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# Estimation Of Global Positioning System Measurement Errors For GAGAN Applications

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***Abstract:*** *The Global Positioning System (GPS) has been in use for providing positioning, navigation and timing (PNT) services in many parts of the world. There are several errors that affect the positional accuracy of GPS. Prominent among them are ephemeris errors, satellite and receiver clock errors, multipath errors, signal propagation errors such as ionospheric delay, tropospheric delay, and instrumental biases of the satellite and receiver. In this paper, prominent estimation techniques to characterize various GPS measurement errors are reviewed. The GPS data in the Receiver INdependent EXchange (RINEX) format obtained from a Dual frequency GPS receiver is used in this analysis. Among all the errors, ionospheric delay is found to be the most dominant. However, these delay measurements are affected by the satellite and receiver instrumental biases. The instrumental biases exist as the signals at the two GPS frequencies experience different delays inside the satellite and receiver hardware. For estimation of the instrumental biases Extended Kalman filter(EKF) technique is adopted. The user equivalent range error (UERE) obtained due to all the error sources is of the order of few metres. After accounting for various errors, the estimation accuracy is significantly improved.The positional accuracy of the GPS Aided GEO Augmented Navigation (GAGAN) system is basically dependent on ranging errors and the satellite constellation geometry[1]. The lineof-sight ionospheric measurements derived from the Global Positioning System (GPS) observables are corrupted by the instrumental biases present in both the GPS satellites and the receivers. The instrumental bias and Total Electron Content (TEC) results (Hyderabad GAGAN station (78.47°E, 17.45°N)) obtained using theExtended Kalman filter technique are presented in this paper. In this work the main focus is towards development of an improved error free approach for aircraft navigation. 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. Accurate, reliable and cost effective navigation solution algorithms that suit the Indian geographic area and area of application are proposed in this work. A non-iterative point solution approach algorithm computes the navigation solution based on the available satellite positions and pseudorange measurements[3]. The improvement in GPS system has given a feasibility of automated operation of satellite based augmenting system in aircraft navigation can augment GAGAN and improves the positional accuracy of the user. In this paper a communication approach , high, accurate processing using EKF scheme is proposed for GPS aided geo augmented navigation (GAGAN) application. The effectiveness of the proposed approach for higher performance is evaluated under variable conditions.*

***Key Words:*** *GPS, GAGAN, Error sources, Data processing, Ionospheric delay, EKF,UKF,UERE*

## I. Introduction

The Global Positioning System (GPS) is a satellite based navigation system developed by the U.S. Department of Defense (DoD)[2]. It can be used for a wide variety of applications with a horizontal accuracy of 20 m and a vertical accuracy of 30 m (with 95% confidence level) 1. However, the accuracy of standalone GPS is not sufficient to meet CAT-I precision approach requirements for civil aviation. Therefore many countries including USA, Europe and Japan are developing regional Satellite Based Augmentation Systems (SBAS). The Indian Space Research Organization (ISRO) and Airports Authority of India (AAI) are jointly implementing an SBAS known as GPS Aided Geo Augmented Navigation (GAGAN) to provide seamless coverage over the Indian airspace 2 Basically, GAGAN will provide three services to users, viz. a ranging signal, which improves availability and reliability; differential GPS corrections (ionospheric and orbital corrections), which improve accuracy; and integrity monitoring which improves safety. The accuracy of the GAGAN user position estimate is mostly affected by the ranging errors. Ranging errors include satellite clock and ephemeris errors, errors due to ionospheric and tropospheric delay, and errors due to instrumental biases and multipath. For better position estimate these errors should be exhaustively analyzed and mitigated. The ionospheric delay, which is a function of the Total Electron Content (TEC) is the most predominant error affecting the accuracy of GAGAN. The dual frequency GPS receiver can be used to estimate the ionospheric delay or TEC, taking advantage of its dispersive nature. One of the main sources of error in the estimation of TEC is the effect of differential instrumental biases of the satellite and the receiver. These biases exist due to the fact that the signals at the two GPS frequencies (f1 = 1575.42 MHz, f2 = 1227.60 MHz) undergo different propagation delays inside the satellite and receiver hardware. Most of the ranging errors are investigated thoroughly by researchers around the world. However, errors due to instrumental biases are not paid adequate attention. Several prominent techniques for estimation of instrumental biases including Kalman filter, Self-Calibration Of pseudoRange Error (SCORE) algorithm, least squares fitting and neural networks are reported in the literature 3-6. Further, errors get magnified due to unfavourable satellite constellation geometry. This aspect also needs due consideration and should be dealt with utmost care especially for augmented configurations such as GAGAN. In this paper instrumental bias error, Geometric DOP (GDOP) in the context of various GPS/GEO/Pseudolites configurations is investigated.

## II. Overview Of GAGAN System

The major segments of GAGAN are ground segment, space segment and user segment shown in Figure.( 1). Ground segment consists of reference stations, Master Control Station (MCS), earth station and communication links. In the initial phase, eight Indian Reference Stations (INRES) at precisely surveyed locations are installed to receive data from GNSS satellites 7. If required additional INRES will be established in future. Communication links transfer data from the reference stations to Master Control Station known as Indian Mission Control Centre (INMCC). The INMCC performs integrity monitoring, ionospheric delay estimation, wide area corrections and orbit determination. The Indian Navigation Land Uplink Station (INLUS) receives messages from the INMCC and uplinks them to the GEO satellite for broadcast to the users. Space segment comprises of GPS/GLONASS satellites for the transmission of ranging signals and also GEO satellites for the broadcast of GAGAN signals. Navigation payload is expected to be carried by an Indian GEO satellite to be positioned in the Indian Ocean region between the orbital arc 48° to 100° E (Ref. 8). User segment consists of a receiver capable of receiving and decoding the GPS/GLONASS/GEO broadcast message. The GAGAN payload will be comprised of C-band Up-link, C-band Down-link and L-band Down-link (L1 and L5) . The signal-in-space (SIS) provides data on GPS and GEO satellites along with ranging information.

**GAGAN Objectives**

• To provide Satellite-based Navigation services with accuracy and integrity required for civil aviation applications over Indian Air Space.
• Better Air Traffic Management over Indian Airspace.GAGAN is a Satellite Based Augmentation on GPS
• GAGAN jointly implemented by ISRO and Airports Authority of India (AAI)
• Compatible and Interoperable with other SBAS
• Provides Seamless navigation
• GAGAN implementation in two phases:GAGAN – TDS (Technology Demonstration System)
GAGAN – FOP (Final Operation Phase) GAGAN (GPS Aided GEO Augmented Navigation)

**GPS Services and Accuracy standards**

In an effort to make GPS service available to commercial, national and international civil users while maintaining the original U.S. military function, two GPS services are provided.

**Standard Positioning Service (SPS):** Available to all users on a continuous and world-wide basis. It uses the C/A code and is provided on the L1 signal only.

**Precise Positioning Service (PPS):** Restricted to U.S. armed forces, and some selected allied military organizations and agencies. It uses the P(Y) code on the L1 and the L2 signal.

The GPS performance is dynamic, changing both with time and place as the satellite geometry and measurement errors change. A global characterization of the performance is based on various parameters such as satellite constellation strength, signal propagation anomalies, and receiver capabilities. The performance specifications are given in statistical terms, for e.g. as rms error or $95^{th}$ percentile of the error distribution. The SPS and PPS positioning and timing accuracy based on a 95% probability level are given in Table 1[4]. The performance levels shown are for the signal in space (SIS) and contributions of ionosphere, troposphere, receiver, multipath error, etc. are not included. The PPS performance is actually better than that for SPS (SA off), even though the actual specifications show lower accuracy [5].

**Table 1** SPS and PPS positioning and timing accuracy based on a 95% probability level

| Accuracy standards | | | |
|---|---|---|---|
| **S.No.** | **Description** | **SPS (SA off)** | **PPS** |
| | **a.)Global average positioning domain accuracy** | | |
| 1. | Horizontal error | ≤ 9 m | 22 m (98.2%) |
| 2. | Vertical error | ≤ 15 m | 27.7 m |
| | **b.) Time transfer accuracy** | | |
| 3. | Time transfer error | ≤ 40 ns | 200 ns |

**Satellite Based Augmentation System (SBAS)**

A Satellite Based Augmentation System (SBAS) consists of a number of dual frequency GPS receivers placed at precisely known reference locations that are spread over a wide geographic area. These receivers continuously monitor all the GPS satellites, and are called wide area reference stations (WRS). The raw GPS measurements collected by the WRS are transmitted to the central processing facilities at wide area master stations (WMS) . The master stations use the measurements to generate wide area differential (WAD) corrections for each satellite . These include satellite clock corrections, a correction for the three-dimensional position of the satellite, and a set of corrections for the ionospheric delay. Additionally, the WMS performs several integrity checks to validate the satellite signals. The differential corrections along with the integrity information are transmitted using C-band signals to the geostationary satellite (GEO), which relay the information using L-band signals to the users. SBAS provides three major components of information for performance enhancement: (i) the differential corrections improve the accuracy of the position solution, (ii) the GPS-like signals transmitted by the geostationary satellite provide an additional ranging signal, which improves the availability and continuity, (iii) the integrity information of the SBAS signals enhance the safety by alerting users within 6 seconds of any malfunction in the GNSS / SBAS system [6].The SBAS system will enable GPS to be used as the primary navigational aid in civil aviation for all phases of the flight from takeoff through Category-I precision approach. The Indian SBAS is being jointly implemented by the Airports Authority of India (AAI) and Indian Space Research Organisation (ISRO) to meet civil aviation requirements for various phases of a flight, over the Indian airspace. All the SBAS systems must comply with Standards And Recommended Practices (SARPs) specified by the International Civil Aviation Organisation (ICAO), for providing seamless navigation of civilian aircrafts across the globe [7].

The first geostationary navigation payload in the C-band and the L1 and L5 frequencies (L-band) will be carried on an Indian geostationary satellite,GSAT-4, placed at 82°E.

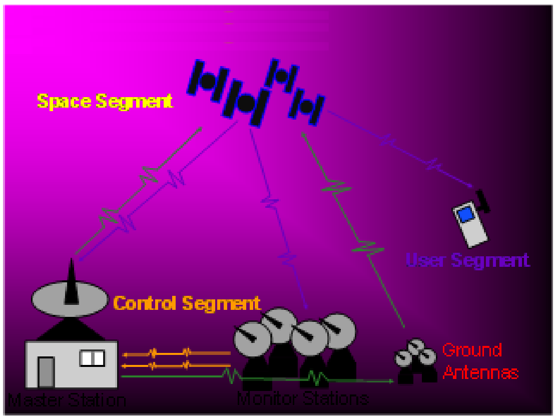


**Figure (1).**Three- Segments in GAGANSystem

The space segment is composed of more than 24 active NAVSTAR (NAVigation Satellite Timing And Ranging) satellites. The satellites forming the nominal constellation are distributed in six 55° orbital planes, with foursatellites in each plane. The orbit period of each satellite isapproximately 12 hours at an altitude of 20,183 km. This provides a GPS receiver with atleast four satellites in view from any point on Earth, at any particular time.The GPS satellite signal identifies the satellite and provides the positioning, timing, ranging data, satellite status and the corrected ephemerides of the satellite to the users. The satellites can be identified either by the Space Vehicle Number (SVN)or the Pseudorandom Code Number (PRN).

- The control segment consists of worldwide monitor and control stations that maintain the satellites in their proper orbits through occasional command manoeuvres, and adjustments of the satellite clocks. It tracks the GPS satellite, uploads updated navigation data, and maintains the health status of the satellite constellation.
- The user segment consists of various GPS receiver equipment, which receive the signals from the GPS satellites and use the received information to calculate the user's latitude, longitude, altitude and the GPS system time. A minimum of four satellites in view are needed to allow the receiver to compute a valid solution.

The GPS employs the Earth Centred Earth Fixed (ECEF) World Geodetic System 1984 (WGS84) as the reference frame to which all GPS positioning and navigation.

**Generates 1023 length C/A Codes for GPS PRNs 1-37:**

g: nX1023 matrix- with each PRN in each row with symbols 1 and 0

sv: a row or column vector of the SV's to be generated valid entries are 1 to 37 fs: optional number of samples per chip (defaults to 1), fractional samples allowed, must be 1 or greater.

For multiple samples per chip, function is a zero order hold. Simulations conducted to generate the C/A codes for PRN 3 and PRN 12 is shown in figure (2) and Simulations conducted to generate the C/A codes for PRN 6 and PRN 12 is shown in figure (3).

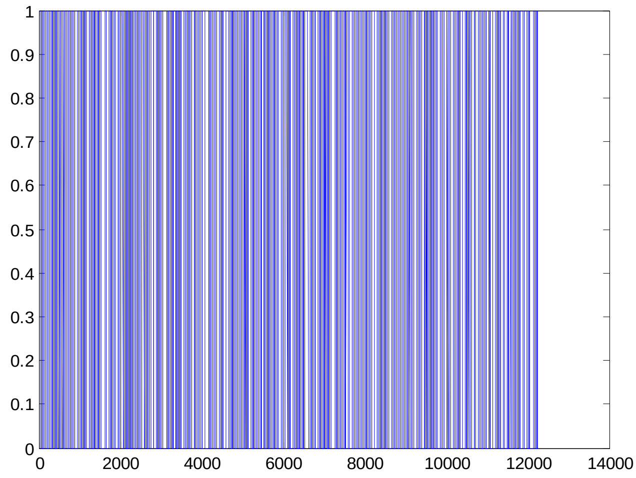


**Figure (2) .** Generation of C/A codes for PRN 3 and PRN 12

Simulations to generate the C/A codes for PRN 6 and PRN 12:

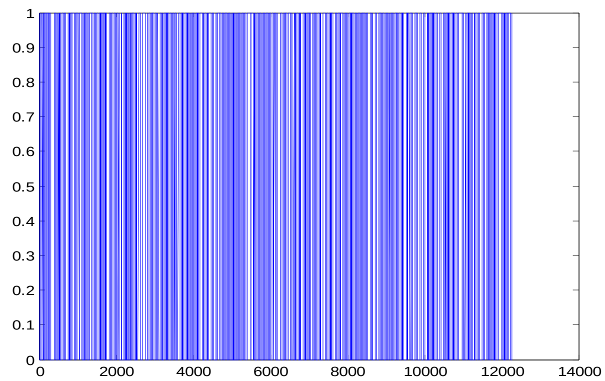


**Figure (3) .** Generation of C/A codes for PRN 3 and PRN 12

## III. Errors in GAGAN / SBAS and Methods Of Error Correction

The objectives of the SBAS are to provide integrity, accuracy, availability and continuity for GPS, GLONASS, and Galileo Standard Positioning Service (SPS). An SBAS system should provide necessary corrections for majority of the GNSS errors. The leftover data errors (referred to as residual errors) are mitigated by the transmission of residual error bounding information. The SBAS corrections improve the accuracy of satellite signals.

Thebasic block diagram of GAGAN / SBAS system is shown in figure (4).The integrity data ensure that the residual errors are bounded [8].The GNSS measurements are affected by several types of random errors and biases. Some of the errors can be removed and some can be reduced. These can be broadly categorized into three categories namely satellite based errors, propagation medium-related errors and receiver based errors. The GPS basic signal modelis shown in figure (5).

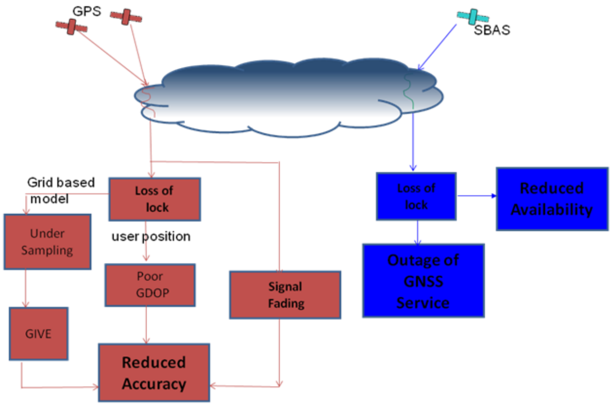


**Figure (4).** Basic block diagram of GAGAN / SBAS system

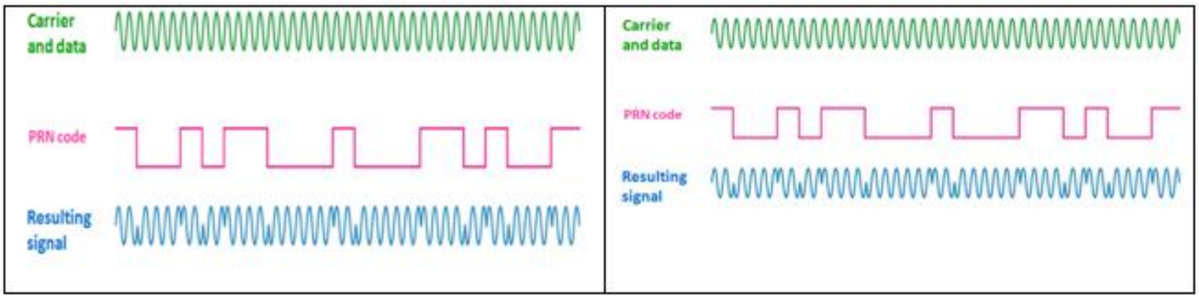


**Figure (5).** GPS signal model

**Satellite based errors**

The errors originating at the satellite include ephemeris error, satellite clock error, relativistic effects due to different gravitational potential experienced by satellites, and the satellite instrumental bias error.

i) Ephemeris error: The GPS Master Control Station (MCS) collects the code and carrier phase data from the monitor stations, and predicts the ephemeris of the satellites using sophisticated software models. The ephemeris parameters are uploaded to the satellites and subsequently broadcasted to the users as part of the navigation message. A small residual error exists due to difference between the actual satellite position and the position predicted by the MCS [17]. The ephemeris error is of the order of 1.5 m. The ephemeris error can be avoided by having a network of reference stations that transmit the three-dimensional error in the reported ephemeris or predicted ephemeris determined based on the reference stations own measurements [4].In component form, these ephemeris data do not decorrelate spatially and decorrelate very slowly in time [5].

ii) Satellite clock error: The GPS satellite clocks although highly stable are correct to about 1 to 2 parts in $10^{13}$ over a one-day period. The satellite clock offset does not decorrelate spatially but can decorrelate temporally. The drift in the satellite clock can cause an error of about 8.64 to 17.28 ns per day. The corresponding range error is about 2.59 m to 5.18 m. The master control station determines the clock error of each satellite and transmits clock correction parameters to the satellites for rebroadcast of these in the navigation message. The satellite clock error for the C/A code pseudorange observation is modeled as a second-degree polynomial (Navstar GPS Joint Program Office, 2004),

$$\delta t^s = a_{f0} + a_{f1}(t - t_{oc}) + a_{f2}(t - t_{oc})^2 + \nabla t_r$$

where $a_{f0}$ =clock bias (s); $a_{f1}$ =clock drift (s/s); $a_{f2}$ =frequency drift (s/s$^2$); $t_{oc}$=clock data reference time (s); t=current time epoch (s); $\nabla t_r$=correction due to relativistic effects (s).

iii) Relativistic effects: The satellite clock is affected by the general and special theories of relativity. According to the general theory of relativity, the satellite clock would run faster than the receiver clock, due to the difference in gravitational potential experienced by the clocks of the satellite and receiver. According to the special theory of relativity, a clock aboard the satellite traveling at a constant speed would appear to run slowly relative to a clock on the ground. General relativity predicts that the GPS satellite clocks should get ahead of receiver clocks by 43 μs per day. Special relativity predicts that the satellite clocks fall behind receiver clocks by about 9 μs per day. The total of these two relativistic effects for the satellite clock is 34 μs faster per day. This leads to a clock rate offset of $4.45 \times 10^{-10}$ faster for the satellite . In order to compensate for the above mentioned relativistic effects, the satellite clock frequency is adjusted to 10.22999999543 MHz prior to launch

(Navstar GPS Joint Program Office, 2004). Then, the frequency observed by the user at sea level would be 10.23 MHz. A user receiver has to make correction for another periodic effect that arises due to the assumption of a circular orbit. In an elliptical orbit, both the speed of the satellite and the gravitational potential change with the position of the satellite in its orbit. This relativistic correction (in seconds) to the satellite clock time is given by (Navstar GPS Joint Program Office, 2004),

$$\nabla t_r = Fe\sqrt{A}\,\sin E_k$$

where F=constant ($-4.442807633\times10^{-10}$ s /√m); e=satellite orbit eccentricity; A=semi- major axis of the satellite orbit; $E_k$=eccentric anomaly.

iv) Satellite instrumental bias: Within the GPS satellite hardware, the L1 and L2 signals propagate through different analog circuitry, before digitization. That is, L1 and L2 signals undergo different propagation delays within the satellite causing instrumental bias . There exists an instrumental bias (delay) in the signals of each of the two GPS frequencies. The difference of the instrumental bias of the individual frequencies is known as the differential instrumental bias, also known as interfrequency bias . The ionospheric delay measurements obtained from a dual frequency receiver are corrupted by the differential instrumental biases of the satellites. The instrumental biases must be estimated and removed to obtain accurate estimates of the ionospheric delay. The satellite differential instrumental bias can be as large as 1.5 m[9].

**Errors due to Propagation medium**

The signal propagation errors include the delay of the GPS signal as it passes through the ionospheric and tropospheric layers of the atmosphere.

i) Ionospheric delay: As stated earlier, ionosphere is a region of ionized gases consisting of free electrons and ions, and extends from about 50 km to more than 1000 km. As the GPS signal travels from the satellite to the receiver, the presence of free electrons in the ionosphere changes the velocity (speed and direction) of propagation of the signals. The ionosphere affects the GPS signal propagation by delaying the code phase measurements and advancing the carrier phase measurements [5]. The ionospheric delay for a satellite at zenith, typically varies from about 1 m at nighttime to about 5-15 m during midday . As India comes under equatorial and low latitude region, the spatial and temporal variability of the ionospheric delay is much greater. In an SBAS system, dual frequency GPS data from various reference stations is used for estimating the ionospheric delay corrections for user receivers. The ionospheric group delay (in metres) at GPS L1 frequency can be obtained using dual frequency code measurements as,

$$I_{L1} = \frac{f_2^2}{(f_1^2 - f_2^2)}(P_2 - P_1)$$

where $f_1$=GPS L1 frequency(Hz); $f_2$=GPS L2 frequency (Hz); $P_1$=pseudorange measurement on L1 frequency (m); $P_2$=pseudorange measurement on L2 frequency (m).

ii) Tropospheric delay: The troposphere is the lower part of the earth's atmosphere where temperature decreases with an increase in altitude. The height of the troposphere extends to about 9 km over the poles and upto about 16 km near the equator. The GPS signals are affected by the presence of neutral atoms and molecules in the troposphere .The troposphere causes a delay in both the code phase and carrier phase observations. Unlike the ionosphere, the troposphere is non-dispersive at GPS frequencies. Since the tropospheric delay is not frequency dependent, it cannot be canceled out by using dual frequency measurements. The total tropospheric path delay can be split into two parts: the dry component, which constitutes about 90% of the total refraction, and the wet component, which constitutes the remaining 10%. These models use meteorological data including local temperature, pressure and relative humidity, and satellite elevation angle to compute the tropospheric delay. The tropospheric delay in the zenith direction is about 2 m . The total tropospheric path delay (in metres) using the Hopfield model is given by [7],

$$\Delta^{Trop}(E) = \Delta_d^{Trop}(E) + \Delta_w^{Trop}(E)$$

where $\Delta_d^{Trop}(E)$ is the dry component given by,

$$\Delta_d^{Trop}(E) = \frac{10^{-6}}{5}\frac{77.64\frac{p}{T}}{\sin\sqrt{E^2+6.25}}[40136 + 148.72(T - 273.16)]$$

and $\Delta_w^{Trop}(E)$ is the wet component given by,

$$\Delta_w^{Trop}(E) = \frac{10^{-6}}{5}\frac{-12.96T + 3.718.10^5}{\sin\sqrt{E^2+2.25}}\frac{e}{T^2}11000$$

and $e = 6.1\frac{RH}{100}10^{7.4475T_C/(234.7+T_C)}$ where P=total pressure (millibars); T=absolute temperature (°K); E=elevation angle (degrees); e=partial pressure of water vapour (millibars);RH=relative humidity (%); $T_C$=temperature (°C).

**Receiver based errors**
The errors originating in the receiver include receiver clock error, receiver measurement noise, multipath error, and the receiver instrumental bias error.

i) Receiver clock error: GPS receivers use relatively inexpensive crystal clocks which are less accurate than the satellite clocks. Due to this, the receiver clock error is much higher than that of the satellite clock. The receiver clock error is estimated by considering it as an additional unknown parameter in the user position estimation [16].The pseudorange measurements and satellite positions from four satellites can be solved to determine the user position in three dimensions ($x_u$, $y_u$, $z_u$) and the receiver clock error ( $\delta t_u$ ). The receiver clock error estimated at an epoch of time using the Bancroft algorithm [10] is 98.13 m for a NovAtel make DL-4 plus dual frequency GPS receiver.

ii) Receiver measurement noise: The GPS measurements are affected by random measurement noise which include thermal noise introduced by the antenna, amplifiers, cables, and the receiver; multi-access noise due to interference from other GPS like signals; and signal quantization noise. With modern microprocessor and chip technology, a GPS receiver introduces less than 0.5 m code measurement error and about 1-2 mm carrier phase measurement error due to receiver noise [5].

iii) Multipath error: Occurs when the signal arrives at the receiver via multiple paths due to reflections from the Earth and objects in the vicinity of a receiving antenna [4]. The reflected signals get superimposed on the desired direct-path signal, and distort the amplitude and phase of the direct-path signal. Multipath affects both code and carrier phase measurements, but the magnitude of the error differ significantly. The multipath mitigation techniques employed in the GPS field are broadly classified into three categories: 1. Pre-receiver techniques, 2. Receiver signal processing techniques, 3. Post-receiver signal processing techniques. Pre-receiver techniques include good antenna design and use of choke-ring or pinwheel antennas to reduce the multipath error . The receiver signal processing techniques mostly rely on modifying the tracking loop discriminator so as to resist multipath signals . The multipath error causes about 1-5 m error in code phase measurements and about 1-5 cm in the carrier phase measurements. The smoothing of the code phase measurements using the carrier phase measurements also reduces the effect of code measurement noise and multipath.

iv) Receiver instrumental bias: There exists an instrumental bias error due to the frequency dependent transmission delays caused by the analog hardware within the receiver. The instrumental bias error is specific to dual frequency receivers. This receiver interfrequency bias or differential instrumental bias of the receiver also affects the ionospheric delay measurements. The receiver differential instrumental delay can be as large as 5.0 m . Various methods based on Kalman filtering, Self Calibration Of pseudoRange Error (SCORE) algorithm, and least squares adjustment technique are reported in literature for estimation the instrumental biases of the satellite and receiver along with the TEC using dual frequency GPS data for mid latitude regions [11].

In the GAGAN configuration, 20 TEC stations are located at various places in India. One such station is located at Hyderabad. The dual frequency receivers used at each of these stations are NovAtel receivers. For the estimation of instrumental biases and GDOP, dual frequency GPS data of Hyderabad GAGAN station is considered. The raw data obtained from GPS receiver is converted into the desired Receiver INdependent EXchange (RINEX) format using the 'Convert'software. Two types of RINEX data files, viz. navigation and observation data are used in the processing. The required ephemeris and time parameters are extracted from the navigation data and the satellite position in earth-centered earth-fixed (ECEF) coordinates is computed. The dual frequency GPS code and carrier phase observables are extracted from the observation data. These are used to obtain the phase smoothed slant TEC measurements.

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. 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.

## IV. Methodology For Estimation Of Instrumental Biases And TEC Using

**Kalman Filter Technique**

The methodology adopted in this paper for estimation of the instrumental biases and TEC using the Kalman filter technique is briefly described in this section. The dual frequency GPS code and carrier phase measurements in meters can be expressed as (subscript i = 1, 2, refers to GPS frequencies, f1and f2) followsPseudolite system and its implementation issues. The proposed GAGAN pseudolite-system consists of multiple pseudolites connected to a central control unit (CCU). The CCU can be connected to the INMCC and can access and process the GAGAN messages. It replaces the data on GEO satellites with the corresponding pseudolite-data such as PRN number, position coordinates, differential corrections and integrity information. This modified information is broadcast through pseudolites on L1 frequency. The user equipped with GPS/GAGAN receiver receives the pseudolite signals in addition to GPS/GEO signals. Pseudolites can be synchronized with GPS/SBAS time reference Though pseudolites are made to imitate GAGAN signals, few modifications in hardware and software are required at the receiver level to process pseudoranges due to pseudolites. As ionospheric corrections are not needed for pseudolite signals, relevant software modifications in the receiver are necessary. Since all the pseudolites are at surveyed locations on the ground, ephemeris corrections are not required. Also stable clocks can be used by pseudolites and can be highly synchronized with the system time to avoid clock errors. Pseudolite signals are susceptible to multi-path disturbances. One of the important techniques to mitigate multi-path effects is shaping of the antenna radiation pattern.

The Extended Kalman Fitering (EKF) is the best known method which is derived by linearizing the system of equations at each time step and applying the Kalman filter technique for the linear system. The key property of the EKF is that it is applied to neural network training, it leads to faster convergence property than the gradient-based algorithm.The EKF algorithm provides first-order approximations to optimal nonlinear estimation through the linearization of the nonlinear system. However, these approximations can include large errors in the true posterior mean and covariance of the transformed (Gaussian ) random svariable, which may lead to suboptimal performance and sometimes divergence of the filter[12].

Unsciented Kalman filter (UKF) First proposed by julier and Uhlmann and furhter extended by Wan and van de Mere is preferable to the EKF for the two important reasons :

The UKF is accurate to the third order for process and measurement errors that are Gaussian distributed, and assuming the prior state is Gaussian. For non- gaussian distributions, the UKF is accurate to at least the second order. Accordingly, the UKF may afford a better performance than EKF. Unlike the EKF, the UKF does not require the computation of Jacobieans, needed for linearizing the process and measurement; hence, the UKF, is simpler than the EKF in implementation. Three satellites are used because of a process of trilateration. In the same way that it takes measurements from three points to determine a position on a flat surface (i.e., 2D trilateration), measurements from three satellites are necessary to determine a position on a three-dimensional Earth (i.e., 3D trilateration). By measuring the distance to one satellite, the user will be placed somewhere on the surface of a sphere. By measuring the distance to two satellites, the user will be placed somewhere along the edge of a common boundary between two spheres. However, by measuring distances to three satellites, there are only two places that the three spheres will intersect, and only one of them will be on the Earth's surface. A fourth satellite is used to remove the second intersection point and also to correct for any timing errors between the satellite clocks and the receiver clocks[13]is as shown in the figure (7 [a-c]).

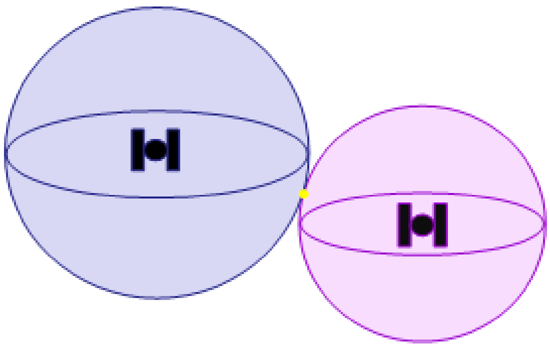

**Figure .7(a).** Two satellites (1-D) Positioning model

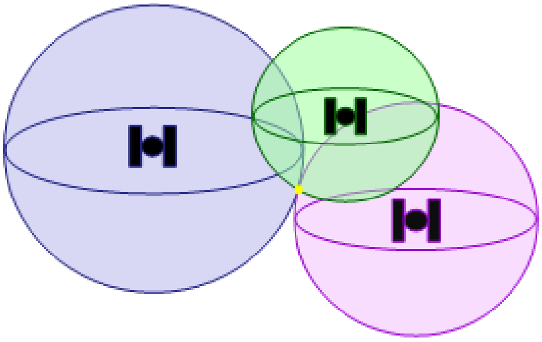

**Figure 7(b).** Three satellites (2-D) Positioning model

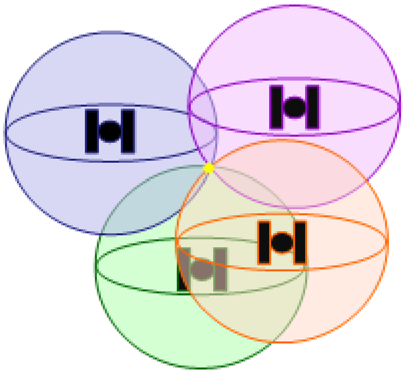

**Figure7(c).** Four satellites (3-D) Positioning model

**Simulation of Extended Kalman filter for GPS positioning :**

The application of GPS Aided GEO Augmented Navigation , signal tracking and measuring positional errors using the ExtendedKalman Filtering function is described in this section. The pseudorange and satellite position of a GPS receiver at fixed location for a period of 25 seconds is provided. Least squares and Extended KF are used for this task. The following is a brief illustration of the principles of GPS[14]. The Global Positioning System(GPS) is a satellite-based navigation system that provides a user with proper equipment access to positioning information. The most commonly used approaches for GPS positioning are the Iterative Least Square(ILS) and the Kalman filtering(KF) methods. Both of them is based on the pseudorange equation:

$$rho = \| Xs - X \| + b + v$$

in which Xs and X represent the position of the satellite and receiver, respectively, and $\| Xs - X \|$ represents the distance between them. b represents the clock bias of receiver, and it need to be solved along with the position of receiver. rho is a measurement given by receiver for each satellites, and v is the pseudorange measurement noise modeled as white noise. There are 4 unknowns: the coordinate of receiver position X and the clock bias b. The ILS can be used to calculate these unknowns and is implemented in this example as a comparison. In the KF solution we use the Extended Kalman filter (EKF)[15] to deal with the nonlinearity of the pseudorange equation, and a CV model (constant velocity)[1] as the process model. It is also found that the results are consistent over the period and the method is accurate and faster for real-time applications like GAGAN systems.

The position computation in GPS is based on the measurement of time, which is required for the signal to propagate from the satellite to the receiver. The simulations of relative positioning errors in x,y and z directions is shown in figure (8). Relative Measurement Of Initial State Estimates and its error performance in Tracking of GAGAN signal is simulated is shown in Figure (9) and figure (10).

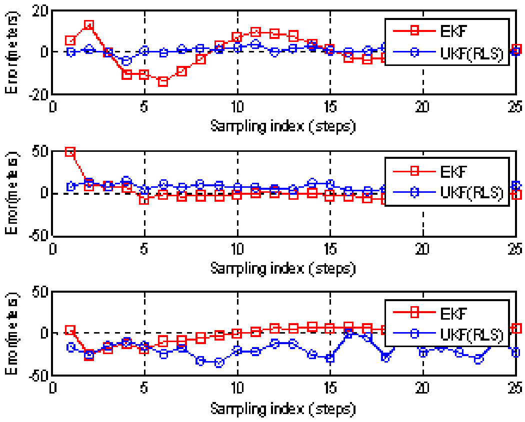


**Figure (8).** Relative positional errors in Tracking of GAGAN signal

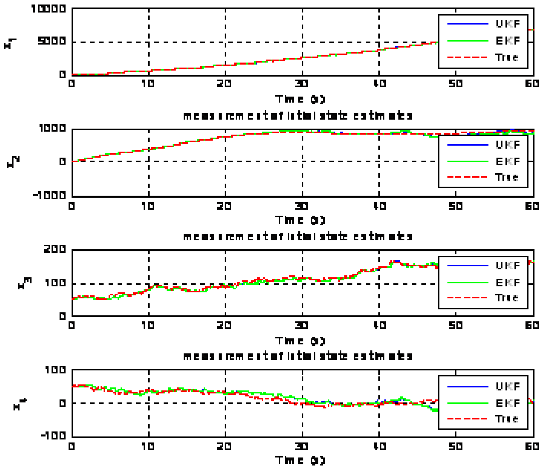


**Figure (9).** Relative Measurement Of Initial State Estimates in Tracking of GAGAN signal

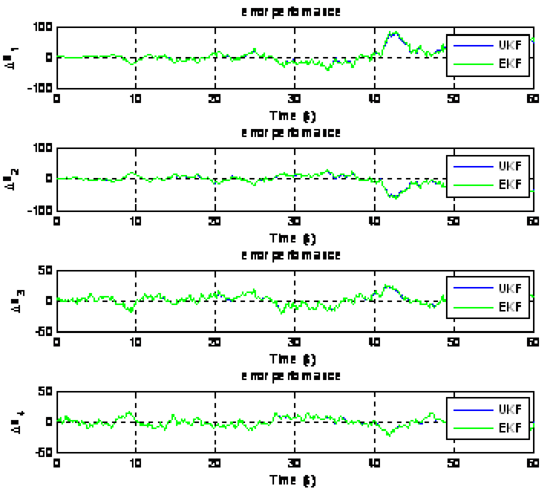


**Figure (10).** Relative Measurement Of ErrorPerformancefor Initial State Estimates in Tracking of Gagan signal

## V. User Equivalent Range Error

The significance of various errors and biases that affect the accuracy of GPS/ SBAS system are discussed. However, one needs a parameter that signifies the effect of all errors. User Equivalent Range Error (UERE) is one such parameter. It is a statistical ranging error that represents the total effect of all the contributing error sources. UERE is defined as the root-sum-square of the various error sources affecting the pseudorange measurement, all expressed in units of length [3,8],

$$\sigma_{UERE} = \sqrt{\sigma_{R1}^2 + \sigma_{R2}^2 + ..... + \sigma_{Rn}^2}$$

where $\sigma_{R1}, \sigma_{R2}, ..., \sigma_{Rn}$ are the rms range errors due to various error sources.

The **analysis of errors computed using the Global Positioning System** is important for understanding how GPS works, and for knowing what magnitude errors should be expected. The Global Positioning System makes corrections for receiver clock errors and other effects but there are still residual errors which are not corrected. User vehicle position is computed by the receiver based on data received from the satellites. Errors depend on geometric dilution of precision and the sources listed in the table below.

**Table:2 Sources of User Equivalent Range Errors (UERE)**

| **Source** | **Effect (m)** |
|---|---|
| Signal arrival C/A | ±3 |
| Signal arrival P(Y) | ±0.3 |
| Ionospheric effects | ±5 |
| Ephemeris errors | ±2.5 |
| Satellite clock errors | ±2 |
| Multipath distortion | ±1 |
| Tropospheric effects | ±0.5 |
| $3\sigma_R C/A$ | ±6.7 |
| $3\sigma_R P(Y)$ | ±6.0 |

Geometric error diagram showing typical relation of indicated position, intersection of sphere surfaces and true receiver position in terms of pseudorange errors, PDOP and Numerical Errors is in fig (11).

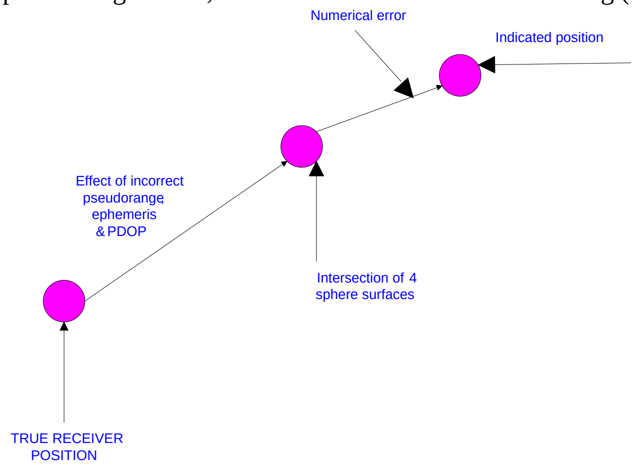


**Figure 11.**Pseudorange errors, PDOP and Numerical Errors

The term user equivalent range error (UERE) refers to the error of a component in the distance from receiver to a satellite. These UERE errors are given as ± errors thereby implying that they are unbiased or zero mean errors. These UERE errors are therefore used in computing standard deviations. The standard deviation of the error in receiver position, , is computed by multiplying PDOP (Position Dilution Of Precision) by , the standard deviation of the user equivalent range errors. is computed by taking the square root of the sum of the squares of the individual component standard deviations.PDOP is computed as a function of receiver and satellite positions. A detailed description of how to calculate PDOP is given in the section, geometric dilution of precision computation (GDOP).

$\sigma_R$ for the C/A code is given by:

$$3\sigma_R = \sqrt{3^2 + 5^2 + 2.5^2 + 2^2 + 1^2 + 0.5^2}\, m = 6.7m$$

The standard deviation of the error in estimated receiver position , $\sigma_{rc}$ again for the C/A code is given by:

$$\sigma_{rc} = \sqrt{(PDOP^2 \times \sigma_R^2 + \sigma_{num}^2)} = \sqrt{(PDOP^2 \times 2.2^2 + 1^2)}\, m$$

The error diagram on the left shows the inter relationship of indicated receiver position, true receiver position, and the intersection of the four sphere surfaces. The GAGAN accuracy and GPS accuracy visually represented in the figure (12).

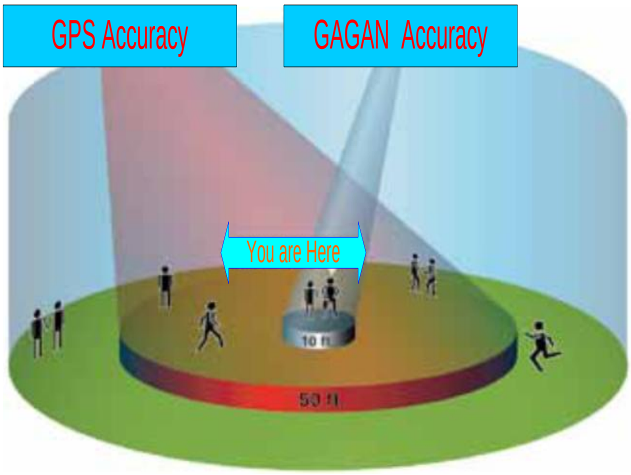


**Figure (12).** Accuracy GAGAN vs. GPS

**Estimation of Error Corrections using Dual Frequency GPS Receiver Data**

Under the GAGAN project, about 20 reference stations are located at various places covering the entire Indian subcontinent. Limited data provided by Space Applications Centre, ISRO, Ahmedabad, India is used for estimation of various errors. The data is acquired at a sampling rate of 60 Hz. The raw data is converted into the Receiver Independent Exchange (RINEX) format using "Convert" software. Three different file types are defined in RINEX, viz. navigation, observation and meteorological data. From the navigation data, 16 ephemeris parameters and 3 clock coefficients are extracted along with time of epoch ($t_{oc}$) and the space vehicle time ($t_{SV}$). These parameters are used to compute the GPS time, satellite position and SV clock correction. The dual frequency carrier phase and pseudoranges are extracted from the observation data. The data processing involves estimation of the various errors, and correction of the measured pseudoranges to provide more accurate pseudorange information. Table 3. shows a typical GPS error budget calculation assuming an HDOP of 1.5 and VDOP of 2.0. The Hyderabad GAGAN station data is used in the estimation of ionospheric delay ,tropospheric delay, multipath error and instrumental biases. The satellite position of various satellites and the corresponding pseudoranges are used to compute the receiver position using Bancroft algorithm [10].

BANCROFT Calculation of preliminary coordinates for a GPS receiver based on pseudoranges to 4 or more satellites. The ECEF coordinates are the first three elements of each row of B. The fourth element of each row of B contains the observed pseudorange. Each row pertains to one satellite. The pseudorange in the first row of B is used to discriminate between the two possible solutions.

**Test values to use in debugging (Bancroft algorithm):**

B =[ -11716227.778 -10118754.628 21741083.973 22163882.029;
-12082643.974 -20428242.179 11741374.154 21492579.823;
14373286.650 -10448439.349 19596404.858 21492492.771;
10278432.244 -21116508.618 -12689101.970 25284588.982];

| Possible positions | values |
|---|---|
| pos(1) = X | 594999.34 |
| pos(2) = Y | -4856504.29 |
| pos(3) = Z | 4078331.01 |
| pos(4) = c*dt | 147.86 |

The slant ionospheric delay is computed from the precise carrier phase observables after removal of integer ambiguities. Further, the elevation angle, slant factor, and ionospheric pierce point coordinates are computed. These parameters along with the slant ionospheric delay are fed to a five state Kalman filter for estimating the receiver instrumental bias (Sunehra et al, 2010. The satellite instrumental bias (PRN 26) provided by Centre for Orbit Determination (CODE), Europe is used in the estimation. The tropospheric delay is estimated by using the pressure, temperature and relative humidity parameters obtained from the meteorological data.The multipath error is estimated using the TEQC software available in public domain.For ephemeris error, satellite clock error and receiver noise, typical values reported in literature are used [5].After estimating the range error due to various sources, UERE is computed.Multiplying the UERE by twice the appropriate Dilution of Precision (DOP) value produces the expected precision of the GPS positioning at the two-sigma ($2\sigma$) level.

**Table 3:** GPS Error Budget Computation(Hyderabad GAGAN station, 4 March 2013, PRN 26, El: 45.91°, 01:30 hrs LT)

| S.No. | Error Source | RMS range error (m) |
|---|---|---|
| 1. | Ephemeris error | 1.5 |
| 2. | Satellite clock error | 1.5 |
| 3. | Tropospheric delay | 2.78 |
| 4. | Ionospheric delay | 6.15 |
| 5. | Receiver noise | 0.5 |
| 6. | Multipath error | 0.18 |
| 7. | Satellite instrumental bias | 0.55 |
| 8. | Receiver instrumental bias | 1.49 |
| **System UERE, rms** | | 7.27 |
| **Horizontal position error (2 $\sigma$ ), m** (= 2×HDOP×UERE) | | 21.81 |
| **Vertical position error (2 $\sigma$ ), m** (= 2×VDOP×UERE) | | 29.08 |

Table 3 presents the rms range error obtained due to various error sources, UERE and the horizontal and vertical position errors in metres. UERE due to all the error sources is of the order of 7.27 m. The positional accuracy of the Global Positioning System (GPS) is limited due to several error sources. The major error is ionosphere. By augmenting the GPS, the Category I (CAT I) Precision Approach (PA) requirements can be achieved. The Space-Based Augmentation System (SBAS) in India is known as GPS Aided Geo Augmented Navigation (GAGAN). One of the prominent errors in GAGAN that limits the positional accuracy is instrumental biases. Calibration of these biases is particularly important in achieving the CAT I PA landings[18].

## VI. Conclusion

The dual frequency GPS code and carrier phase observations are affected by various biases and errors. In order to obtain better position estimates, it is necessary to correct the GPS observations for various errors. In this investigation, prominent existing methods are used for estimation of various errors for improving the position accuracy. It is obvious from the GPS error budget (Table 3) that ionospheric delay is the most predominant error and is typically of the order of 5-15 m during midday. The dual frequency GPS receiver can be used to estimate the ionospheric delay accurately. However, the instrumental biases of the satellite and receiver affect the ionospheric delay measurements obtained from a dual frequency receiver. The instrumental delay due to the satellite can cause an error as large as 1.5 m in the ionospheric delay estimate, whereas the instrumental delay due to the receiver can be as large as 5 m. In order to estimate the ionospheric delay accurately, these instrumental biases have to be estimated and removed. The data processing methods suggested here can be extended to other GAGAN stations. C/A codes are generated and simulated using matlab . The satellite position of various satellites and the corresponding pseudoranges are used to compute the receiver position using Bancroft algorithm with matlab simulations. The positional accuracy of the GAGAN is limited due to several error sources can be minimized using tracking of GPS signal using EKF/UKF. Simulations are conducted for estimation of instrumental biases and TEC using the Extended Kalman filter technique to mitigate multi-path effects in GAGAN systems.

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