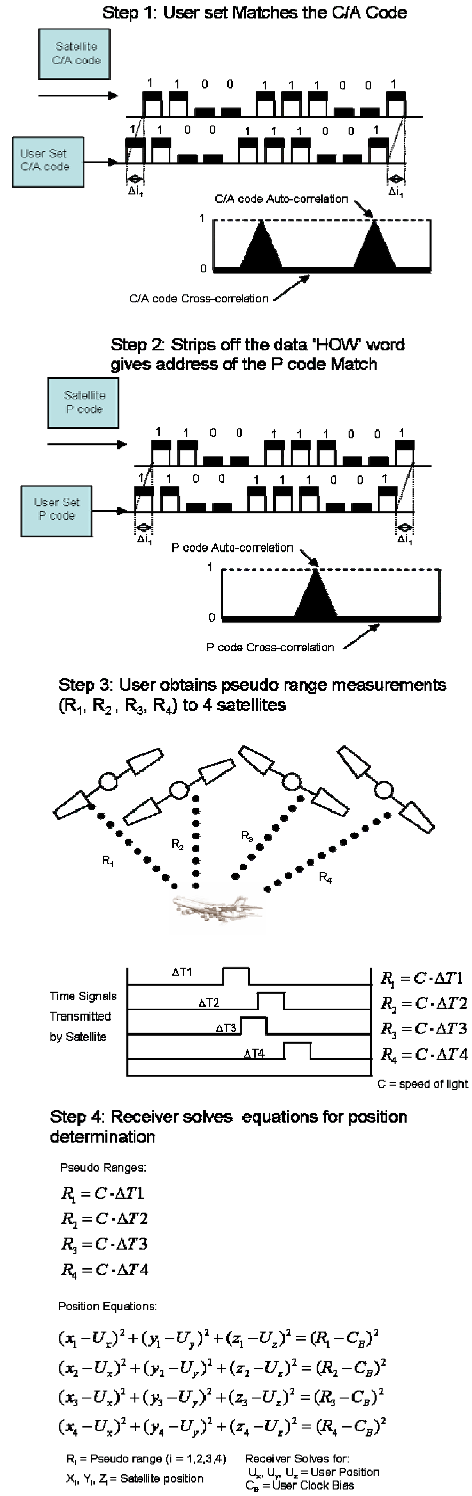


Figure 2.6: GPS Receiver Theory of operation adopted from [135]

3 GPS POSITIONING METHODS

3.1 Differential GPS

One technique that overcomes many GPS' biases is the Differential GPS "DGPS", which enhances the receiver position's accuracy. The DGPS necessitates two receivers: one is called the base station (with a known location) and the second one is called the rover receiver (with an unknown location) see Figure 3.1. The key principle behind the DGPS is the role of the base station, which ensures a solid local reference point after securing all satellites' measurements. The assumption is that the two receivers are close to each other within a few hundred of kilometers. Therefore the signal, which attains both of them, is assumed that it has traveled the same portion of the atmosphere and therefore has encountered almost the same errors.

There are two possible DGPS implementations:

(a) The first differential GPS implementation can be satisfied by making continuous corrections to the coordinates, then broadcasting them from the base station to the rover receiver. This method is considered the easiest to implement, however it has some severe limitations:

- The base receiver is located at a known position
- The corrections ΔX, ΔY, and ΔZ are computed after comparing the known and instantaneous receiver's position.
- The corrections are broadcasted to the rover receiver(s) for instant corrections of the coordinates.

Emphasizing the fact that both the rover and base receivers need to use the identical satellite constellation to create their position solutions, otherwise large errors can occur. This fact is considered momentous limitation for this implementation, and occurs when the receivers are far away from each other, or when the rover receiver is functioning in an urban environment where the same satellite constellation is not visible simultaneously for all receivers.

(b) The second differential GPS implementation is based on correcting the ranges before the computation of the receiver's positions. The implementation steps of this method are similar to the first one:

- The base receiver is located at known position.
- The true range is computed based on the known position.

- The pseudo-range corrections data are calculated by comparing true range versus the observed one.
- The correction data is broadcasted to the rover receiver which makes the correction of ranges prior to generate the position's solution.

The second technique is advantageous since the correction is done to the pseudo-ranges, and therefore the rover GPS receiver can select the best combination of corrected ranges to obtain a solution, and not just the need to use the same satellite constellation used at the base station.

There are several DGPS scenarios possible:
The DGPS technology may be implemented in real-time or post-processed mode. The second DGPS method based on the range corrections is more suitable for real-time applications since only the set of corrections for all visible satellites need to be transmitted. The work done by [36] presents in details two algorithms for DGPS reference station design. The DGPS is in support of autonomous navigation and vehicle tracking applications. The autonomous navigation is known for providing a precise GPS position to the rover and for its own usage. The vehicle tracking application is known for monitoring the rover receiver's position at central station.

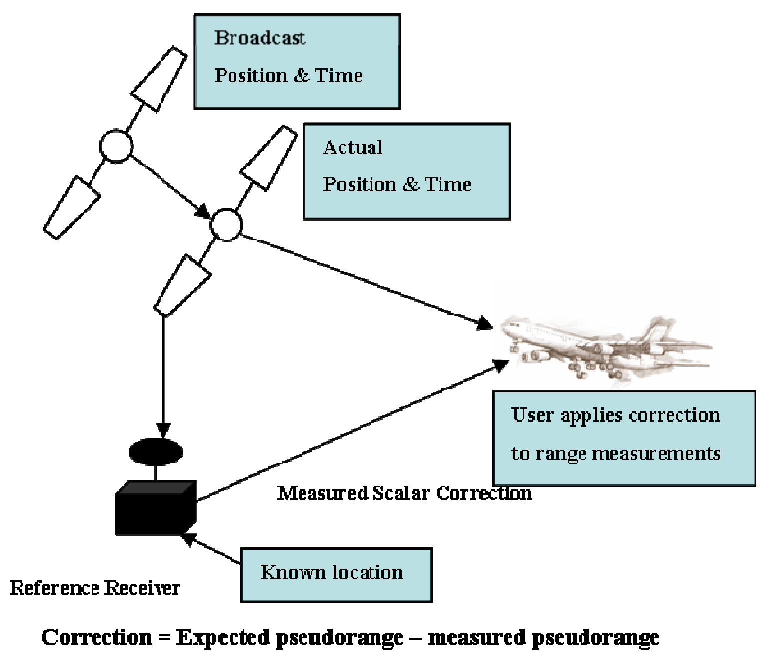


Figure 3.1: Local area differential GPS. The reference receiver calibrates the correlated errors in ranging to the satellites. These filtered errors are then transmitted to the user as range corrections

3.2 Pseudolites

The Pseudolites (PLs) consist of ground stations that transmit GPS-like signals. This technique can initialize carrier-phase differential GPS (CDGPS) in seconds to accomplish real-time positioning with an accuracy as low as 1 cm. Synchronized pseudolites are called synchrolites, which have the ability to derive their timing from the GPS satellites. A well studied set of synchrolites is able to start CDGPS navigation even with the presence of only one GPS satellite signal [96]. The system, developed in Stanford University and composed of pseudolites and synchrolites, is called Integrity Beacon Landing System (IBLS), which can provide a backup for GPS satellites allowing the navigation even if the satellite constellation fails. The major role of IBLS system is to give enough accurate and reliable data for an airplane to land and navigate in bad weather [96]. An ordinary DGPS can't provide enough accuracy to allow airplane landing in bad weather only if additional GPS transmitters are placed in the vicinity of the airport hence using CDGPS, which allows navigation with only few centimeters as error.

3.3 Wide area differential GPS

The wide area differential GPS (WADGPS) is a technique, which gives a correction error vector for each GPS satellite. Whereas in the DGPS technique, a scalar range error correction is calculated. The architecture of the WADGPS network is composed with at least one master station, many monitor stations, and communication links where the monitor stations are equipped with a first-class clock and a first-class GPS receiver having the capability of tracking all available satellites. All the monitor stations measurements are then sent to the master station which calculates the GPS error and transmitted to the users via a communication link see Figure 3.2. The accuracy of WADGPS method is approximately constant in the observed area [96].

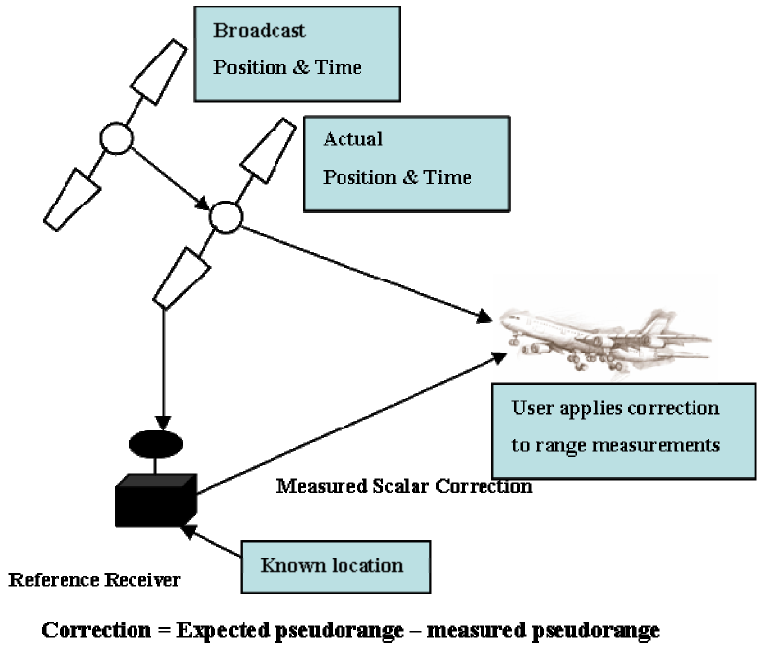


Figure 3.2: Wide area differential GPS concept

3.4 Wide area augmentation system

The wide area augmentation system (WAAS) system is developed by the Federal Aviation Administration (FFA) and the Department of Transportation for use in precision flight approaches. The WAAS has around 25 ground reference stations located across the US which monitor the data from the GPS satellite and two master stations. The WAAS technique fixes the GPS signal errors caused by ionospheric disturbances, timing, and satellite orbit errors. The accurate differential data is then transmitted through one or two geostationary satellites. The WAAS does not necessitate further receiving equipment and offers extensive coverage both inland and offshore, while DGPS is land-based and does require additional equipments.

3.5 Carrier-phase GPS

The carrier phase differential GPS (CDGPS) is one of the highest precision levels for relative real-time positioning techniques and applications. The high precision is due to the low level of noise on these measurements. The CDGPS has many different positioning algorithms where the basics are very similar. The heart of this technique is the ability of using the raw GPS L-Band carrier signals for positioning rather than using the pseudo range measurements. The CDGPS technique has accuracy of fractions of centimeters once the integer number of wavelengths between the vehicles and reference station has been determined.

Carrier phase measurements are used in two ways:

- With the pseudo-range: the measurements can smooth the high noise pseudo-range observations before their usage in the computation of the positions.
- On their own: the measurements are able to accommodate static surveying applications as well as dynamic applications with centimeter level accuracy.

Carrier phase-based positioning has the ability to either remove, or drastically condense, the basic measurement biases based on observations made by ground receivers to the constellation of visible GPS satellites. The receiver dependent biases (principally the receiver clock bias) are eliminated when GPS observations made by a receiver to several satellites are differenced. Further, the satellite dependent biases are eliminated (or considerably diminished) when a number of GPS observations are made by several receivers simultaneously to the same satellite. Therefore at any epoch of measurement, the differencing of pseudo-range observations made simultaneously by a pair of receivers, to a pair of satellites yields to the double-difference observable technique used in [52]. Consequently, the combination of four pseudo-range measurements can create a new "observable", with a noise level that is double that of a single one-way pseudo-range measurement.

The same procedure can be applied to carrier phase measurements that yields to a similar relation in addition of a new double-differenced ambiguity term, which is an integer.
The use of double difference carrier phase is problematic since any data processing method must guarantee the estimation of two classes of parameters:

- The baseline parameters (contained within the geometric range term)
- The ambiguity parameter (for each pair of independent satellites).

Many of the following comments may be made with regard to the processing of carrier phase data:

- When collecting a sufficient epochs of data (up to one hour or more) which ensures the separability of the position and ambiguity parameters within a Least Squares adjustment scheme, the problematic issue of processing ambiguous carrier phase data is overcame. This technique is used in static GPS surveying applications, and gives reliable and accurate determination of both sets of parameters.

In effect the ambiguous double-differenced phase observable is converted to the unambiguous double-differenced pseudo-range observable and the position estimation problem becomes one involving very precise range observables. The process of estimating ambiguity parameters, and then selecting the best fit integer values, is called ambiguity resolution, and its consistency is a function of the followings:

- The distance between the baseline and the receiver should be in the range of no more than 20 km.
- The number of visible satellites is crutial, the more satellites are visible the better the estimation is.
- The satellite-receiver geometry (Dilution of precision “DOP” explained in the next section.
- The observations made on both frequencies (dual-frequency L1 and L2, not just on one frequency) can reduce the determination of the ambiguities parameters.
- The period of the observation session, the longer the observation the better is the estimation.
- The ambiguity resolution is a process which can be applied not only to the static GPS carrier phase, but also to dynamic applications called on-the-fly.

Ambiguity resolution is therefore the process, by which a precise, but ambiguous, carrier phase observation is converted to an unambiguous range quantity, having all the advantages of a pseudo-range observation but with much lower measurement noise.
Techniques for achieving this have been progressively refined. The ambiguity resolution procedure consists of several stages:

(1) Definition of the apriori values of the ambiguity parameters.
(2) Operation of a search algorithm to identify likely integer values.
(3) Implementation of a decision-making algorithm to select the best set of integer values.
(4) Application of the ambiguities to the data to create unambiguous range measurements.

Ideally the first three steps can occur transparently to the user, with minor delay and with high reliability. Several techniques have been developed to address steps (2) and (3), including:

- The Fast Ambiguity Resolution Approach (FARA).
- The Cholesky Decomposition based search technique.
- Spectral Decomposition based search technique.
- The Least Squares Ambiguity Search Technique.
- The Fast Ambiguity Search Filter (FASF) technique.
- The Least-squares AMBiguity Decorrelation Adjustment (LAMBDA) technique.
- The Ambiguity Function Method.
- Direct estimation from a combination of phase and pseudo-range data.

There are an increasing number of applications for high precision carrier-phase based positioning, for vehicle tracking, control, and vehicle guidance. The real time carrier phase-based positioning is applicable when an appropriate communications link is provided over which the carrier phase data collected at a static base receiver can be made available to the rover receiver's onboard computer; to generate the double-differences, resolve the ambiguities, and perform the position calculations. Even though, the availability of such systems is broad, the system compatibility is not always available since the producers use different and proprietarily formats of transmitted carrier phase data, and hence it is not generally possible for a brand type "X" base receiver to communicate to a brand type "Y" rover receiver. A broadcast carrier phase service is being offered in the U.S. and parts of Europe and Asia, based on a message format that is compatible with a number of GPS receivers. On the other hand, in the case of pseudorange corrections, an industry standard transmission format is available. Table 3.1 summarizes the different achievable accuracy for the different differential GPS methods

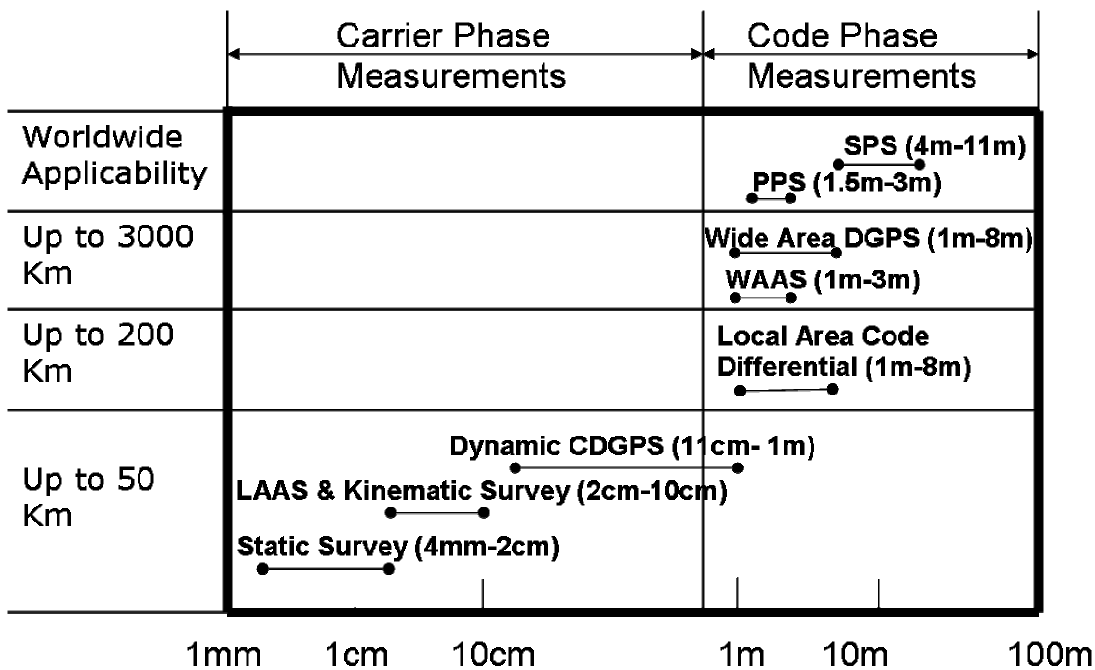


Table 3.1: Summary of expected differential GPS concepts, GPS-augmented, and accuracies

4 FACTORS INFLUENCING GPS ACCURACY

Error sources can be categorized into the following three major types: satellite errors, atmospheric errors, and receiver and antenna errors. The satellite errors are normally due to error in orbital modeling of the satellites and to satellite clock errors. The atmospheric errors are due to the residual Tropospheric and Ionospheric delays. The receiver and antenna errors are due to noise, receiver clock, interference and multipath errors see Figure 4.1.

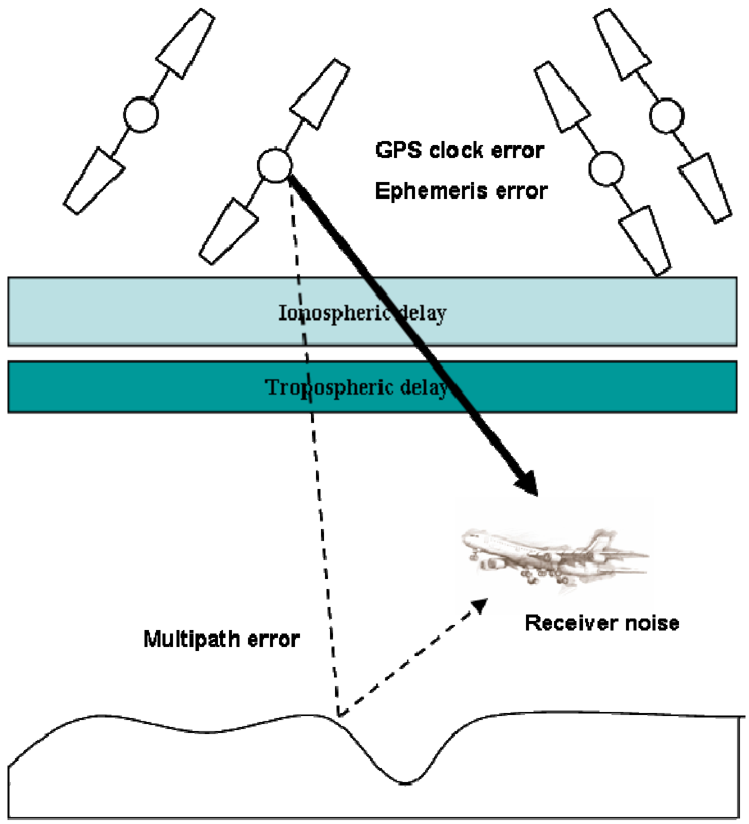


Figure 4.1: Error sources in GPS measurements

4.1 Orbital errors

Orbital errors are caused by errors in the broadcast ephemeris and usually vary from 2 to 10 m [96]. The orbital errors are spatially correlated for two receivers at the same time tracking the same satellite and can be reduced by single differencing measurements between the receivers. Precise orbits can be used in post-mission data analysis and to a limited extent in ultra-rapid real time operation to reduce orbital error effects.

4.2 Satellite clock bias

The satellite clocks data are incorporated in the broadcast navigation message. The modification is normally less than 1 ms and the broadcast of 29 corrections has a distinct accuracy range of 5 to 10 ns or evenly around 1.5 to 3 m in units of length [96]. As the satellite clock error is general to all the receivers concurrently tracking the same satellite, the effect can be removed by single differencing measurements between receivers.

4.3 Atmospheric delay

- **Tropospheric Effects**

For GPS purposes, the troposphere can be defined as the region of the atmosphere extending from the Earth's surface to approximately 50 km in altitude. The troposphere is non-dispersive at GPS frequencies. Its contribution to GPS signal degradation is small in terms of attenuation and signal delay. The tropospheric attenuation of the GPS signal varies with the elevation angle of the satellite. Attenuation ranges from 0.4 dB at the horizon to typically 0.04 dB at the zenith. The attenuation effect is due to oxygen attenuation while effects due to water vapor, rainfall, and nitrogen are negligible at GPS frequencies [96]. As the GPS signal is refracted as it travels through the atmosphere, the received signal is delayed.

The troposphere can be divided into two components as far as the delay is concerned. These are the dry and wet components. The dry component accounts for the majority (about 80-90%) of the delay effect and can be easily modeled. The dry effect corresponds to a delay of typically 2.3 m at the zenith and varies by less 32 than 1% over a few hours. On the other hand, the wet component varies by 10-20% over the same period. The magnitude of this delay is relatively smaller, namely 1-80 cm at the zenith. Lower elevation satellite signals have a much larger delay as the tropospheric path length increases. The delay terms for the wet and dry components can increase by up to a factor of ten as the elevation angle decreases. In general, for any satellite signal the tropospheric delay ranges from 2 to 25 m.

The tropospheric models can typically correct for about 90% of the delay. There are several models that estimate the tropospheric error [109] proposed a constant lapse rate model for troposphere that estimates the delay as a function of elevation. [58] developed separate zenith models for the dry and wet components of the troposphere. This was further extended by [11] to include an elevation angle mapping function. The tropospheric delay should be corrected by about 80-90% through modeling in any single point GPS receiver. In differential GPS, the spatial correlation of the delay between stations is very high and allows for the majority of the effect of the delay to be corrected by differencing.

- **Ionospheric Errors**

The ionosphere is a gigantic source of range error for GPS. This region of the atmosphere theoretically extends from 50 to 1000 km above the Earth, and encloses electrons freed by ionizing radiation from the sun. The free electrons disturb the propagation of RF signals including GPS signals.

The Ionospheric induced delay can vary from only a few meters at the zenith to many tens of meters at the horizon [96]. The ionosphere is a dispersive medium; that is, the refractive index of the ionosphere is a function of the frequency. Therefore, dual frequency GPS users can make use of this property to measure and correct for range and range-rate error effects. Single frequency GPS users rely upon a set of broadcast ionospheric correction coefficients included in the GPS navigation message. As the ionospheric error is spatially correlated, it can be significantly reduced by single differencing between receiver measurements or equivalently by corrections from a nearby reference station.

Other Ionospheric effects consist of Faraday rotation and scintillation. Faraday rotation on electromagnetic signals triggers a linearly polarized signal to endure supplementary rotation along the plane of its polarization. Since GPS signals are circularly polarized, Faraday rotation has no consequence on GPS signals [96]. Ionospheric scintillation is affected by electron density abnormalities in the ionosphere [96]. Scintillation is a rapid variation in the amplitude and/or phase of an RF signal. These variations concur with to high levels of solar and geomagnetic activities. The existence of these irregularities can cause GPS signals to experience phase and amplitude scintillation effects. Receiver carrier tracking bandwidth is usually not designed to accommodate such fast frequency variations and this may result in loss of lock. The frequency of occurrence of such events varies with location and levels of solar activity [96].

4.4 Pseudorange error model

Noise on the pseudorange and doppler measurements increases as signal power decreases. This is due to increasing thermal noise jitter in the carrier and the code tracking loops. Measurement noise depends on correlation bandwidth, code tracking loop bandwidth, carrier tracking loop bandwidth, and type of correlation method. The noise power depends directly on bandwidth of the coherent signal integration. Doppler measurement noise depends on the thermal noise of the carrier tracking loop and thus depends on the correlation bandwidth. 38 Pseudorange measurement noise depends on the bandwidth of the delay lock loop used in code tracking. It should be noted that this bandwidth can be greatly reduced by a carrier-aided DLL [130]. In addition, pseudorange measurement noise depends on the correlation spacing and associated pre-correlation bandwidth. In other words, utilizing narrow correlation techniques significantly reduces Pseudorange measurement noise.

4.5 Receiver noise

The L1 C/A codes are pseudorandom noise codes (PRN codes). In general, noise correlated with noise results only in noise. Thus, as these codes are designed to be noise-like, their mutual interference after the correlation process should be minimal. However, the autocorrelation and cross-correlation properties for the C/A code are not ideal. The C/A codes have the following problems in terms of correlation properties:

- There are small autocorrelation peaks in the periods between maximum autocorrelation peaks [130].
- C/A-codes have line spectra as a result of a repeating 1 ms long code sequence, and this is responsible for vulnerability to continuous wave (CW) interference [130]. A narrow bandwidth coherent carrier tone signal, when overlaying a strong C/A-code spectral line, will correlate with the C/A-code and 39 may cause distortion of the correlation peak, lead to tracking of a false peak, or result in loss of tracking entirely.

Since a C/A-code is only 1023 chips long, it has undesirable cross-correlation characteristics even amongst the 32 C/A-code Gold codes chosen for GPS usage. Of the possible C/A-codes that can be generated, the Gold codes have the more desirable cross-correlation properties. The cross-correlation functions have peak levels that reach -24 dB with respect to the autocorrelation peak [130]. This is known to result in tracking of false correlation peaks at certain Doppler offsets and signal strength differences between signals [130]. These C/A-code properties can be especially problematic during search and acquisition mode operations. Acquisition of a false correlation peak is due to cross-correlation signals or possible CW jamming leads to large measurement error.

4.6 Multipath

Multipath is one of the larger error sources in both single point and differential GPS. Multipath is the error caused by reflected signals entering the RF front end and mixing with the direct signal. These effects tend to be more pronounced in static receivers close to large reflectors. Reflectors of electromagnetic signals could be buildings, metal surfaces, water bodies, the ground, etc. Multipath errors are also specific to a receiver's antenna as each antenna has a different gain pattern.

Multipath effects on a Pseudo Random Noise (PRN) ranging receiver were studied by [128] and [13]. Multipath was experienced by several researchers including [35] and [71] in marine DGPS experiments, and [22] in static and dynamic land experiments. [123] observed multipath occurring at various locations, such as rock embankments, high-tension overhead wires, highway overhead wires, saltwater/freshwater horizon etc. Notably, [45] detected carrier phase multipath using dual frequency receivers. Similarly, there have been numerous publications [16], [17], [59], [62], [72], and [87] on multipath experiences in various situations. Significant work has been done to reduce the multipath effects using various methods, which can be broadly classified as:

- Antenna-based mitigation
- Improved receiver technology
- Signal and data processing

Antenna-based mitigation involves improving the antenna gain pattern to counter the effects of multipath. This method includes the use of special antennas, spatial processing with multi-antenna arrays, antenna location strategies and long-term signal observation to infer multipath parameters, facilitated by the changing reflection geometry. A choke ring with a RF absorbing ground plane has been found to be quite effective in this regard [35], [71], and [123]. By designing an antenna with very low gain for left hand circularly polarized (LHCP) signals, and using an antenna array to have a sharp cutoff below a certain elevation angle, significant improvements can be achieved [7], and [27]. However, most of these methods are costly, and have the disadvantage of large size and weight. Most importantly, they can not effectively mitigate multipath signals arriving from above the horizontal [131].

A comprehensive overview of receiver technologies to mitigate multipath appears in the research of [126]. Narrow CorrelatorTM ([37], [125]) has 0.1 chip spacing and a larger bandwidth at the IF and provides good long delay multipath mitigation. The Multipath

Elimination Technique (METTM), is an improvement of Narrow CorrelatorTM with respect to multipath mitigation [120]. It estimates the slope of the two sides of the autocorrelation peak as well as the amplitude, thus estimating for two lines that intersect at the peak, irrespective of the slope. Multipath Estimation Delay Lock Loop (MEDLLTM), utilizes multiple narrow-spaced correlators to estimate multipath and remove it from the correlation function to provide a more pure signal correlation function [129]. MEDLLTM was further extended by [121] for carrier phase multipath mitigation. [86] described various methods to mitigate multipath effects by using the Multiple Signal Classification (MUSIC) technique with multiple antennas and an extended MEDLLTM. The Edge CorrelatorTM technique [40] shows slightly better performance than the narrow correlator for long delay multipath. The Strobe CorrelatorTM and Enhanced Strobe CorrelatorTM [41] use the slope of multiple narrow correlators and show very good long delay multipath mitigation performance. However, in a strong and fast-changing multipath environment, they do not completely eliminate the effects. [116] describe a multipath mitigation correlator-based technique called ClearTrackTM, which has a maximum code multipath error equal to one quarter of the maximum error in Narrow CorrelatorTM. These techniques, however, are not very effective for slow multipath, due to close-by reflectors. Also, one of the major problems with using receiver related techniques to mitigate multipath, is that many of the users do 5 not have access to the receiver hardware, and none of these techniques can be directly used with all kinds of existing receivers. Several researchers have devised methods to counter multipath effects using measurement data and other information generated by the receiver. Code multipath can be reduced to a great extent by smoothing the pseudorange with the carrier phase ([22], [54], [72]). Another method developed by [45], uses L1-L2 measurements to estimate the carrier phase multipath error using the relationship between the frequency of the carrier phase multipath error and the carrier wavelength. [111] used state variable models for the estimation of multipath in differential GPS ground stations.

[5] and [25] have used a Signal-to-Noise-Ratio (SNR) based technique to correct the multipath error in differential phase measurements. This technique is effective mainly when dealing with short delay or slow multipath. High frequency multipath is still a problem with this technique. Moreover, this technique requires the knowledge of the antenna gain pattern. SNR measurements are further utilized by [106] to identify an effective reflector, and to generate carrier phase multipath correction profiles. The day-to-day repeatability of multipath along with SNR measurements are used by [114]. The geometrical aspects of reflection in combination with a special arrangement of GPS antennas are exploited [8] to detect and track multipath in a simulated multipath environment. [99] investigated the use of multiple reference stations in order to estimate both code and carrier multipath. [19] used adaptive filters and multiple DGPS receivers to remove multipath and other errors in kinematic positioning. Code multipath is calibrated and estimated using spherical harmonics in static applications by [30], [62] proposes spectral decomposition based multipath mitigation technique, which combines carrier smoothing, carrier SNR and repeatability.

Noise source	Error
Receiver Clock Error	1 m
Ephemeris data errors	1 m
Tropospheric (atmospheric water vapor) signal refraction	1 m
Ionospheric (atmospheric electron content) signal refraction	10 m
Multipath	10 m

Table 4.1: Factors influencing GPS accuracy

4.7 Geometric dilution of precision

The derivation of the Satellite-receiver geometry is derived from a basic 4-D estimation problem which has a unique solution (four independent measurements, and four unknown quantities), however, when the number of measurements is greater than four, the method of Least Squares can be applied to obtain the optimal solution.

This optimal solution can provide not only the values of the parameters, but also can provide the variance-covariance matrix which contains the standard deviations of the estimated parameters.

The main steps to a Least Squares computation technique are outlined below [132]:

- **Set up the solution:**

Compute the elements of the design matrix A which contains the partial derivatives of the range observations with respect to the parameters x, y, z, and t:

$$\frac{\partial\rho}{\partial x} = -\frac{x^S - x}{\rho}$$
$$\frac{\partial\rho}{\partial y} = -\frac{y^S - y}{\rho}$$
$$\frac{\partial\rho}{\partial z} = -\frac{z^S - z}{\rho}$$
$$\frac{\partial\rho}{\partial t} = 1$$

- **Define approximate, or apriori, values of the parameters:**

The coordinate parameter $\dot{x}$ is used for the computation of the partial derivatives and the residual quantities or difference between the actual and calculated observations, the sum of squares of which are to be minimized:

$$\dot{v} = \left(l - f(\dot{x})\right)$$

where, l is the vector of actual observations and $f(\dot{x})$ is the functional model for the observations.

- **Specify the quality of the observations:** by constructing the variance-covariance (VCV) matrix

$$Q_l = P^{-1}$$

where, P is the weight matrix of the observations. Usually the VCV matrix contains only diagonal elements, the square of the standard deviation of the random measurement error for each satellite $\sigma_{URE}{}^2$

- **Form the normal matrix:** $N = A^T PA$**, and solve the system of equations:**

$$\delta\hat{x} = N^{-1} A^T P \dot{v}$$

where, $\delta\hat{x}$ are corrections to the apriori values of the parameters $\delta\dot{x}$

The quality of the estimated parameters can be extracted from the VCV matrix of the parameters $Q_{\hat{x}\hat{y}\hat{z}} = N^{-1}$

This is the standard mode of pseudo-range positioning used in GPS navigation, in which the receiver clock error is treated as an additional unknown.

All other biases are assumed to be insignificant and the accuracy with which position can be determined is therefore not just a function of the measurement precision σ_{URE}, and the correct modeling of the significant biases, it is also a function of the satellite-receiver geometry.

The variance-covariance matrix $Q_{\hat{x}\hat{y}\hat{z}}$ contains both the contribution to positioning error of the geometry and the random measurement error. Traditionally, for navigation applications, the components of the VCV matrix of the parameters are transformed into the Dilution of Precision (DOP) factor [73]. DOP is simply the ratio of the positioning precision to the measurement error:

$$\sigma = DOP \bullet \sigma_{URE}$$

where, σ_{URE} is the measurement precision (root-mean-square of the random errors)
σ is the position precision (root-mean-square of the position error)

The DOP is a number greater than unity in most cases. There are a number of different definitions of DOP factors, depending on the coordinate component, or combination of coordinate components, of interest. For example, the two factors often used in GPS positioning is PDOP (Position DOP):

$$PDOP = \sqrt{\sigma_E^2 + \sigma_N^2 + \sigma_h^2} = \sqrt{\sigma_X^2 + \sigma_Y^2 + \sigma_Z^2}$$

and, GDOP (Geometric DOP):

$$GDOP = \sqrt{\sigma_E^2 + \sigma_N^2 + \sigma_h^2 + \sigma_T^2} = \sqrt{\sigma_X^2 + \sigma_Y^2 + \sigma_Z^2 + \sigma_T^2}$$

where
$\sigma_E^2, \sigma_N^2, \sigma_h^2$ variances of the east, north and height error components
$\sigma_X^2, \sigma_Y^2, \sigma_Z^2$ variances of the X, Y, and Z error components
σ_T^2 is the variance of the error of the estimated receiver clock offset parameter
The GDOP and PDOP are the diagonal elements of the VCV matrix of the Least Squares position solution $Q_{\hat{x}\hat{y}\hat{z}}$

The Figure 4.2 illustrates the situations of good and poor GDOP.

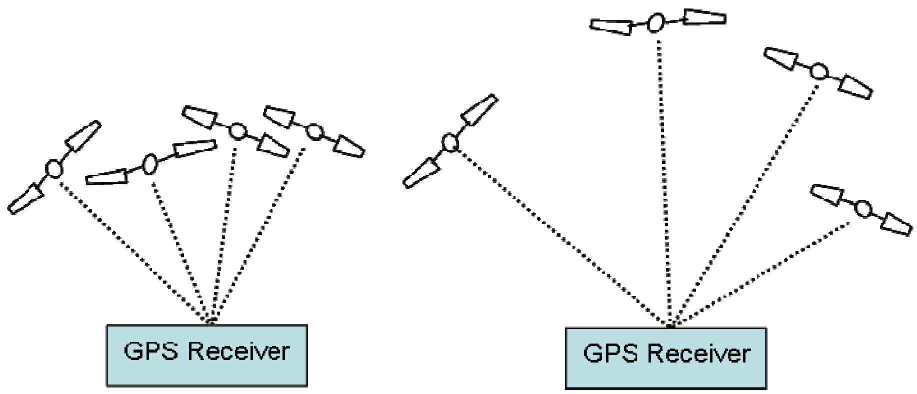


Figure 4.2: The relationship between satellite-receiver geometry (GDOP),bad GDOP left; good GODP right

The following comments can be made regarding DOPs:

- A smaller value of DOP generates higher position accuracy solutions and does not highly amplify the measurement errors.
- DOP is usually greater than unity, however, if many satellites are observed (greater than eight), the value of DOP can be less than unity.
- The vertical DOP component (VDOP) is consistently larger than the horizontal DOP (HDOP).
- DOP is used as the basis of selecting the best fit satellites for solution.
- A high DOP (greater than ten) indicates an outage in which the position solution is unreliable.
- DOP varies with time of day and geographic location, however the pattern of DOP at a location repeats itself each day with a delay of 4 minutes since the constellation is unchanged from day-to-day, and thus it is highly predictable.

5 INDOOR APPLICATIONS

The demand for personal navigation and location-based services is driving research and development of enhanced civilian GPS receivers for use in increasingly difficult operational environments. Receivers with longer signal integration times and external means of acquiring the navigation message are lowering the acquisition and tracking power thresholds to levels at which even indoor operation is possible. The enhanced availability of measurements in environments where signals are highly attenuated benefits solution availability in urban canyons and under heavy foliage.

However, interference in such environments can introduce large measurement errors. GPS signal deterioration occurs by signal masking caused by natural (e.g. foliage) and man-made (e.g. buildings) obstructions, interference due to reflected signals, signal self-interference, jamming, antenna effects, and receiver implementation losses. The impact of any one of these can result in partial to total loss of signal tracking and/or tracking errors, depending on the severity of the effect and the receiver tracking characteristics. Tracking errors, especially if undetected by the receiver firmware, can result in large position errors. Partial loss of tracking results in geometry degradation, which in turn affects position accuracy.

5.1 High Sensitivity GPS and Assisted GPS

A high-sensitivity GPS receiver, it is a receiver which operates autonomously and uses enhanced signal processing hardware and special algorithms for satellite code phase data collection, and to propagate the error corrections forward in time. Enhanced sensitivity receivers make measurements in signal conditions where conventional sensitivity receivers falter. The use of measurements acquired using high sensitivity methods in degraded signal environments can however be detrimental to the navigation solution if measurement faults due to signal deterioration are not identified and understood.

A receiver utilizing such long integration methods will hence be referred to as a high sensitivity GPS receiver or HS receiver. Conventional GPS receivers typically use integration times less than the 20 ms nominal maximum coherent interval and are limited in terms of their operational environments to places with strong signals. Signal masking due to man-made and natural obstructions limit the use of such receivers. HS receivers may be capable of tracking and acquiring signals in some of these environments. The most challenging of which often include indoors, is under heavy foliage and in urban canyons. Interference in these environments, such as multipath, can degrade the measurements of the GPS signals. In addition, measurement faults can result from the tracking of false correlation peaks. The ability to provide measurements and positions, when otherwise impossible using conventional tracking, has clear advantages for users in terms of solution availability. However, position degradation will result if measurement faults are included in solution

Investigations into the use of low power GPS signals using long dwell times have been performed by [2], [42], [53], [85], [96], [113], [118], [127]. These investigations have focused on the ability to provide measurements and positions when previously impossible using conventional GPS. Little research regarding prevalent interference sources and characterization of measurement degradation while using HS methods has been performed. [34] discusses, to a limited extent, pseudorange multipath and noise using HS GPS in urban canyons and some indoor environments but recognizes that further investigation and development of test metrics are needed. [60] discusses signal power degradation modeling for mobile satellite communications. [76] also discusses signal power degradation modeling using HS GPS as a measurement tool. Both of these studies relied on limited data. Thus, further testing with HS receivers for environmental characterization could enhance models of signal power and measurement degradation.

AGPS is a term for assisted or aided GPS. The AGPS is able to determine a 3-D fix with improved sensitivity. Aided GPS techniques are usually understood to be either ephemeris or almanac aiding. Assisted GPS methods include time, frequency, location and Doppler aiding and typically involve a wireless network. Assisted GPS describes a system where outside sources, such as an assistance server and reference network, help a GPS receiver perform the tasks required to make range measurements and position solutions. The assistance server has the ability to access information from the reference network and also has computing power far beyond that of the GPS receiver. The assistance server communicates with the GPS receiver via a wireless link. With assistance from the network, the receiver can operate more quickly and efficiently than it would unassisted, because a set of tasks that it would normally handle is shared with the assistance server. The resulting AGPS system, consisting of the integrated GPS receiver and network components, boosts performance beyond that of the same receiver in a stand-alone mode.

5.2 Pseudolites navigation system

A pseudolite is a signal generator that transmits GPS-like signals to nearby users. The pseudolite uses the same carrier frequency, PRN code generation method, and navigation message protocol as GPS satellites. As a result, the GPS receiver can track pseudolite signal with some minor receiver modification. This means that pseudolite provides an extra signal source to GPS receiver. The pseudolite navigational system can be classified see Figure 5.1.

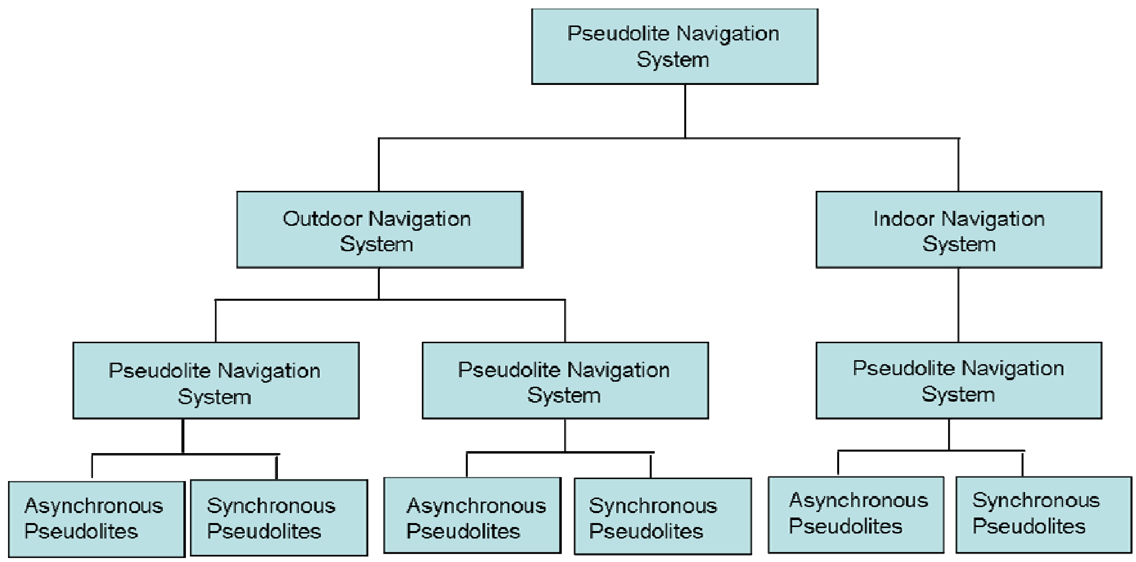


Figure 5.1: Classification of pseudolite navigation system [134]

The difference between asynchronous and synchronous system is that the pseudolite clocks are synchronized or not.

5.2.1 Pseudolite signal modeling

In Figure 5.2, the indoor navigation measurement definition is illustrated. Figure 5.2 can be used to get the mathematical pseudolite signal model for indoor navigation system by pseudolite constellation [65], [63], [134], and [64].
The integrated carrier-phase (ICP) measurement can be expressed as follows:

$$\phi_u^i \equiv (R^i - R_u) \cdot \hat{e}_u^{\,i} + B_u - b^i + \lambda \cdot N_u^i + \varepsilon_\phi$$

$$\phi_r^i \equiv (R^i - R_r) \cdot \hat{e}_r^{\,i} + B_r - b^i + \lambda \cdot N_r^i + \varepsilon_\phi$$

Since there is no atmospheric effect in an indoor environment, the indoor navigation carrier-phase measurement equation is the same as that of the outdoor navigation excluding the delay terms (ionospheric and tropospheric) caused by atmospheric effect

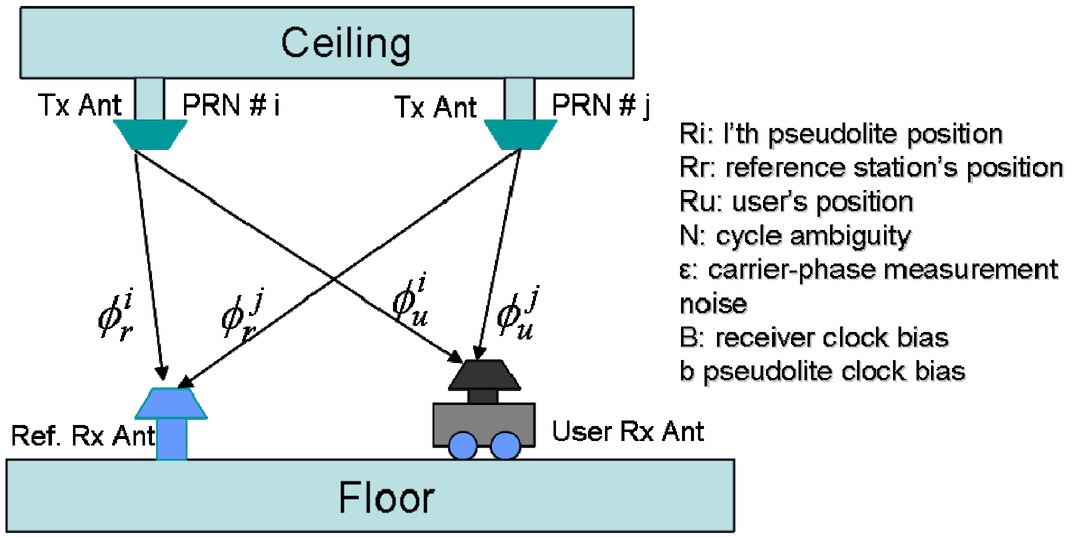


Figure 5.2: Measurement Definition in Indoor Navigation adopted from [63]

Then, the single difference integrated carrier-phase measurement is defined as follows:

$$^{i}\nabla^{j}\phi_u \equiv \phi_u^i - \phi_u^j$$
$$^{i}\nabla^{j}\phi_r \equiv \phi_r^i - \phi_r^j$$

If another difference operation to the single ICP equation, the double differenced ICP can be obtained as the following:

$$^{i}\nabla^{j}{}_{u}\Delta_r\phi \equiv {}^{i}\nabla^{j}\phi_u - {}^{i}\nabla^{j}\phi_r$$

5.2.2 Asynchronous pseudolite navigation system

Asynchronous pseudolite navigation system is composed of pseudolite module, reference station, and user as shown in Figure 5.3

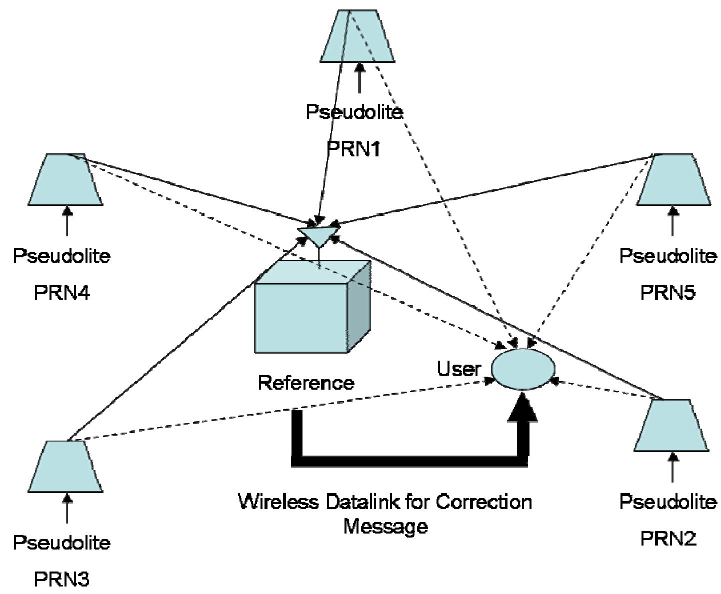


Figure 5.3: Asynchronous pseudolite navigation system [64]

Pseudolite module of asynchronous navigation system generates GPS L1 carrier wave and PRN codes by using its independent clock. Therefore, an enormous clock biases is present and need to be removed to calculate the user position.

The pseudolite clock error can be calculated using the raw data measured at the reference station, with the assumption that positions of the reference station and pseudolites are known exactly. The reference station transmits these clock errors to user via wireless data link as shown in Figure 5.3. The asynchronous pseudolite navigation algorithm uses double-differenced measurements to remove pseudolite clock errors. This method requires the following assumptions:

- Pseudolite positions are known exactly
- Reference station position is also known exactly
- The initial user's position is known

5.2.3 Synchronous pseudolite navigation system

Synchronous pseudolite navigation system is categorized and implemented into two types. Both types I and II are composed of pseudolite module, reference station, and user as shown in Figure 5.4 and Figure 5.5. Each pseudolite module requires a precise frequency controlled clock, which supplies reference clock for pseudolite signal generation. The first type system is composed with a reference station, which generates clock synchronization command for all the slave pseudolite modules. In case of the second type system, the slave pseudolite module contains its own clock synchronization module.

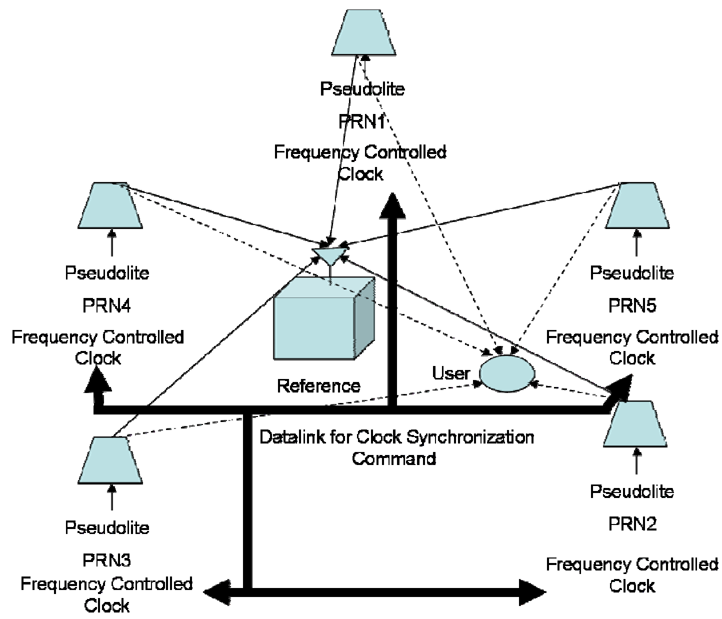


Figure 5.4: Synchronous pseudolite navigation system – Type I [134]

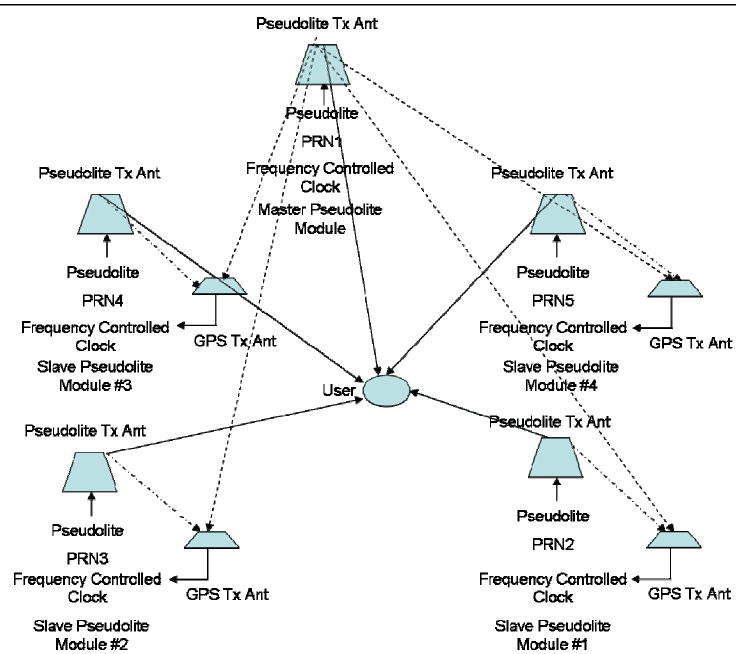


Figure 5.5: Synchronous pseudolite navigation system – Type II [134]

From both types, only Type I needs reference station. The clock synchronization errors between master and slave pseudolites can be measured since all the positions of reference station and pseudolites are known. With these measured errors, reference station operates clock synchronization loop filters and generates clock commands. The commands are transmitted through data link to slave pseudolite modules. Each slave pseudolite module drives its precise frequency controlled clock according to the commands and synchronizes its clock to the clock of master pseudolite

In synchronous pseudolite navigation system, the user can calculate its position without using correction messages from reference station. This means that the wireless data link between reference station and user is removed. This is not the case in asynchronous pseudolite navigation system.

The synchronous pseudolite navigation algorithm uses single differenced measurements. This method requires the following assumptions:

- Pseudolite positions are known exactly
- The initial user's position is known

5.2.4 Pseudolite application

In 1999, the Seoul National University GPS Lab (SNUGL) developed a centimeter-accuracy indoor navigation system using asynchronous pseudolites. Using this system as a position and attitude sensor, SNUGL implemented a vehicle control system and obtained 1-2 centimeter control errors. These results demonstrated that, if pseudolites are used, GPS navigation is possible in indoor environments, or where GPS signals are blocked.
The SNU indoor navigation system incorporates pseudolites, a reference station, and a user vehicle. Figure 5.4 shows an overview of the system. As shown in the figure, the pseudolites are fixed; so, their positions can be calibrated off-line. To calculate pseudolite positions, [65] used carrier-phase measurements and applied inverse carrier phase differential GPS (ICDGPS).

There are two problems as shown in figure 5.5:

- Near problem: The power of one signal is much higher than the others, a receiver tracks only one signal (high-powered signal acts as noise).
- Far problem: The power of one signal is much lower than the others, a receiver cannot track that signal

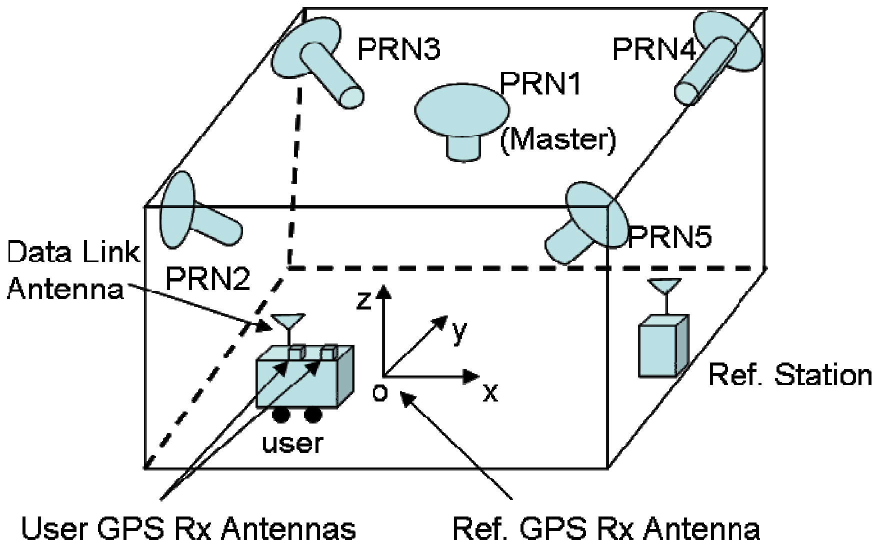


Figure 5.4: Overview of indoor navigation system [65]

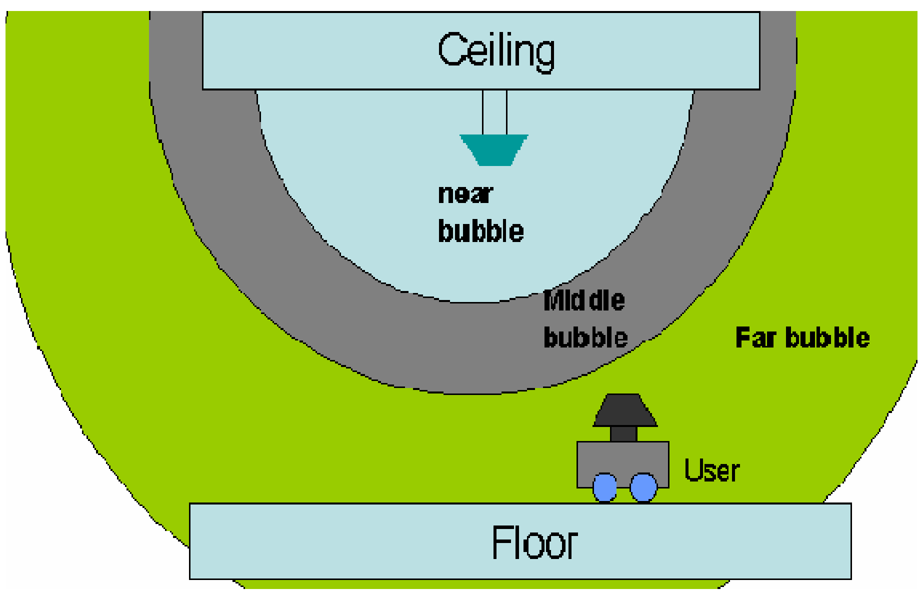


Figure 5.5: Near/Far Bubble adopted from [64]

6 CONCLUSION

The Global Positioning System (GPS) receivers are widely used in the land vehicle navigation and the tracking systems applications. The main concern of all these applications is the ability to determine the location of the vehicle. A comprehensive overview of the development of autonomous enabled GPS navigation systems for outdoor vehicle appears in the research of [3], [29], [31], [46], [78], [88], [90], [91], [92], [93], [107], and [108]. Multi-Robot task division using GPS for localization was studied by [78], and [108]. [31] uses the "A Solution to the Simultaneous Localization and Map Building" (SLAM) technique to enhance the localization.

Theoretically, the GPS receiver is the ideal sensor which satisfies the main purpose for land the land and tracking applications due to its ability to compute its location in three dimensions. However, due to its too high frequency transmission, the GPS receiver is intended to lose the lock from the satellites in urban sites, inside buildings, and dense foliage. The GPS receiver alone is unable to provide a continuous position fix for these applications, therefore the necessity of other sensors such as gyroscope, compass, and odometer. The individual navigation sensor contributes to the overall system performance [1]. The inertial measurement unit (IMU) sensor has a great benefit for outdoor land vehicle navigation due to its high update rate when providing the acceleration, angular rotation and attitude data. The IMU sensor has the property of non wheel slip contrary to the most used sensor the wheel encoder. However, the IMU has the disadvantage of inaccurate readings originating from the misalignment of the unit's axes with respect to the local navigation frame [119]. A combination of GPS receiver and INS system is considered as one of the best and competent navigation system due to the dual compensation of both sensors since the GPS receiver can compensate for the long term drift of an INS sensor, and an INS also compensate for the short term noise and the low data rate of a GPS receiver [50]

This paper has provided an overview for different techniques used in GPS technology to perform navigation and positioning for outdoor and indoor environments. The up-to-date techniques had been illustrated carefully. The importance of the indoor GPS navigating and its crucial role for now and future applications had been covered. The usefulness of the high sensitivity GPS receiver technology has been demonstrated not only for indoor applications, but also for the outdoor applications and its most pertinent problems. The high sensitivity as described above enhances the GPS receiver when the GPS signal deterioration occurs due to signal masking caused by foliage or buildings, therefore imposes its usefulness for both indoor and outdoor GPS navigation.

APPENDIX

KALMAN FILTER IN THE GPS TECHNOLOGY

The use of Kalman filters for GPS data processing is a growing trend. The standard Least Squares estimation technique is usually used when the estimation problem is over-determined (more observations than required to estimate the position parameters).

In kinematic applications Least Squares techniques can be applied to data on an epoch-by-epoch basis. However, the parameters of interest such as the position, and/or dominant system error parameters, are time-varying quantities. Therefore, the utilization of techniques based on the extension of the Least Square for the data processing is the most suitable, efficient, and optimal, thus can be considered as the most appropriate for such applications which encompasses the concepts of prediction, filtering and smoothing.

The three concepts of prediction, filtering and smoothing are closely related can be illustrated as following:

- The filtering concept can be defined as the process of computing the vehicle's position in real-time, in other words when observations are made at time t_k, then the position results are computed at t_k.

- The prediction concept can be defined as the computation of the expected position of the vehicle at some consequent time t_k, based on the last measurements at t_{k-1} is properly termed prediction.

- The smoothing concept is when the estimation of where the vehicle was at time t_k, once all the measurements are post-processed to time t_{k+1}.

Although the three procedures differ, however they can be used not only separately, but also they can used sequentially:

• The prediction step: based on past positioning information together with a kinematic model, the expected position and its precision at the next epoch of measurement are computed. The kinematic model is composed, as is the measurement model, of functional and stochastic components. Thus four models must be considered and, given a particular application and a certain data type, the filter design process is therefore one of selecting the appropriate models.

• The filtering step: is a classical adjustment, except that a fairly good apriori estimate of the parameters is already provided from the prediction step. Basically, the resulting parameter estimates are weighted combinations of predicted quantities and measurement data.The Kalman filter is a particular form of the generalized Least Squares filter.

• The smoothing step: by which all the measurements are reprocessed after the last measurement has been made and the filtering step has been completed.

As indicated above, the implementation of the filter requires the specification of the stochastic and mathematical models for both the measurement system and the system dynamics. Once the mathematical and stochastic models have been defined, the implementation within a Kalman filter is, in principle, relatively straightforward, although there are several different implementations which may have different advantages from the computational, numerical stability or quality control point-of-view.
For more details, the reader is referred to such classic texts as [18], [44], [49], and [81].

The Kalman filtering techniques are particularly appropriate for GPS navigation because of the following:
• Standard Least Squares procedures treats each measurement epoch independently, and hence does not use information on the system dynamics, such as the motion of the vehicle to which the GPS receiver is attached.
• Permits the rigorous computation of precision and reliability measures.
• The Kalman filter is also central to many quality control or fault detection procedures which can be implemented in real-time in order to detect failure, when poor quality data is introduced into the process, or when there is an error in the measurement or system dynamics models, to then identify the source of error, and to then adapt the system to ensure that the results are not biased due to this system failure.
• Estimate small biases that affect the data over many epochs. For example, many measurement biases in modern navigation technology have the signature of drifts which are not apparent at the single epoch level.
• By taking into account information on system dynamics, such as the regular motion of the GPS receiver, it is possible to carry out position estimation even if there is insufficient data – for example, when only two satellites are visible.
• KF technique is considered as an optimal linear estimator in the presence of Gaussian white noise.
• A Kalman filter can accept data as and when it is measured, and does not have to be reduced to some specified epoch.
• The Kalman filter is well suited for fusion of various type of sensors.
Most of the GPS receivers if not all incorporate Kalman filters as the navigation computing algorithm, but their real utility is generally only obvious when the positioning system involves several sensors such as when GPS is integrated with Dead Reckoning

sensors, example of using Kalman filter in sensor fusion can be found in [67], [108]. However, Kalman filters can be misleading with large erroneous results if the input data is cynical, or if wrong assumptions are made regarding the model for the system dynamics.

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