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Modelling and Simulation of Pseudolite-based Navigation: A GPS-independent Radio Navigation System

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ABSTRACT

The use of global positioning system (GPS) for precision guidance of weapons is being questioned due to its vulnerability of jamming and spoofing for non-military code users. In this paper a novel approach is proposed for guidance of weapons where use of GPS or other civilian Satellite-based navigation system is threatened. The proposed approach is modelled and simulated using SIMULINK for realistic trajectories and scenario. The results of simulation are validated with the actual GPS data.

Keywords: Pseudolite, global navigation satellite system, indian regional navigation satellite system, inverted positioning, carrier phase navigation

1. INTRODUCTION

There are three potential risks involved in using global positioning system (GPS), any civil global navigation satellite system (GNSS) or Indian regional navigation satellite system (IRNSS) based navigation system for military applications. These are integrity risk, availability risk and accuracy risk. Integrity risk is involved due to deceptive jamming or spoofing of the receiver, and hence, can be misguided to give wrong navigation solution. Availability risks are due to full control of system by the foreign agencies or civil authority and due to intentional and unintentional in-band interferences for civil system, due to which the signal can be degraded in critical situations. The third is accuracy risk. This is due to the fact that the civil code is not very accurate for guidance of weapon systems for military applications. Using authorised civil code, one cannot get accuracy better than few tens of meters. To mitigate the risks involved in using civil GNSS or IRNSS, i.e., integrity, availability, and accuracy under jamming environment, there is a requirement to develop a radio navigation system which will augment the functionality of the existing satellite-based navigation system in a normal situation and in a critical situation should be able to provide precise navigation solution independent of civil navigation satellite systems.

The existing systems using pseudolite reported in literature are mainly for augmentation of the existing GPS system. Tuhino[1], *et al*. mentioned that a pseudolite based battlefield navigation system has been developed by Rockwell Collins (an American military hardware developer) in partnership with DARPA, UAV Battle lab and SSC, San Diego, Calofornia. This system augments the GPS-based system. Dovis[2], *et al.* explain the use of GPS pseudolite for guiding the rover. LeMaster[3], *et al.* proposed a pseudolite based local navigation system for mars navigation system independent of GPS. The proposed pseudolite transceiver placed on the Mars surface can self-calibrate the position of pseudolite transmitter and does not need any external aid for navigation of rover to be deployed on Mars. Similar concept is used in this paper with difference of using pseudolite transceiver on high altitude platform such as airship and use of improved algorithm such that the user equipped with pseudolite receiver can get position fix with accuracy >10 m. Also the degradation of GDOP due to practical constraint of deployment of pseudolite transceiver is mitigated by reducing the errors in pseudorange by carrier phase measurement scheme and differencing mechanism. The proposed concept is modelled and simulated using SIMULINK in integrated manner so that the final user position can be fixed with an accuracy of 10 m. The simulation was carried out for the independent mode of operation of pseudolites.

2. PROPOSED APPROACH

Five number of pseudolite transceivers (required for double differencing algorithm mentioned in Section 4.0) will be placed on high altitude platform such as airship, for local area navigation, which will generate GPS like signal as shown in Fig. 1. The whole system will be divided in three parts–high altitude platform segment, ground segment, and user segment. The high altitude platform segment will consists the pseudolite transceivers placed on high altitude platform. The ground segment will consists ground-based pseudolite transceivers and the control centre for finding the position of pseudolite transceivers placed on high

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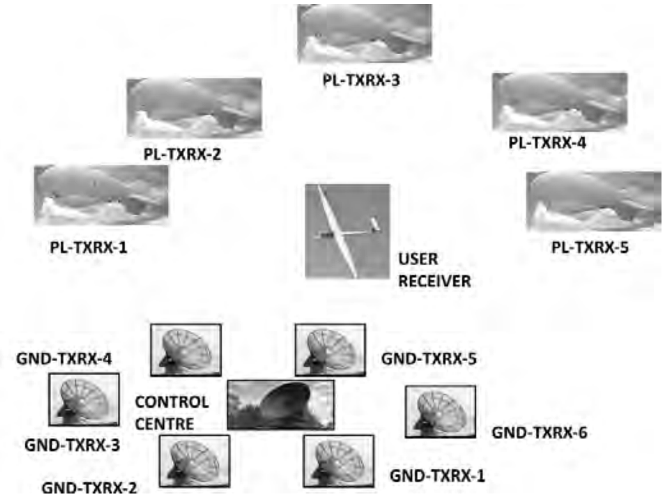

Figure 1. The proposed prototype for the system showing five pseudolite transceivers placed on high altitude platform (PL-TXRX 1 to 5), six ground-based pseudolite transceivers (GNDTXRX 1 to 6), and the user pseudolite receiver

altitude platform. The user segment will consists the pseudolite receiver placed on user platform such as aircraft for which the position fixing will be required. The network of pseudolite transceivers placed on ground as a part of ground segment will use inverted GPS concept[4] to find the position of pseudolite transceivers placed on high altitude platform. The computed position of pseudolite transceivers placed on high altitude platform along with timing information will be broadcasted as navigation signal similar to GPS satellite signal. By selecting the suitable frequency of operation and the navigation message structure, it is ensured that this system will not affect the operation of GPS or other satellite-based navigation system. The pseudolite receiver in user segment will be minimum four pseudolite signals of high altitude platform segment to find the position fix similar to GPS receiver.

Many applications do not allow the optimum placement of ground-based transceiver and high altitude platform to get good GDOP. So the algorithm used to find the position of pseudolite transceiver placed on high altitude platform and user pseudolite receiver will be designed such that user equivalent range error (UERE) is minimised, e.g., if best possible GDOP is 100, then User range error (URE) shall be minimised to 10 cm to get position accuracy better than 10 m. The centimeter accuracy level-positioning algorithm is reported[5] using carrier phase-based pseudorange measurement for indoor applications. Hence, following two algorithms proposed to minimise the UERE:

1. Bi-directional self-differenced carrier phase measurement algorithm for finding the position of pseudolite placed on high altitude platform.
2. Double-differenced carrier phase differential GPS algorithm for finding the position of pseudolite receiver in the user segment.

A detailed description of each algorithm is given in the following sections. This algorithm is modelled using SIMULINK and detailed simulation was carried out to find out the suitability of these algorithms.

3. POSITION COMPUTATION OF PSEUDOLITE TRANSCEIVER PLACED ON HIGH ALTITUDE PLATFORM

GPS transceiver, which combines the function of a GPS receiver and pseudolite (PL), has been proposed by LeMaster[3], *et al.* Such GPS transceivers can communicate and synchronise each other, and then estimate relative positions using the ranging information among them. Conventional GPS pseudolite arrays require that the devices be pre-calibrated through a survey of their locations, typically to sub-centimeter accuracy. This can sometimes be a difficult task, especially in remote or hazardous environments. Using the GPS signals that pseudolites will broadcast, however, it is possible to have the arrays self-survey their own relative locations, creating a self-calibrating pseudolite array (SCPA), and hence, position error of ground-based pseudolite will be self-calibrated and initial inaccuracies will be taken care by this method[3].

To provide the bi-directional ranging signals between devices necessary for array self-calibration, pseudolite transceivers must be used. The basic principles behind the use of transceivers is to create an SCPA were first presented by LeMaster[3], *et.al.* The same algorithm will be used for finding the position of pseudolite transceiver placed on high altitude platform with a difference of carrier phase measurement instead of code phase, as proposed[3].

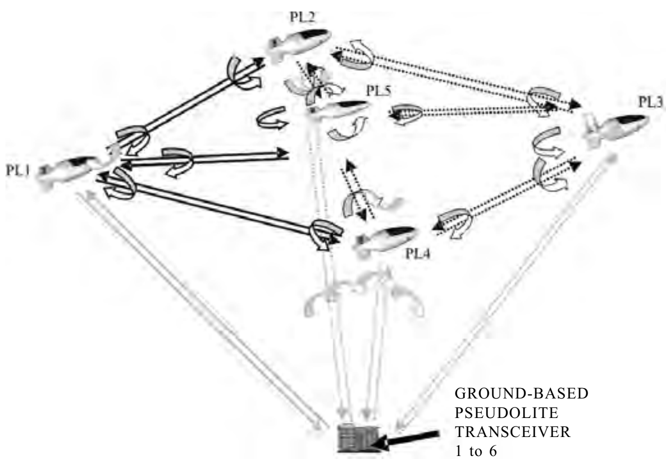

Figure 2. Five pseudolite transceivers placed on high altitude platform and ground-based transceivers for the formation of self-differencing equation.

In the proposed algorithm, first the inter-transceiver ranging and self-differencing will be done among them and with the ground-based pseudolite transceivers 1 to 6.

The simplest navigation solution using self-differencing transceivers directly determines the range between the antennas on a pair of devices themselves. Figure 3 shows

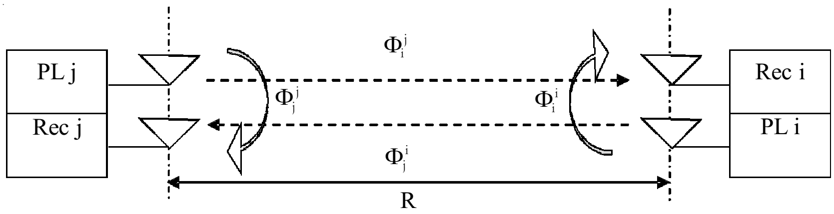

Figure 3. A pair of pseudolite transceiver for formation of self difference equation.

following such pair of devices:

b_i^j Line bias from PL j to Rec i.
R_{ij} Range between device antennas.
Φ_i^j Rec i's measurement of PL j.
$\hat{o}^j$ Clock bias of PL j.
$\hat{o}_i$ Clock bias of Rec

The measurements taken by each receiver of the signals from the two pseudolites are given as

$$\begin{Bmatrix} \Phi_i^i \\ \Phi_i^j \\ \Phi_j^i \\ \Phi_j^j \end{Bmatrix} = \begin{Bmatrix} b_i^i \\ b_i^j \\ b_j^i \\ b_j^j \end{Bmatrix} + \begin{Bmatrix} \tau^i \\ \tau^j \\ \tau^i \\ \tau^j \end{Bmatrix} + \begin{Bmatrix} \tau_i \\ \tau_i \\ \tau_j \\ \tau_j \end{Bmatrix} + \begin{Bmatrix} 0 \\ R_{ij} \\ 0 \\ R_{ij} \end{Bmatrix}$$

Eliminating any receiver clock biases or common mode effects by taking internal single (self) differences between the signals received by a given receiver, as shown

$$\ddot{A}\Phi_i = \Phi_i^j - \Phi_i^i = (b_i^j - b_i^i) + (\tau^j - \tau^i) + R_{ij} \qquad (1)$$

$$\ddot{A}\Phi_j = \Phi_j^j - \Phi_j^i = (b_j^j - b_j^i) + (\tau^j - \tau^i) - R_{ij} \qquad (2)$$

Combining the measurements from both receivers and inverting the above equation, one can determine both range between the antenna pair and the relative clock bias of the pseudolite transceivers.

$$\begin{Bmatrix} \tau^j - \tau^i \\ R_{ij} \end{Bmatrix} \frac{1}{2} \left\{ \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix} \begin{Bmatrix} \Delta\Phi_i \\ \Delta\Phi_j \end{Bmatrix} \right\} \begin{Bmatrix} b_i^j - b_i^i \\ b_j^j - b_j^i \end{Bmatrix}$$

By forming the vectors of inter-transceiver ranging and clock biases among the pseudolite transceivers placed on high altitude platform and six ground-based transceivers, the SCPA algorithm was used as mentioned by LeMaster[3], *et al.* with a difference that in LeMaster[3], *et al* 's proposal, the rover has to move in predetermined trajectory for collecting inter-transceiver ranges, but the authors have proposed six number of ground-based pseudolite transceivers for collecting these ranges. The ILS (iterative least square) technique was used to get position of all the five pseudolite transceivers placed on high altitude platform, as mentioned by LeMaster[3], *et al.*

Since this algorithm computes the position of pseudolite transceiver placed on high altitude platform every second, the position instability due to rotational and translational motions of high altitude platform does not affect the final user accuracy significantly as the position of these platform gets updated every second and pseudorange measurement with carrier phase for user pseudolite receiver position fixing is done with each updated position of pseudolite transceiver placed on high altitude platform.

4. POSITION COMPUTATION OF PSEUDOLITE RECEIVER IN USER SEGMENT

The position and relative clock bias of each pseudolite transceiver placed on high altitude platform will be computed using methodology mentioned in Section 3. This information will be broadcasted similar to GPS satellite signal. The pseudolite receiver in user segment (UserPL receiver) will receive these signals and will compute its position. In many practical scenarios, the GDOP will not be good enough to give the position accuracy better than 10 m. Hence a double difference carrier phase measurement technique has been proposed to reduce the pseudorange error to give user equivalent range error (UERE) < 10 cm. So even if GDOP due to deployment constraint of high altitude platform is 100, the final user position accuracy will be better than 10 m.

The most basic solution method for carrier differential GPS (CDGPS) is called 'single-differencing,' and involves the subtraction of ranging measurements from the user and the reference station on a pseudolite-by-pseudolite basis. In this process, the pseudolite clock bias, which is identical for both users, is eliminated. The atmospheric error is also assumed to be nearly identical and is therefore eliminated. In practical scenario the residual will remain after single differencing. But these residuals will be significantly less than individual atmospheric errors.

Double difference is performed by subtracting the single differences from two pseudolites. In this formulation, the clock biases between the receivers are also eliminated because these are common between each single-difference. More importantly, assuming that each receiver has only one antenna, the differential line bias between the two receivers will be the same for each pseudolite, and therefore also cancels. This simplifies the practical aspects of the design, because no line bias calibration will be needed.

In finding the double difference solution, it is assumed that user pseudolite receiver has line-of-sight from all the pseudolite transceiver placed on high altitude platform. Figure 4 illustrates the double-difference scheme.

Out of five pseudolite transceivers placed on high altitude platform (as shown in Fig. 2) four will be used for formulating the double-difference carrier observable for generating one set of double-difference equation for the user pseudolite receiver. Fifth one is assumed to be reference pseudolite transceiver (Ref PL). Thus, four sets of pseudolite transceivers are formed as (PL1, PL2, Ref PL, user PL receiver), (PL1, PL3, Ref Pl, user PL receiver), (PL1, PL4, Ref Pl, user PL receiver), and (PL2, PL4, Ref Pl, user PL receiver).

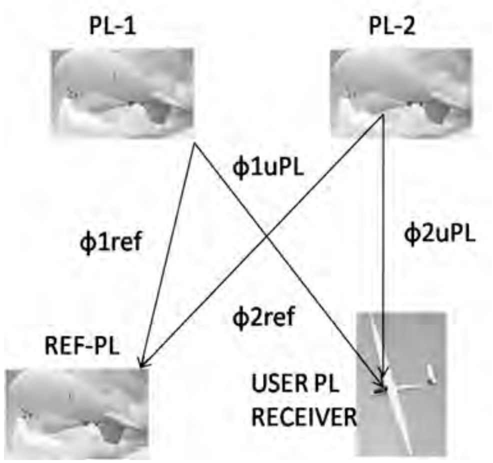

Figure 4. Formation of double-difference equation.

Using each set, one double-difference equation will be generated. Thus, the above four sets gives the four double-differenced equations. These four equations will be solved by least square technique to give four unknowns, i.e., *x*, *y*, *z* coordinates of user PL receiver and integer ambiguity. It is to be noted that the clock bias error of user gets cancelled due to double-difference mechanism. Integer ambiguity needs to be resolved since it is unknown in the carrier phase measurement. Figure 4 illustrates the mechanism for generating a double-difference equation for the set (PL1, PL2, Ref PL, user PL receiver). As shown in Fig. 4, the following carrier phase observable equations are formed. The ionospheric delay errors is assumed to be zero as all transmitters are below the ionosphere.

Φ1ref =[(true_range_1_ref + tropo_del _1_ref + clk_biases_1 + multi_del_1_ref +xr_noise_ref)/lam] – N_1_Ref

Φ1uPL=[(true_range_1_UPL + tropo_del_1_UPL +clk_biases_1 + multi_del_1_UPL +xr_noise_UPL)/lam] – N_1_UPL

Φ2ref =[(true_range_2_ref + tropo_del _2_ref +clk_biases_2_+ multi_del_2_ref +xr_noise_ref)/lam] – N_2_Ref

Φ2uPL=[(true_range_2_UPL + tropo_del_2_UPL +clk_biases_2 + multi_del_2_UPL +xr_noise_UPL)/lam] – N_2_UPL

where,

Φmref = carrier phase observable between pseudolite transmitter m

(m=1,2,3,4) and reference pseudolite receiver

ΦmuPL= carrier phase observable between pseudolite transmitter m

(m=1,2,3,4) and user pseudolite receiver

true_range_m_ref = true geometric range between pseudolite transmitter m (m=1,2,3,4) and reference pseudolite receiver

true_range_m_UPL= true geometric range between pseudolite transmitter m (m=1,2,3,4) and user pseudolite receiver

tropo_del _m_ref= tropospheric delay error between pseudolite transmitter m (m=1,2,3,4) and reference pseudolite receiver

tropo_del_1_UPL = tropospheric delay error between pseudolite transmitter m (m=1,2,3,4) and user pseudolite receiver

clk_biases_m = clock error at pseudolite transmitter m (m=1,2,3,4)

multi_del_1_ref = multipath error between pseudolite transmitter m (m=1,2,3,4) and reference pseudolite receiver

multi_del_1_UPL= multipath error between pseudolite transmitter m (m=1,2,3,4) and User pseudolite receiver

xr_noise_ref = reference pseudolite receiver measurement noise error

xr_noise_UPL= user pseudolite receiver measurement noise error

lam= Wavelength of carrier wave

N_m_Ref = integer ambiguity between pseudolite transmitter m (m=1,2,3,4) and reference pseudolite receiver

N_m_UPL = integer ambiguity between pseudolite transmitter m (m=1,2,3,4) and user pseudolite receiver

By taking first single difference

▲ $\Phi1_{PL1\_PL2}$ = Φ1ref-Ö1uPL=[((true_range_1_ref-true_range_1_UPL) + (tropo_del _1_ref - tropo_del_1_UPL) ++(multi_del_1_ref - multi_del_1_UPL) + (xr_noise_ref-xr_noise_UPL))/lam] + (N_1_UPL- N_1_Ref)

Similarly, by taking second single difference

▲ $\Phi2_{PL1\_PL2}$ = Φ2ref-Φ2uPL=[((true_range_2_ref-true_range_2_UPL) + (tropo_del _2_ref - tropo_del_2_UPL) ++(multi_del_2_ref - multi_del_2_UPL) + (xr_noise_ref-xr_noise_UPL))/lam] + (N_2_UPL- N_2_Ref)

Finally, taking the double difference

▼▲ $\Phi_{PL1\_PL2} = \Phi1_{PL1\_PL2} - \Phi2_{PL1\_PL2}$ = [((true_range_1_ref - true_range_1_UPL- true_range_2_ref + true_range_2_UPL) + (tropo_del _1_ref - tropo_del_1_UPL - tropo_del _2_ref + tropo_del_2_UPL) +(multi_del_1_ref - multi_del_1_UPL-multi_del_2_ref + multi_del_2_UPL))/lam] + (N_1_UPL-N_1_Ref - N_2_UPL + N_2_Ref)

It is to be noted that the clock bias error of PL1, PL2 ref Pl and User PL receiver gets cancelled. If pseudolite transmitters are geographically less separated, i.e., within 50 km ranges, all atmospheric errors, i.e., tropospheric delay errors get cancelled. Beyond 50 km separation, it is assumed that the atmospheric errors get corrected as in the case of wide area DGPS technique, and hence, error due to this is minimal. Other errors give a residual error which is minimised in the pseudolite receiver using least

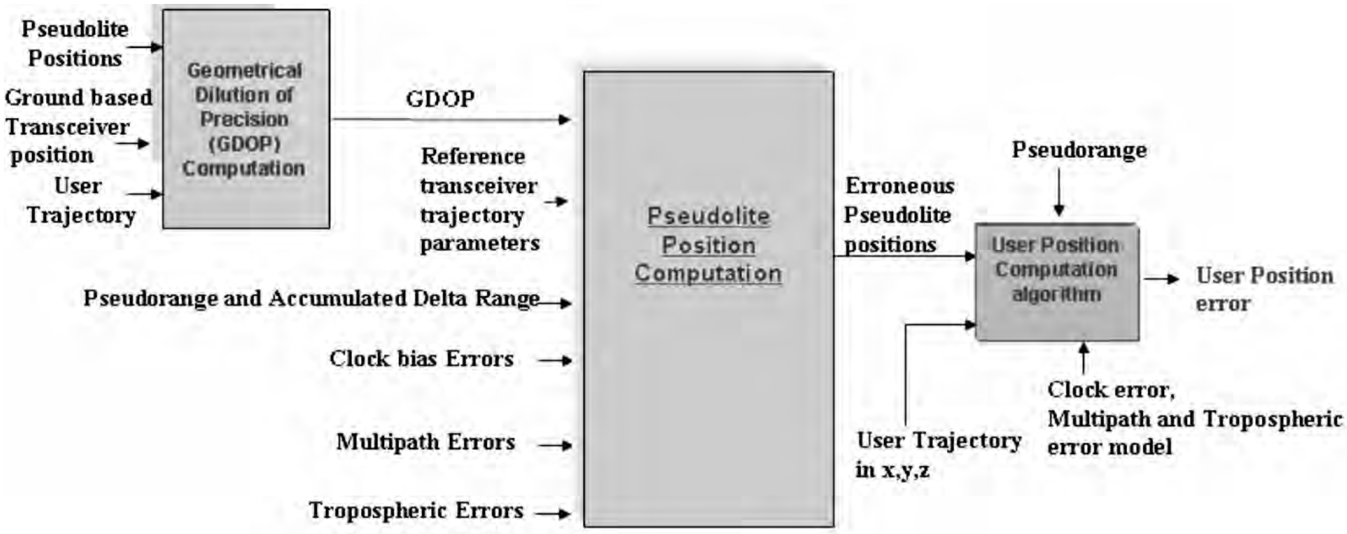

Figure 5. Modelling and simulation scheme.

square technique while solving the four double difference equations and better error models.

5. MODELLING AND SIMULATION SCHEME

Figure 5 shows three main modules-geometrical dilution of precision computation (GDOP), position computation of pseudolite transceiver placed on high altitude platform, and position computation of pseudolite receiver in user segment. GDOP module computes the optimum GDOP possible for the position computation of pseudolite transceiver placed on high altitude platform for a possible combination of ground based transceivers. The GDOP computation block takes input as erroneous position of pseudolite transceiver placed on high altitude platform and ground-based transceivers positions which are further optimised for minimum GDOP for particular user nominal trajectories[7]. The GDOP computation for user pseudolite receiver is done in user position computation algorithm to give the final position accuracy achievable.

The optimum PL position for minimum GDOP thus computed goes as input to pseudolite position computation module, which uses algorithm explained in Section 3. The erroneous pseudolite position given to the user position computation block simulates the carrier phase double difference pseudorange measurement algorithm as mentioned in Section 4. The navigation algorithm finds the position of user at each simulation time step. The computed user positions at each sample point are compared with the user nominal trajectories to find out the error in user position computation algorithm.

These algorithms also take errors input for clock bias, multipath, and tropospheric delays. Ionosphiric delay errors are not considered since the high altitude platform and user pseudolite receiver are placed below the Ionosphere. The error models for troposphere, multipath, clock bias model, pseudorange and accumulated delta range measurement are used from GPS simulation tool box (by LUPASH Consulting, USA) and integrated with the three module as shown in Fig. 5.

6. SIMULATION SCENARIO

Figure 6 depicts a typical scenario used for the simulation. The user nominal trajectory is taken to cover a range of maximum 500 km. The position of ground-based transceiver is varied within 100 km × 100 km area near to launch point

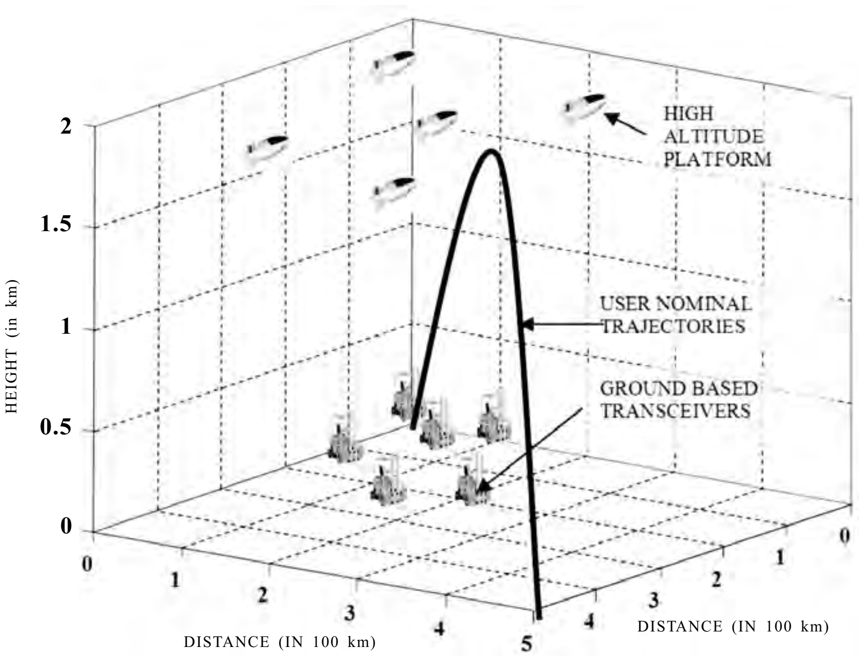

Figure 6. Typical simulation scenario.

of user nominal trajectory to simulate the situation of constrained situation where the ground station can not be placed very near to end part of user nominal trajectory. Similarly, the position of high altitude platform is also placed within 100 km × 100 km area near to launch point of user nominal trajectory. The height of the high altitude platform is varied between 15 km to 20 km to ensure the line-of-sight between pseudolite transceiver placed on high altitude platform and user pseudolite receiver. To simulate the drift in the high altitude platform, position (x, y, z) of pseudolite transceiver placed on high altitude platform is varied randomly in all 360° direction to simulate translation and rotational movement of the high altitude platform. To simulate the geographical separation among the pseudolite transceivers, different values of errors due to tropospheric propagation delay, multipath, clock bias error, and pseudorange measurement noise are considered randomly as shown in Table 1, e.g., the multipath model was simulated and error due to multipath was generated by varying the value of C/N (in dB-Hz) from 15 dB-Hz to 55 dB-Hz. The clock model was simulated and error due to transmitter and receiver clock was generated by varying the value of sb from 4.e-10 to 4.e-25 and sf was varied from 1.5791e-10 to 1.5791e-25 in GPS toolbox-provided model. The tropospheric model was simulated using Black & Eisner Model[6] in the GPS toolbox. The tropospahereic model was simulated and error due to troposphere was generated by varying the atmospheric pressure from 1 mBar to 2 mBar, T from 273 K to 300 K, and elevation angle from 15° to 90°.

GDOP computation simulation scenario is considered integrated for the pseudolite transceiver placed on high altitude platform and user pseudolite receiver. For a given nominal trajectory of user pseudolite receiver the optimum location of high altitude platform was computed as discussed by Sarma[7]. It is ensured that throughout the area of operation of user pseudolite receiver the GDOP value should not exceed more than 100. Once the optimum location of pseudolite transceiver is found then by varying the positions on ground-based transceiver, GDOP values of all five transceiver placed on high altitude platform were computed. The positions of ground based pseudolite transceiver was varied so that it is optimized to get the GDOP values of all the five transceiver placed on high altitude platform so that the GDOP value of each one should not exceed 100 .The optimization algorithm is used as mentioned by Moreno-Diaz[8]. GPS tool box for GDOP computation was used for the simulation.

Once the optimum approximate position of ground-based transceivers and high altitude platform was computed these values were used as initial values for position computation algorithm of pseudolite transceiver placed on high altitude platform as explained in Section 3. The updation rate of position computation of pseudolite transceiver placed on high altitude platform was selected such that the drift in high altitude platform position does not add significantly in the position inaccuracy of user pseudolite receiver. For the computation of user pseudolite receiver position, the update rate was kept at every one second similar to GPS receiver position fix up date rate.

The initial value for user pseudolite receiver position computation algorithm was taken from the first value of (x, y, z) of user nominal trajectory. The subsequent sample points on the nominal trajectory were used only for the computation of pseudorange and carrier phase observables. Each sample point (position) of the user nominal trajectory and position of pseudolite transceiver placed on high altitude platform iwas used for generating the pseudorange and carrier phase observable using GPS toolbox. These observable for each point of the nominal trajectory were used in algorithm mentioned in Section 4 in sequence, i.e., to simulate the situation of moving user pseudolite receiver. For each sample point of the nominal trajectory, the double-difference equations were solved using least square technique. The converged value of the least square solution gives the position of user pseudolite receiver. This converged value is also used as the initial erroneous position value for the next sample point on the user pseudolite receiver trajectory. The converged value of the user pseudolite position value was compared with the nominal value. Difference in these two values gives the accuracy of position fixing for each sample point of user pseudolite receiver.

7. SIMULATION TEST PARAMETERS AND RESULTS

The developed simulation software repeatedly executed by varying all the error model parameters to find the accuracy to which pseudolite transceivers placed on high altitude platform, and user pseudolite receiver position error can be computed. Here, first the ranges of various input parameters in Table 1 will be listed for the model followed by plot for inaccuracies with pseudolite transceiver and user position computation.

The magnitude of various error input parameters used for a single simulation run is shown in Tables 2 and 3 for the position computation algorithm mentioned in Sections 3 and 4. These values are changed in random manner in the range as shown in Table 1 (for pseudolite transceivers and user pseudolite receiver) to have multiple simulation run. The RMS value of error of all the simulation run is used to compute the final user pseudolite receiver accuracy.

During the entire testing scenario, results of all the error models were stored to study the effect of error models on the accuracy of estimated user position. The accuracy to which user position can be determined depends on the magnitude of different error sources, which contributes to error in pseudo range measurement. To find out the effect of individual error sources such as clock error, multipath error, troposphere error and GDOP, error analysis was carried out. To carryout the analysis, magnitude of input parameters of only one error source was varied from a pre-decided lower limit to upper limit keeping all input parameters of other error sources the same. While varying the input parameter of an error source model, user error thus obtained were also recorded and plotted. For example, the effect of multipath model on the accuracy of user position determination is described below.

Table 1. The range of all the input parameters considered for simulation

Model:	Multipath error	Troposheric error				Clock error	
Parameter	C/N (dB-Hz)	Partial pressure of dry air (mBar)	Temperature (K)	Elevation angle (deg)	Geodetic Latitude (deg)	Sb*	Sf*
Ranges	15 to 55	40 to 60	273 to 320	15 to 90	16 to 18	4.e-10 to 4.e-25	1.5791e-10 to 1.5791e-25.

Table 2. The magnitude of input parameters for all error models running at pseudolite transceiver placed at high altitude platform

Model:	Multipath error	Troposphere error			Clock error	
Parameter / Station Name	C/N (dB-Hz)	Partial pressure of dry air (mBar)	Temperature (K)	Elevation angle (deg)	Sb*	Sf*
Pseudolite 1	33	48.82	300	30	4.e-20	1.5791e-17
Pseudolite 2	36	57.39	303	35	4.e-23	1.5791e-18
Pseudolite 3	35	44	310	45	4.e-18	1.5791e-16
Pseudolite 4	32	50	298	37	4.e-19	1.5791e-15
Pseudolite 5	34	53.56	306	28	4.e-15	1.5791e-21

Table 3. The magnitude of input parameters for all error models running at ground pseudolite transceiver

Model:	Multipath error	Troposphere error			Clock error	
Parameter / Station Name	C/N (dB-Hz)	Partial pressure of dry air (mBar)	Temperature (K)	Elevation angle (deg)	Sb*	Sf*
Pseudolite 1	33.9	46.82	298	20	4.e-21	1.5791e-17
Pseudolite 2	39.4	59.39	301	25	4.e-22	1.5791e-16
Pseudolite 3	35.7	40	309	35	4.e-17	1.5791e-19
Pseudolite 4	32	50	297	47	4.e-18	1.5791e-25
Pseudolite 5	34.8	51.45	306	48	4.e-14	1.5791e-26
Pseudolite 6	36.4	55.56	311	58	4.e-25	1.5791e-24

* Sb is white noise spectral density amplitude for the first component corresponding to clock bias, in seconds.
* Sf is white noise spectral density amplitude for the second component corresponding to clock drift, in second/second

For multipath error, model takes C/N ratio (dB-Hz) as input and outputs the multipath error which in turn is given as error to user position determination block. The magnitude of C/N was varied from 15dB-Hz to 55dB-Hz to simulate a typical multipath effect and the plot obtained with error in estimated user position (in m) in Y axis and C/N ratio (in dB-Hz) is as shown in Fig. 7. Similarly to find out the effect of other (i.e. tropospheric and clock) error models on the developed algorithm, simulations were carried out by varying the values of input variables, i.e., antennae elevation angles, water vapour pressure and geodetic latitude to tropo and 'sb' and 'sf' for clock error model. Due to space limitation, these plots are not given here. However their combined effect is plotted in Figs 8 and 9.

Table 4 shows the RMS error for all the five pseudolites downrange, cross-range, and altitude range and the Fig. 8 shows the variation of error in the computed pseudolite transceiver position for the entire user trajectory for one of pseudolite transceiver placed on high altitude platform.

As shown in Fig. 8, X-axis is sample number in the user trajectory. The trajectory or the path followed by the user was stored in a MATLAB .mat file with point number in the first row, downrange in the second row, cross-range in the third row and altitude range in the fourth row. Down range, cross range, and altitude can be imagined as X, Y and Z coordinates of the user pseudolite receiver, respectively.

Y-axis of the plot is error in computed pseudolite position in downrange, cross-range, and altitude range.

Any point in the plot describes the instantaneous error in the pseudolite transceiver position placed on high altitude platform. From the graph, it is clear that error in the estimated pseudolite position is less than 5 m for the entire duration of the simulation.

The plot below shown in Fig. 9 shows the error in

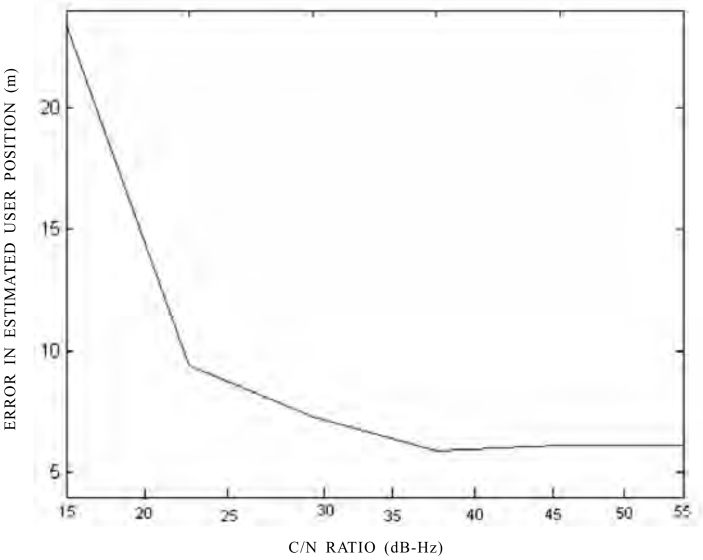

Figure 7. Variation of pseudolite position accuracy wrt C/N ratio.

estimated user position for the entire duration of the trajectory.

In Fig. 9(a) peak in magnitude of error, around 150 sample number in the user pseudolite receiver trajectory is observed because the sample values in this region, i.e., 130 to 170 are more widely spaced in terms of time update in the nominal user trajectory file compared to rest of points in the nominal trajectory file. This caused the large initial error for the least square solution for the position computation, and hence, the error peaking is observed between sample 130 to 170. From the graph, it is clear that error in estimated user position < 10 m through out the user pseudolite receiver trajectory.

8. CONCLUSIONS

This paper presents the approach used for the development of simulation software for pseudolite-based navigation system using SIMULINK. Each sub-system is modelled, developed, and integrated. Pseudolite transceivers placed on high altitude platform position and user position

Table 4. The RMS error in position computation of pseudolite transceiver placed on high altitude platform

	Pseudolite 1	Pseudolite 2	Pseudolite 3	Pseudolite 4	Pseudolite 5
RMS Error in Down Range	0.4672	0.2489	0.4151	0.2293	0.415
RMS Error in Cross Range	0.7713	0.7288	0.5175	0.6059	0.8505
RMS Error in Altitude Range	1.165	1.427	2.453	1.625	1.363

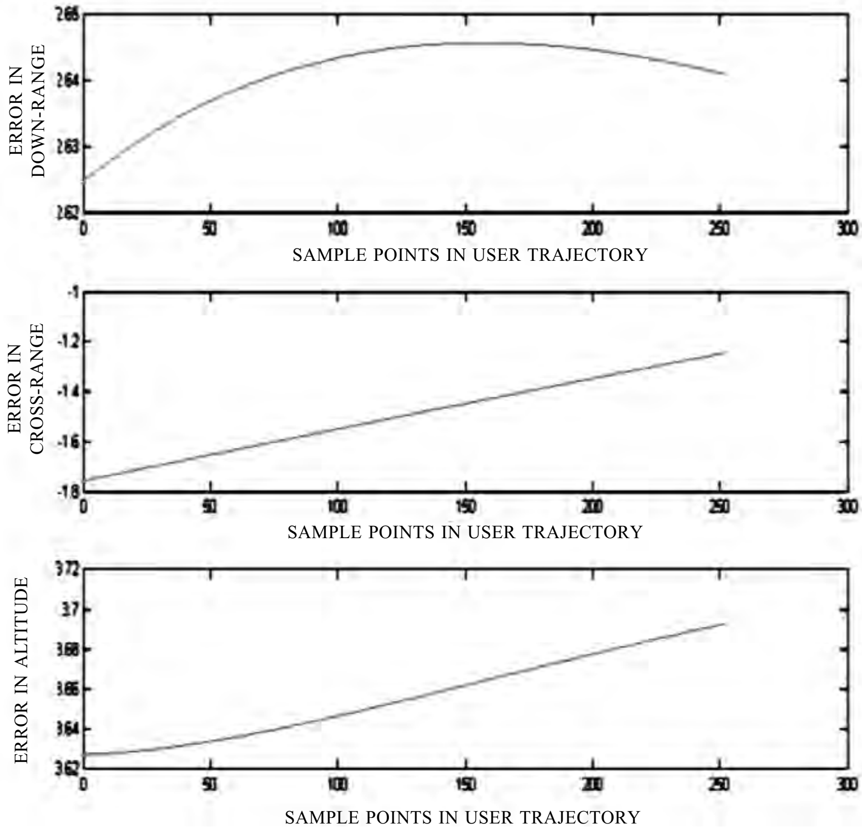

Figure 8. Error in computed pseudolite transceiver position in downrange, cross-range, and altitude-range.

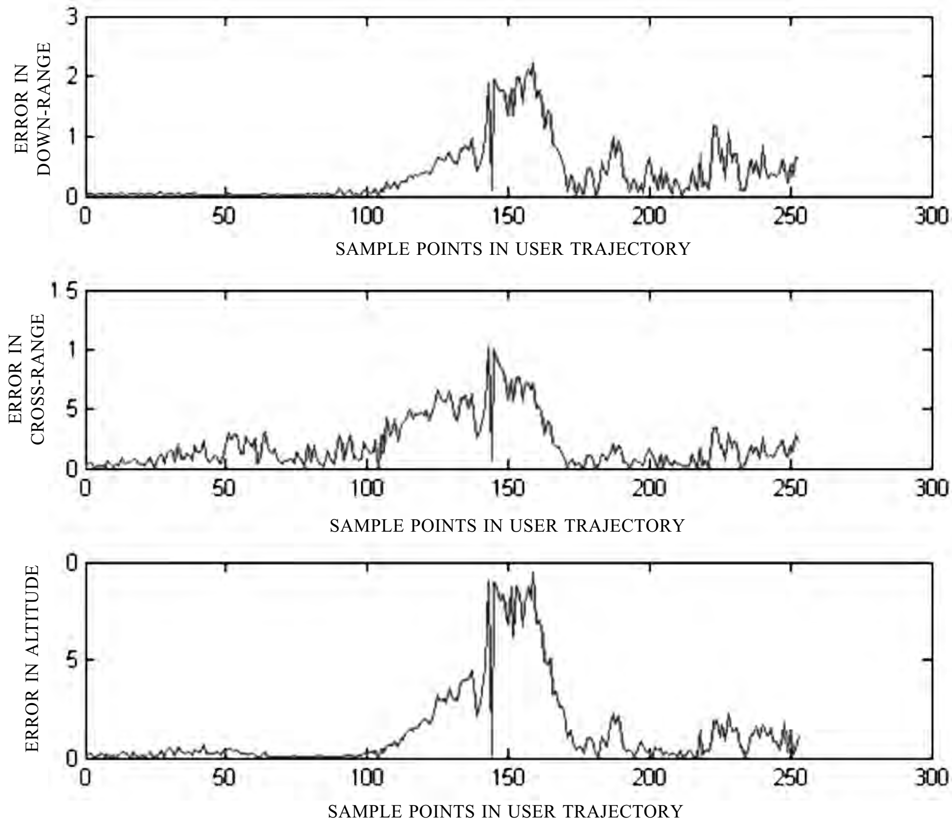

Figure 9. Error in computed user pseudolite receiver position in downrange, cross-range, and altitude.

was computed by varying the parameters of error model. The simulation results are analysed to find the limit of accuracy achievable for user pseudolite receiver.

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