CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Navigation is the process of directing a moving vehicle or a person from one known place to the other known place. The modern navigational aids uses the Electromagnetic (EM) waves in the VHF and UHF range for providing the accurate knowledge of user position. The radio navigation receiver processes these EM signals and performs the necessary computations such as distance, bearing and estimated time of arrival for the user to navigate to the desired location. The conventional navigational aids that provide the course, distance and horizontal and vertical guidance during precision approaches are VHF Omni Range (VOR), Distance Measuring Equipment (DME) and Instrument Landing System (ILS) respectively. The advent of Global Positioning System (GPS) has revolutionized the field of navigation particularly in the field of civil aviation sector. The GPS is a reliable, all weather satellite based radio navigation system that provides accurate three dimensional (3D) position, velocity and timing information up to $10^{-6}$ seconds anywhere on or above the earth’s surface. The 3D position determination is based on the trilateration concept. In this concept, the unknown position of the receiver is computed by estimating the satellite positions in the space and measuring the pseudoranges to each satellite from the receiver. Even though satellite based
navigation systems offers much better accuracies than the conventional navigational aids (VOR, DME and ILS), the position accuracy is affected by several error sources such as ionospheric delay, tropospheric delay, satellite clock bias, receiver noise, multipath and satellite geometry. Because of these errors, the standalone GPS does not meet the requirements of critical navigation applications such as Category I (CAT I) Precision Approaches (PAs), where the required horizontal and vertical accuracies are 16m and 4.5-7m respectively. However, the required accuracy can be achieved by augmenting the GPS. The generic name given to the GPS augmentation system is known as Space Based Augmentation System (SBAS). The first SBAS was developed by US and is known as Wide Area Augmentation System (WAAS). The European space agency has developed their own SBAS known as European Geostationary Navigation Overlay System (EGNOS). Similarly in India, SBAS is implemented jointly by the Airport Authority of India (AAI) and Indian Space Research Organization (ISRO) and is known as GPS Aided Geo Augmented Navigation (GAGAN).

At present, all the SBASs including GAGAN are meeting the requirements of enroute navigation (2.2nmi accuracy, 2 minutes integrity) accuracy and approaches with vertical guidance (220m horizontal, 20m vertical and 10sec integrity). The SBAS is not able to achieve the CAT I aircraft landing requirements (16m horizontal, 4.5-7m vertical, 200’ decision height and 6 sec integrity) (ICAO manual 1999). The various reasons that contribute in not achieving this required accuracy are selection of a proper
navigation solution algorithm in the receiver, modeling of GPS signal errors, geographic location of the receiver and the satellite-receiver geometry. The satellite-receiver geometry is different in low latitude region (6°N-36°N) than at other latitudes. The metric used to measure the satellite receiver geometry is known as Geometric Dilution of Precision (GDOP). The predominant factor that significantly influences the navigation solution accuracy is the proper selection of a user receiver position estimation algorithm. Even though several position estimation algorithms are developed world wide, they are not available in the public domain because of commercial and security reasons. Therefore, it is necessary to develop a suitable navigation solution for receiver position estimation due to various satellite geometry configurations.

In this thesis, two new algorithms namely Jacobian determinant based multi polynomial resultant (JMR) technique and the Minkowski function based absolute position (MAP) algorithm are developed. The first one reduces the nonlinear GPS pseudorange equations into quadratic equations. The nonlinear terms in the four GPS pseudorange equations are eliminated by subtracting one equation from the other three pseudorange equations. The other one is the Minkowski function based absolute position algorithm, which is very computationally efficient. Unlike least squares estimation, this method takes only the actual measurement into account to estimate the object position. This method uses the Minkowski functional for four-space for obtaining the accurate navigation solution. The results of the two algorithms are compared with the standard recursive least squares (RLS)
estimation and the proposed algorithms have been validated with the real time dual frequency GPS receivers data. This thesis also highlights the satellite and receiver clock error impact on the proposed navigation solutions and the statistical error analysis of the position errors computed due to various navigation solutions. The practical data required for the analysis and validation of these algorithms is collected from the dual frequency GPS receivers located at Andhra University College of Engineering, Visakhapatnam (17.73°N/83.319°E), Airports Authority of India, Visakhapatnam Airport (17.73°N/83.223°E), NGRI, Hyderabad (17.417°N/78.558°E) and IISc, Bangalore (13.021°N/77.5°E).

1.2 OBJECTIVES OF THE THESIS

The main aim of the thesis is to develop new satellite based navigation solutions using Jacobian determinant based multipolynomial resultant technique and the Minkowski function based absolute position algorithm and to find out the GPS receiver clock, satellite clock and relativistic error impact on the position accuracy over the Indian subcontinent for precise position applications. To achieve the above objectives, the following tasks are carried out.

i) A new navigation solution based on multipolynomial resultant technique by finding Jacobian determinant that suits the Indian subcontinent is developed.
ii) A new non iterative absolute position algorithm based on the
Minkowski function is developed for the estimation of user position for
precise applications.

iii) The performance of the two proposed algorithms (Jacobian determinant
based multipolynomial resultant technique and the Minkowski function
based absolute position algorithm) are compared by implementing the
standard recursive least squares algorithm and validated with the real
time dual frequency GPS receivers.

iv) The satellite atomic clock behavior is predicted and analysis is carried
out in terms of bias, drift and drift rate to find their impact on timing
and positioning accuracy.

v) The satellite clock, receiver clock and the relativistic error impact on
the proposed navigation solutions are carried out. The statistical error
analysis of the position errors computed due to various navigation
solutions over the Indian subcontinent is also carried out.

vi) Satellite-receiver geometry impact analysis over time and space is
carried out to investigate how the DOP can change the position
accuracy significantly under Best-4 and All-in-view configurations
using the DOP algorithm.

1.3 LITERATURE SURVEY

To fulfill the objective of the thesis, the fundamental concepts of the
GPS signal structure, GPS observables, GPS errors and augmentation are
essential. The characteristics of L1 (1575.42MHz), L2 (1227.6MHz) signals and PRN codes transmitted by GPS satellites are dealt by several authors (Rao 2010, Parkinson and Spilker 1996, Hoffman et. al., 2007, Borre and Strang 1997, Leick 2004 and Pratap 2006). All these aspects are understood.

To develop the non iterative absolute position algorithm based on the Minkowski function, concepts of the GPS navigation solution are to be thoroughly understood. For this, several books (Ananda 1988, Nagaraja 1982, Rabbany 2002, Kayton and Fried 1997 and Xu 2003), journals (Milliken 1978, Parkinson et. al., 1995, Hoshen 1996, Toshiaki et. al., 2000, Enge et. al., 2001, Van Dierendonck and Spilker 2001, David and John 2003, Per Enge 2003, Kibe 2006, Sasibhushana Rao 2007, Bakhoum 2010) were referred. Several algorithms were developed to compute the Dilution of Precision (DOP), which is a measure of satellite-receiver geometry. Based on the concepts of satellites position in the space (Hoffman et. al., 2007, Langley 1999, Leick 2004), DOP algorithm is used to investigate the best satellite geometry configuration for low latitude GPS applications.

Presently, GPS is used in various applications because of its confidence and usefulness. Each GPS satellite generates a unique code sequence of zeroes and ones. By matching the time difference of the pseudo random noise code generated by the satellite's atomic clock and the user's clock, the receiver is able to match the code and calculate a time difference between them (Rao 2010). Based on the calculated time difference which is known as travel time of the satellite signal and known value of the speed of
light, the distance between the satellite vehicle (SV) and the receiver can be determined (speed of light multiplied by time) (Daily and Bell 1996). The satellite and receiver clock discrepancies and inaccuracy of the transmitted ephemeris, the electromagnetic wave propagation through the atmosphere slows down. Because of these reasons, the computed distance between each satellite and the receiver is known as pseudorange (Ivan 1993). Simultaneous observations of four pseudoranges are necessary to determine the X, Y and Z coordinates of GPS receiver antenna and clock bias. Literature shows that different approaches have been developed to solve the system of nonlinear equations, some closed-form solutions and some through linearization process. These position estimation algorithms have been studied and analyzed (Seiji and Toshiyuki 2006, Andrew 2004, Farrell and Barth 1999).

The GPS position accuracy relies on the precise knowledge of the satellite orbits and the time. The GPS is a ranging system and was designed as a one-way system, where signals are transmitted only from the satellite to user. In this system, there is an offset between the independent satellite and receiver clocks, which translates into a position error (because the receiver position is calculated from the time delay between the signal transmission at the satellite and reception at the receiver). This timing offset must be included as unknown parameter in the position solution in addition to the three X, Y and Z coordinates (Rao 2010). The behavior of satellite clock errors and their impact on timing and positioning accuracy is studied. Using
GPS for precise determination of user position, the clock ticks from the GPS satellites must be known to an accuracy of 20-30 nsec. However, because the GPS satellites are constantly orbiting relative to observers on the Earth, the Special and General theories of relativity effects predicted must be taken into account to achieve the desired 20-30 nsec accuracy. The relativistic error effect on the navigation solution is explored (Xu 2003). The GPS range measurements contain several errors, resulting from a variety of sources. These biased time delay measurements are therefore referred to as pseudoranges. Pseudorange errors can be broadly grouped into two major categories: biases, which are systematic and which can be modeled in an equation describing the measurements thereby removing or significantly reducing their effect and noise or random error, each value of which cannot be modeled but whose statistical properties can be used to optimize the analysis results (Kaplan 2006). The statistical analysis of the GPS position accuracy can be made by considering different accuracy measures like distance root mean square (DRMS), twice distance root mean square (2 DRMS), the circular error probable (CEP) and the horizontal 95% accuracy (R95) for two dimensional (2D). Similarly for three dimensional (3D) position accuracy, statistical analysis can be made by considering the Spherical Error Probable (SEP), Mean Radial Spherical Error (MRSE), the 90% spherical accuracy standard and 99% spherical accuracy standard (Frank 2007, Langley 2010). All these aspects are understood for developing new navigation solution algorithms to suit the Indian subcontinent conditions.
1.4 TECHNICAL APPROACH

Literature survey reveals that though several navigation solution algorithms were developed world wide (Nainesh et. al., 2002, Sirola and Syrjarinne 2002, Xiao-Wen and Christopher 2003, Klaus et. al., 2006, Kongzhe and Young 2006, Niilo 2006, Liqiang et. al., 2007, Christopher et. al., 2008, Lubna et. al., 2009, Pfeil et. al., 2009), they are not available in the public domain because of the commercial and security reasons. Hence, accurate, reliable and cost effective navigation solution algorithms that suit the Indian geographic area and area of application are developed. The existing navigation solutions are based on iterative algorithms and require an initial estimate of the receiver position for computing the navigation solution which is not possible in all conditions. A non-iterative point solution approach algorithm computes the navigation solution based on the available satellite positions and pseudorange measurements. The non-iterative algorithm does not require any initial estimate of the receiver position \((x_0, y_0, z_0)\). The observation equation of the pseudorange measured between the unknown receiver \((x_u, y_u, z_u)\) and known \(i^{th}\) satellite \((x_i, y_i, z_i)\) is given by (Klobuchar 1991, Bryan and Patrick 1994, Klobuchar 2001, Joachim 2003, Norsuzila and Mardina 2009, Rao 2010)

\[
\rho_i = \rho + d\rho + c(\Delta t_{sv} - dT) + \text{iono} + \text{trop} + \varepsilon_{PR} \tag{1.1}
\]

where,
\[ \rho = \text{geometric (or true) range} \]
\[ d\rho = \text{orbit errors} \]
\[ \Delta t_{sv} = \text{satellite clock error} \]
\[ dT = \text{receiver clock error} \]
\[ \text{iono} = \text{ionospheric error} \]
\[ \text{trop} = \text{tropospheric error} \]
\[ c = \text{velocity of light in vacuum} \]
\[ \varepsilon_{PR} \text{ represents the pseudorange noise respectively} \]

In order to determine user position in three dimensions \((x_u, y_u, z_u)\) and the receiver clock offset \((dT)\), pseudorange measurements are made to four satellites resulting in the system of equations

\[ \rho_i = |S^i - u| - c\ dT \tag{1.2} \]

where, vector \('S^i'\) represents the position of \(i^{th}\) satellite relative to coordinate origin and is located at coordinates \(x_s, y_s, \text{ and } z_s\) within the earth centered earth fixed (ECEF) coordinate system. This vector is computed using the orbital parameters broadcasted by the satellite. Vector \('u'\) represents receiver position with respect to the ECEF coordinate system. \('i'\) ranges from 1 to 4 and is used to reference the satellites. The Eq. (1.2) can be expanded into the following set of equations.

\[
\rho_1 = \sqrt{(x_1 - x_u)^2 + (y_1 - y_u)^2 + (z_1 - z_u)^2}
\]
\[
\rho_2 = \sqrt{(x_2 - x_u)^2 + (y_2 - y_u)^2 + (z_2 - z_u)^2}
\]
\[
\rho_3 = \sqrt{(x_3 - x_u)^2 + (y_3 - y_u)^2 + (z_3 - z_u)^2}
\]
\[
\rho_4 = \sqrt{(x_4 - x_u)^2 + (y_4 - y_u)^2 + (z_4 - z_u)^2}
\tag{1.3} \]
In the above equations, \( x_u, y_u \) and \( z_u \) are the unknown user position co-ordinates. The above nonlinear equations can be solved for user position ‘\( u \)’ by linearization using Taylor series expansion about the approximate user position (\( \hat{u} = x_0, y_0, z_0 \)).

\[
\begin{align*}
  x_u &= x_0 + \Delta x \\
  y_u &= y_0 + \Delta y \\
  z_u &= z_0 + \Delta z
\end{align*}
\]  

(1.4)

where, \( x_u, y_u \) and \( z_u \) are the receiver true ECEF solution and \( \Delta x, \Delta y \) and \( \Delta z \) are the difference between the true solution and the initial guess (\( x_0, y_0, z_0 \)). To correct the initial guess we need to calculate \( \Delta x, \Delta y \) and \( \Delta z \) in order to update \( x_u, y_u, z_u \). After expanding the above equations about the approximate user position and considering the first order derivatives only, the following matrix equations can be obtained.

\[
\Delta \rho = H \Delta x
\]  

(1.5)

where \( \Delta \rho = \begin{bmatrix} \Delta PR1 \\ \Delta PR2 \\ \Delta PR3 \\ \Delta PR4 \end{bmatrix} \), \( H = \begin{bmatrix} ax_1, ay_1, az_1, 1 \\ ax_2, ay_2, az_2, 1 \\ ax_3, ay_3, az_3, 1 \\ ax_4, ay_4, az_4, 1 \end{bmatrix} \), \( \Delta x = \begin{bmatrix} \Delta x_u \\ \Delta y_u \\ \Delta z_u \\ -c\Delta dT \end{bmatrix} \)

\( \Delta \rho \) and \( \Delta x \) are derivatives of the actual user position from approximate position and \( ax_i, ay_i \) and \( az_i \) are the direction cosines of the unit vector pointing from approximate user position to the \( i^{th} \) satellite. So the user position can be found as given below
The GPS position accuracy improves with best GDOP. In order to estimate the accuracy of the navigation solution computed, the DOP
algorithm is used. Using this algorithm, the best GDOP is investigated for different satellite configurations. The satellite clock error is caused by satellite oscillator not synchronized to true time (GPS time). The satellite clock corrections are sent much more frequently than any other component of the vector correction. These errors represent the difference between the time reported by the satellite and the GPS system time.

The behavior of satellite clock errors and their impact on timing and positioning accuracy is investigated using the proposed navigation solution by collecting data from various dual frequency GPS receivers using standard formulae. The desired clock ticks from the GPS satellites must be with an accuracy of 20-30 nsec for precise user position determination. However, because the satellites are constantly moving relative to observers on the Earth, effects predicted by the Special and General theories of relativity must be taken into account to achieve the desired 20-30 nsec accuracy. When the satellite is at perigee, the satellite velocity is higher and the gravitational potential is lower because of which the satellite clocks run slower. When the satellite is at apogee, the satellite velocity is lower and the gravitational potential is higher, and so the satellite clocks run faster. This effect can be compensated by standard relativistic error formula. Due to rotation of the earth during the time of signal transmission, a relativistic error is introduced, which is called the sagnac effect. During the propagation time of the SV signal transmission, a clock on the surface of the earth will experience a finite rotation with respect to the resting reference frame at the
geo-centre. If the receiver experiences a net rotation away from SV, the propagation time will increase and vice-versa. The satellite clock, receiver clock and the relativistic error effect on the three navigation solutions is carried out. Two new algorithms viz. Jacobian determinant based multi polynomial resultant technique and the Minkowski function based absolute position algorithm are proposed for the estimation of precise user position. Since the GPS measurements are like many other signals in that with enough samples the probability distribution for each of the three components (x, y, z coordinates) is typically bell-shaped, allowing us to use a particularly powerful error model (Langley 2010). The statistical error analysis for the estimated user position is carried out using the popular 2D accuracy measures like DRMS, 2DRMS, CEP and R95; and 3D accuracy measures like SEP, MRSE, 90% spherical accuracy standard and 99% spherical accuracy standard. The proposed models are accurate and faster for real time applications like GAGAN. The practical data required for calculating different parameters in this work are taken from the dual frequency GPS receivers located at Andhra University College of Engineering, Visakhapatnam; Airports Authority of India, Visakhapatnam Airport; NGRI, Hyderabad and IISc, Bangalore.

1.5. APPLICATIONS OF THE THESIS

i) The proposed non-iterative Jacobian determinant based multi polynomial resultant technique and the Minkowski function based absolute position
algorithm navigation solutions can be used for precise surveying and GAGAN applications over the Indian subcontinent.

ii) The navigation solution error analysis carried out for single and dual frequency GPS receivers is useful for the civil aviation sector in India to implement the Global Navigation Satellite System (GNSS) by 2012 as supplement to the existing ground based navigation systems as per the International Civil Aviation Organization (ICAO) regulation.

iii) By incorporating the proposed multi polynomial resultant navigation solution in the GNSS aircraft receiver, the GNSS navigation shares the advantages of increased fuel efficiency, improved air space utilization, reduced flight times and precision approach capability.

iv) The onboard atomic clocks on the satellites are the basis for control of time and frequency of navigation signals. The prediction of atomic clock behavior plays an important role in the GPS performance. The satellite clock and relativistic error analysis made in this thesis will be useful for precise GPS positioning due to the increasing number of users requiring centimeters accuracy, particularly in the multi system and multi environment scenario.

v) The built-in quartz clocks in the GPS receivers yields relative frequency offsets that are 3-4 orders higher than atomic clocks. The frequency stability of quartz clock is two orders worse than the atomic clocks. Enhancement of receiver position accuracy is the primary goal of all GPS users. To achieve this, statistical error analysis is made on the
relationship between GPS receiver clock and GPS positioning precision due to the proposed navigation solution. This analysis is mainly carried out because all the aircraft receivers are equipped with quartz based clocks as the atomic clocks are very costly and cannot be afforded.

1.6. ORGANIZATION OF THE THESIS

This thesis consists of seven Chapters including the Introduction and Conclusions. Chapter 2 presents the principle of operation of the satellite navigation system, GPS signal characteristics and the various error sources in the GPS observables/observations. Chapter 3 discusses the important steps followed in GPS receiver signal processing: signal conditioning, acquisition, tracking and navigation data recovery. The navigation message and the observation data formats are also explained in this chapter. In Chapter 4, the proposed navigation solutions Jacobian determinant based multi polynomial resultant technique and the Minkowski function based absolute position algorithm and the recursive least squares approximation algorithm are presented for precise navigation solution. The results of position error analysis made for these three methods are also presented in this chapter. Chapter 5 presents the satellite clock and relativistic error impact on the navigation solution. The effect of satellite-receiver geometry on the position accuracy of GPS system is presented in Chapter 6. The frequency distribution of receiver position, 2D, 3D position accuracy measures due to the three navigation solutions, statistical error analysis of
the receiver clock and satellite clock error and its impact on the proposed navigation solution and the overall results are presented in Chapter 7. The overall conclusions along with the suggestions for further work are presented in Chapter 8.