ANALYSIS OF DIFFERENT ALGORITHMS FOR CLOCK ERROR ESTIMATION OF IRNSS

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Abstract : The IRNSS (Indian Regional Navigation Satellite System) has been conceived by Indian space research organization (ISRO) and is a constellation of 7 navigation satellites. Every GNSS (Global Navigational satellite system) receiver has a crystal oscillator which provides time that should be synchronized with the onboard satellite's precise and stable atomic (Rubidium or Cesium) clocks. But in most of the cases, receiver clock is not exactly synchronized with satellite onboard clock, hence a variable clock offset is observed between receiver and satellite clocks, which in turn affect the position accuracy. This paper aims at studying different estimation algorithms to determine accurate clock and hence to determine receiver position accurately. MATLAB is used to develop Iterative least square (ILS), Extended Kalman Filter (EKF) estimation and Batch least square algorithms to estimate clock error and receiver position. Data from Accord's NavIC receiver is considered for estimation process and respective results are compared with Accord's receiver's position values.

***IndexTerms* - IRNSS, IGS receiver, Iterative least square(ILS), Extended kalman filter(EKF), Batch least square.**

I. INTRODUCTION

The IRNSS (Indian Regional Navigation Satellite System) has been conceived by ISRO (Indian Space Research Organization) and is a constellation of 7 navigation satellites, wherein 3 satellites are placed in geostationary Earth orbit (GEO) and 4 satellites are put in inclined geosynchronous orbit (GSO) and is shown in FIG 1. It is designed to provide accurate position in and surrounding India up to 1500Km.

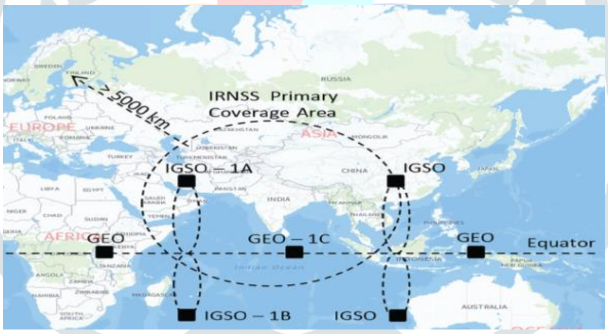


Figure1. IRNSS CONSTELLATION

IRNSS-GPS-SBAS (IGS) receiver designed and developed by Accord software and system's Pvt Ltd, supplied by ISRO to DSCE, is used to receive both L5 and S band signals. But in most of the cases, receiver clock is not exactly synchronized with satellite onboard clock, hence a variable clock offset is observed between receiver and satellite clocks, which in turn affect the position accuracy. Estimation could be a method of finding a value that's usable for a few purpose although input could also be incomplete, unsure or unstable. Estimation involves using the value derived from a sample to estimate the value of corresponding parameter. Clock error and user position estimation requires Pseudo range measured between satellite and receiver. In this paper, clock error is estimated and hence receiver position is estimated using data from the NavIC receiver.

In GNSS (Global navigation satellite system) several estimation methods are used to determine precise position, orbit determination and clock estimation. Nonlinear Least square (LS) method is employed for position computation from pseudo ranges, the accuracy of estimated results are increased by considering various iterations [1]. In paper [2] least square method is used by considering combination of pseudo range and carrier phase measurements and position accuracy is increased by 45% compared to earlier work. Weighted least square algorithm is employed for GPS using the real time data [3]. Paper [4] used kalman filter algorithm for clock estimation of GPS satellite, Accuracy of the orbit and clock product is assessed with a precise orbit determination of the MetOp satellite. In paper [5] "Use of Kalman Update algorithmic program for vivid enhancements of GPS and navigation", explains about Kalman-filter algorithm that uses a series measurements determined over time, that contains errors and other inaccuracies. Extended kalman filter algorithm is used for GAGAN application that overcomes the disadvantages of kalman filter that is kalman filter is used for only linear filter [6]. This paper uses batch least square (BLS) and Extended Kalman Filter (EKF) algorithm are considered for satellite parameter estimation in paper [7], This paper deals with the combination of both the algorithm to overcome the disadvantages of both the algorithm.

The paper is organized as follows: Section II explains about Iterative least square algorithm followed by Extended kalman filter (EKF) and Batch least square in Section III and section IV. Methodology employed is explained in section V. The results obtained from both the algorithms are discussed in section VI and concluding remarks are given in section VII.

I. ITERATIVE LEAST SQUARE

Iterative least square(ILS) algorithm is used by GNSS (Global navigation satellite system) for estimating precise position [3,4]. Iterative Least square (ILS) is computed for each time instant and output is obtained for that instant. The ILS estimates the clock and position using pseudo range values. The pseudo range is calculated using satellite position, receiver position and clock bias.

Algorithm steps:

1. The inputs to the estimation algorithm are satellite and receiver position, observed pseudo range.
2. In the next step theoretical Pseudo range is calculated for each satellite using the formula,

$$\rho = \sqrt{(X - Xs)^2 + (Y - Ys)^2 + (Z - Zs)^2}$$

Where, (X,Y,Z) are receiver position coordinates and (Xs,Ys,Zs) are satellite position coordinates.

3. Jacobian matrix is formed, i.e. a matrix of partial derivatives of change in theoretical pseudo range with respect to (X, Y, Z) coordinates is calculated in every iteration. Considering the change in clock bias to be linear, the last column is taken to be 1.

$$G = \begin{pmatrix} \frac{\delta\rho_{itr}}{\delta X_{itr}} & \frac{\delta\rho_{itr}}{\delta Y_{itr}} & \frac{\delta\rho_{itr}}{\delta Z_{itr}} & 1 \\ \frac{\delta\rho_{itr}}{\delta X_{itr}} & \frac{\delta\rho_{itr}}{\delta Y_{itr}} & \frac{\delta\rho_{itr}}{\delta Z_{itr}} & 1 \\ \frac{\delta\rho_{itr}}{\delta X_{itr}} & \frac{\delta\rho_{itr}}{\delta Y_{itr}} & \frac{\delta\rho_{itr}}{\delta Z_{itr}} & 1 \\ \frac{\delta\rho_{itr}}{\delta X_{itr}} & \frac{\delta\rho_{itr}}{\delta Y_{itr}} & \frac{\delta\rho_{itr}}{\delta Z_{itr}} & 1 \end{pmatrix}$$

Itr= Number of iterations

4. Difference between theoretical pseudo range and observed pseudo range (pseudo range from the IGS receiver) is calculated, the result obtained is residue ($\delta\rho$)
5. Least squares is used to determine the differential position error as shown below.

$$\delta X = (G^T . G)^{-1} * G^T . \delta\rho$$

$$\delta X = \begin{bmatrix} \delta X_{itr} \\ \delta Y_{itr} \\ \delta Z_{itr} \\ b \end{bmatrix}$$

6. The delta values obtained in the previous step are added to the initial values to obtain the correct position and clock bias.

Estimated value = Initial value + δX

Hence, receiver position and clock bias can be estimated precisely using this algorithm.

II. EXTENDED KALMAN FILTER (EKF)

Kalman filter is used to estimate precise position when linear data is present, but the data which is obtained from the receiver has nonlinear data so Extended Kalman filter is used. The algorithm works in a two-step process, the time prediction step and the measurement update step [6, 7]. In the prediction step, the Kalman filter produces estimates of the present state variables, besides their uncertainties. In the measurement update step, the prediction is corrected using a weighted average of the noisy sensory input. EKF will take some of the iteration to converge.

Algorithm for EKF:

- X = [x V_x y V_y z V_z b d] is the initial state vector with x, y, z being the coordinates of the initial receiver position and V_x , V_y , V_z are the velocities in x,y,z direction respectively. 'b' denotes the initial clock bias of the receiver and 'd' is the clock drift value.
- $[X_0, P_0]$ is the estimated state vector and its covariance respectively
- f is the function for state transition
- g is the function for measurement
- Q is the process noise covariance
- R is the measurement noise covariance
- Z is the set of pseudo ranges measured from the receiver to the satellite (actual measurement)
- P is the 'priori' estimated state covariance

Linearize input functions f and g to get f_y (state transition matrix) and H (observation matrix) for an ordinary Kalman filter

1. $X_p = f(X)$: one step projection, also provides linearization point
2. $f_y = f(X_p)$

   $f_y = \frac{df}{dX} |$ X = X_p : Linearize state equation, f_y is the Jacobian of the process model
3. $H = \frac{dg}{dX} |$ X = X_p: Linearize observation equation, H is the Jacobian of the measurement model.

   [gX_p ,H] = g(X_p) : gX_p is the predicted measurement calculated using the station coordinates and the estimated satellite position in the previous step.

4. The covariance of X_p

$$P_p = f_y * P * f_y' + Q$$

5. Kalman Gain

$$K = \frac{P_p * H'}{H * P_p * H' + R}$$

6. The output state X_0

$$X_0 = X_p + K * (Z - gX_p)$$

The difference between the actual and predicted measurement ($Z - gX_p$) is called as residual. The present state is estimated using the predicted state, predicted measurement and the new measurement.

7. Covariance of X_0

$$P_0 = [I - K * H] * P_p$$

III. BATCH LEAST SQUARE

Batch least squares (BLS) approach where all the data for a fixed period is collected and processed together. The BLS estimates the clock error by considering the observed pseudo range values. The pseudo range is calculated using satellite position, receiver position.

Algorithm steps:

1. The input to the estimation algorithm are receiver and satellite position and observed pseudo range which is considered from the receiver.
2. In the next step theoretical Pseudo range is calculated for each satellite using the formula,

$$\rho = \sqrt{(X - Xs)^2 + (Y - Ys)^2 + (Z - Zs)^2}$$

Where, (X,Y,Z) are receiver position coordinates and (Xs,Ys,Zs) are satellite position coordinates.

3. Jacobian matrix is formed, i.e. a matrix of partial derivatives of change in theoretical pseudo range with respect to (X, Y, Z) coordinates is calculated in every iteration. Considering the change in clock bias to be linear, the last column is taken to be 1. The jacobian matrix generated in each iteration is stored as array in another matrix which will be of size (N * 4).

$$\frac{\delta\rho_N}{\delta X_N} = \frac{X_{sat} - X_N}{\rho_N}$$

N = Number of time duration in seconds considered for estimation

$$G = \begin{pmatrix} \frac{\delta\rho_{11}}{\delta X_{11}} & \frac{\delta\rho_{11}}{\delta Y_{11}} & \frac{\delta\rho_{11}}{\delta Z_{11}} & 1 \\ \frac{\delta\rho_{12}}{\delta X_{12}} & \frac{\delta\rho_{12}}{\delta Y_{12}} & \frac{\delta\rho_{12}}{\delta Z_{12}} & 1 \\ \frac{\delta\rho_{13}}{\delta X_{13}} & \frac{\delta\rho_{13}}{\delta Y_{13}} & \frac{\delta\rho_{13}}{\delta Z_{13}} & 1 \\ \frac{\delta\rho_{14}}{\delta X_{14}} & \frac{\delta\rho_{14}}{\delta Y_{14}} & \frac{\delta\rho_{14}}{\delta Z_{14}} & 1 \\ \frac{\delta\rho_{21}}{\delta X_{21}} & \frac{\delta\rho_{21}}{\delta Y_{21}} & \frac{\delta\rho_{21}}{\delta Z_{21}} & 1 \\ \frac{\delta\rho_{22}}{\delta X_{22}} & \frac{\delta\rho_{22}}{\delta Y_{22}} & \frac{\delta\rho_{22}}{\delta Z_{22}} & 1 \\ \frac{\delta\rho_{23}}{\delta X_{23}} & \frac{\delta\rho_{23}}{\delta Y_{23}} & \frac{\delta\rho_{23}}{\delta Z_{23}} & 1 \\ \frac{\delta\rho_{24}}{\delta X_{24}} & \frac{\delta\rho_{24}}{\delta Y_{24}} & \frac{\delta\rho_{24}}{\delta Z_{24}} & 1 \\ & \vdots & & \\ \frac{\delta\rho_{N1}}{\delta X_{N1}} & \frac{\delta\rho_{N1}}{\delta Y_{N1}} & \frac{\delta\rho_{N1}}{\delta Z_{N1}} & 1 \\ \frac{\delta\rho_{N2}}{\delta X_{N2}} & \frac{\delta\rho_{N2}}{\delta Y_{N2}} & \frac{\delta\rho_{N2}}{\delta Z_{N2}} & 1 \\ \frac{\delta\rho_{N3}}{\delta X_{N3}} & \frac{\delta\rho_{N3}}{\delta Y_{N3}} & \frac{\delta\rho_{N3}}{\delta Z_{N3}} & 1 \\ \frac{\delta\rho_{N4}}{\delta X_{N4}} & \frac{\delta\rho_{N4}}{\delta Y_{N4}} & \frac{\delta\rho_{N4}}{\delta Z_{N4}} & 1 \end{pmatrix}$$

4. Using observed pseudo range (pseudo range from the IGS receiver), theoretical pseudo range value residue ($\delta\rho$) is calculated for each iteration. Thus the matrix of N * 4 is generated

$\delta\rho$ = residue = Observed pseudo range (ρ_o) - Theoretical pseudo range (ρ_t)

5. Least squares is used to determine the differential position error and bias as shown below.

$$\delta X = (G^T . G)^{-1} * G^T . \delta\rho$$

$$\delta X = \begin{bmatrix} \delta X_{itr} \\ \delta Y_{itr} \\ \delta Z_{itr} \\ b \end{bmatrix}$$

6. The delta values obtained in the previous step are added to the initial values to obtain the correct position and clock bias.
   Receiver position = (Receiver position) ^{T} + δX (1:3)
   bias = bias + δX (4)

IV. Methodology

clock error estimation of the receiver is carried out as shown in the flow chart below:

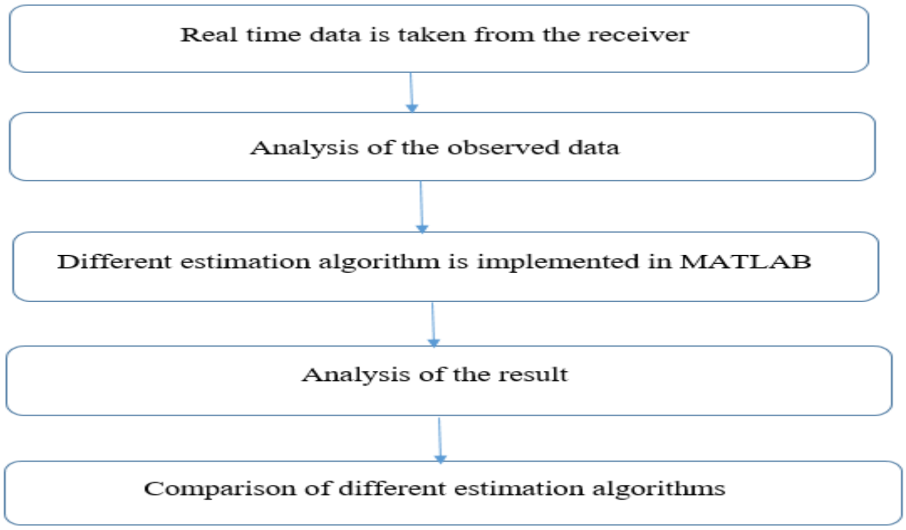


Figure 7: Flow chart

- The real time data required for the estimation is considered from the NavIC (Navigation with Indian Constellation) receiver. The data considered for estimation algorithm are:
  - Receiver and satellite position and their velocities
  - Pseudo range from the receiver
  - Ionosphere, Troposphere and satellite clock corrections

  Initially receiver position and clock bias value is considered to be zero. The data from the receiver will be in the form of EXCEL or RINEX file format.
- After collecting the real time data from the receiver, for analysis of data the graph is plotted to see the variations of clock bias, clock drift and also satellite clock correction.
- Different estimation algorithms are studied and MATLAB code is developed for clock error estimation of IRNSS and hence to find receiver position. The different estimation algorithms are
  - Iterative least square
  - Extended Kalman filter
  - Batch least square
- The result obtained from the estimation algorithms are plotted and analysis of the graph is made.
- Comparison of different estimation algorithms result are considered for finding the best estimation algorithms.

V. Results and observations

The estimation algorithm is executed in MATLAB and the results obtained are tabulated and discussed in this section. The unknown receiver position was estimated by considering initial values of receiver (X,Y,Z) to be zero. The input required for clock and receiver position estimation is four satellite positions, station position, pseudo range measurements for four satellites (IRNSS 1B, IRNSS 1C, IRNSS 1D and IRNSS 1E) and initial clock bias value that is taken from the IGS receiver. The data obtained from the IGS receiver will be in the form of Excel sheet.
Extended kalman filter (EKF) with and without satellite clock correction:
In this case EKF is considered for position estimation with satellite clock correction and without satellite clock correction.
Case1: EKF without satellite clock correction
Pseudo range = NavIC (Navigation with Indian constellation) pseudo range – Ionosphere delay – Troposphere delay

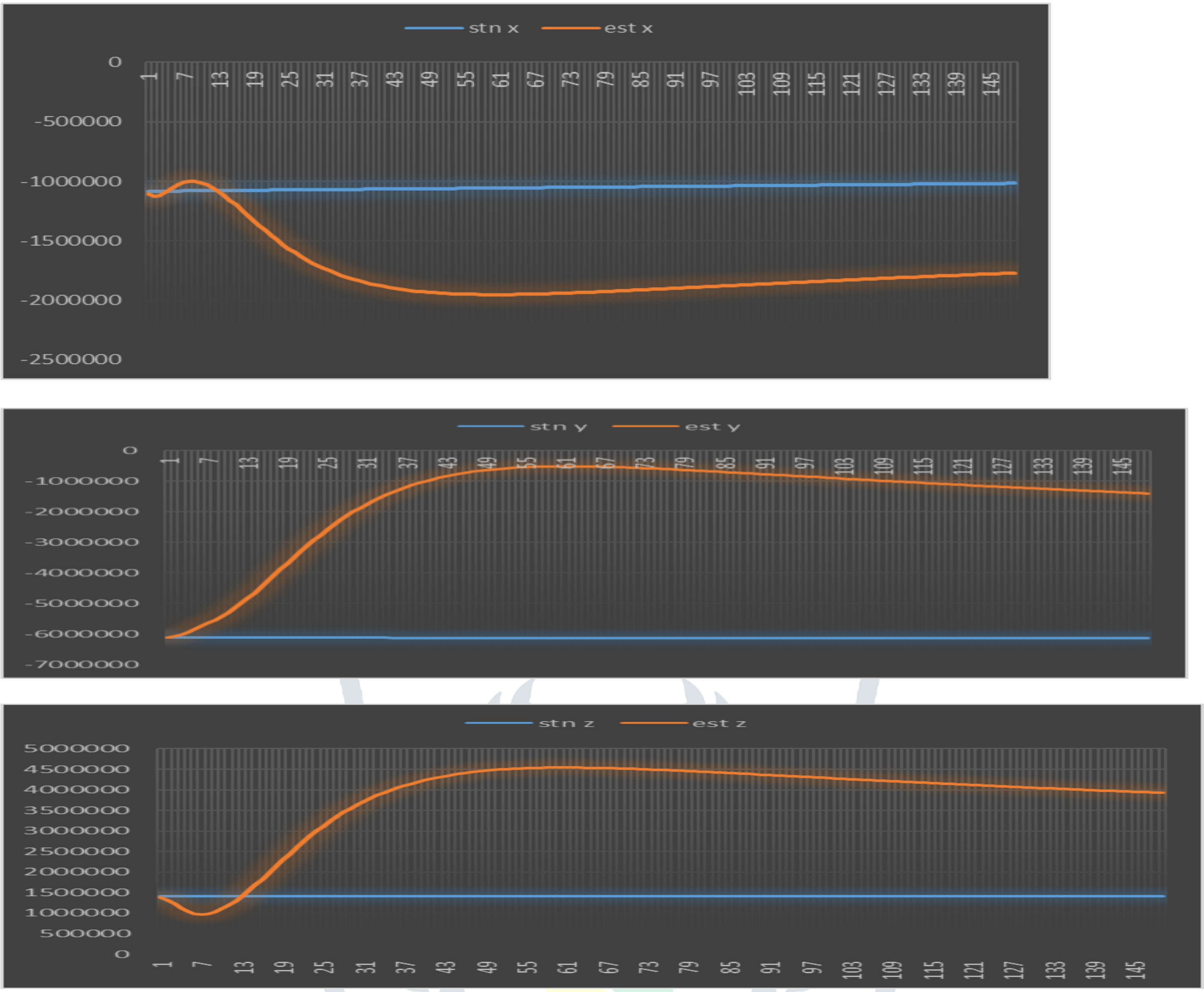


Fig 3: Graph of receiver (X,Y,Z) position in comparison with estimated receiver position without satellite clock correction.

Figure 3 shows the graph of receiver (X, Y, and Z) coordinates observed from the GNSS receiver in comparison with that of estimated receiver position. It is clearly observed from the graph the estimated receiver position is varying at a larger rate in comparison with the receiver position observed in the NavIC receiver

Table 1: Error in receiver position estimation

Time	Error in receiver position estimation without satellite clock correction		
	X	Y	Z
0	24751.63	4043.002	33043.68
5	629998.6	3904976	1936500
10	562114	3255453	1481226
15	545977.1	2918607	1241494
20	546354.7	2690166	1078071
25	555071.4	2518708	955804.3
30	569083.1	2383323	860207.5
35	586781.7	2272615	783306.8
40	607140	2179465	720109
45	629450	2099100	667284.2
50	653154.1	2028140	622465.5
55	677828.1	1964169	583976.2
60	703027	1905570	550662.1

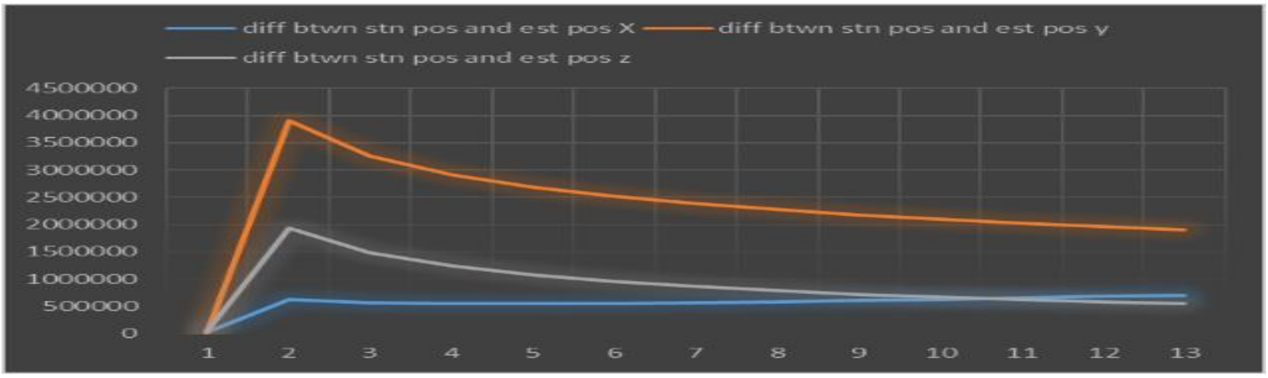


Fig 4: Error in receiver position estimation

Figure 4 and table 1 shows error in receiver position that is difference between receiver position observed from the NavIC receiver and estimated receiver position. It is seen from the above graph the error in finding receiver position is large when satellite clock correction is not considered.

Case 2: EKF with sat correctionPseudo range = NavIC pseudo range – Ionosphere delay – troposphere delay + satellite clock correction

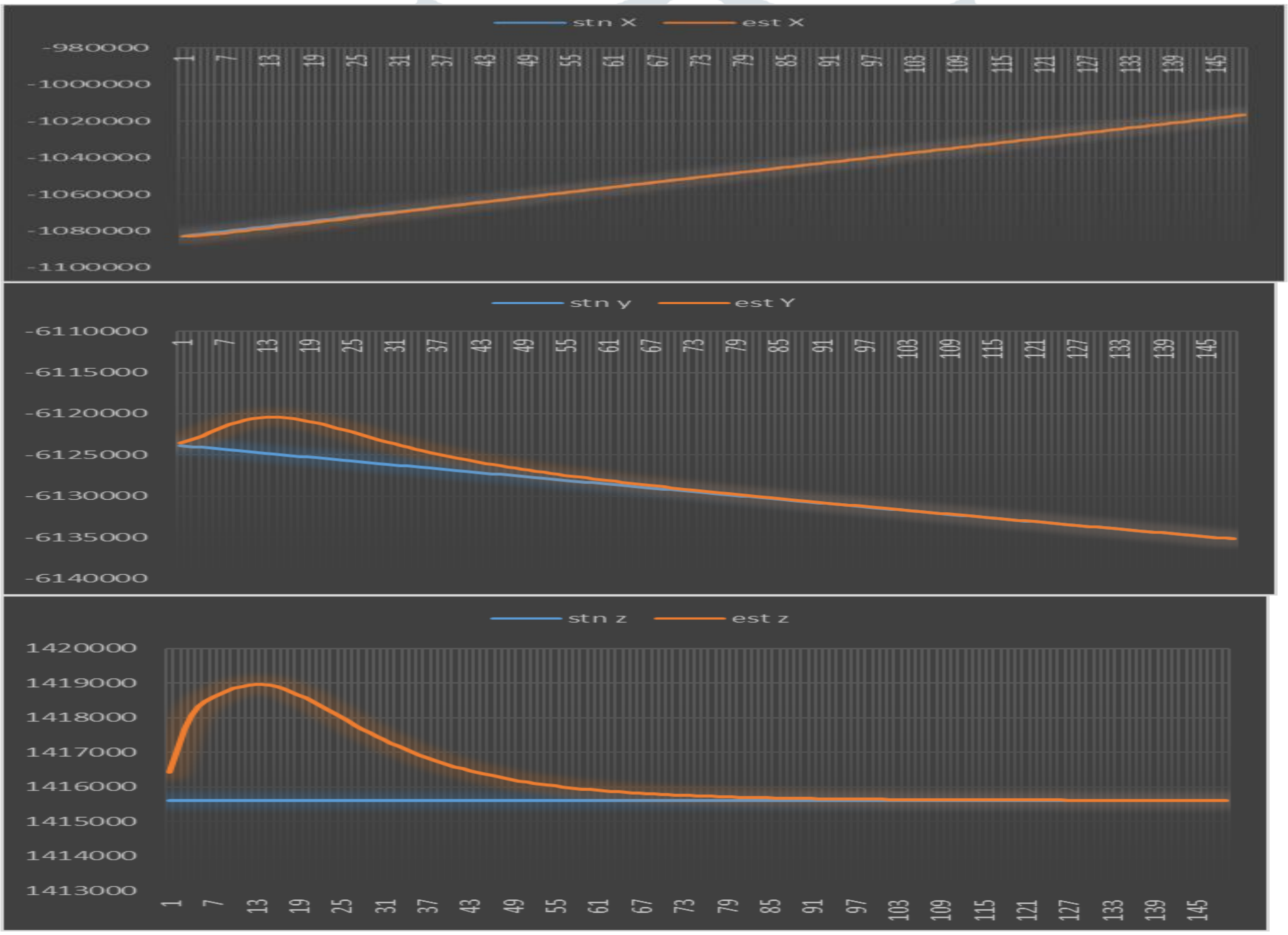


Figure 5: Graph of receiver position from the NavIC receiver in comparison with the estimated receiver position.

Figure 5 shows the graph of estimated receiver position in comparison with the receiver position observed from the NavIC receiver when satellite clock correction is considered. It is seen from the figure 5 the estimated and values from the receiver are almost equal after some iterations because kalman filter takes some iteration to converge.

Table 2: Error in receiver position estimation

Time(min)	Error in receiver position estimation with satellite clock correction		
	X	Y	z
0	20.65887	278.4753	801.6773
5	0.250316	3.323588	2.281735
10	0.129924	1.336295	0.468949
15	0.216002	0.950768	0.213427
20	0.343209	1.592595	-0.29532
25	0.211819	0.812834	0.603531

30	0.264966	0.641324	0.522622
35	0.149235	0.725133	0.422133
40	0.346458	0.960156	0.496927
45	0.24423	0.535786	0.016542
50	0.377546	0.186172	0.622774
55	0.286052	0.351995	0.221607
60	0.149393	1.078295	0.252671

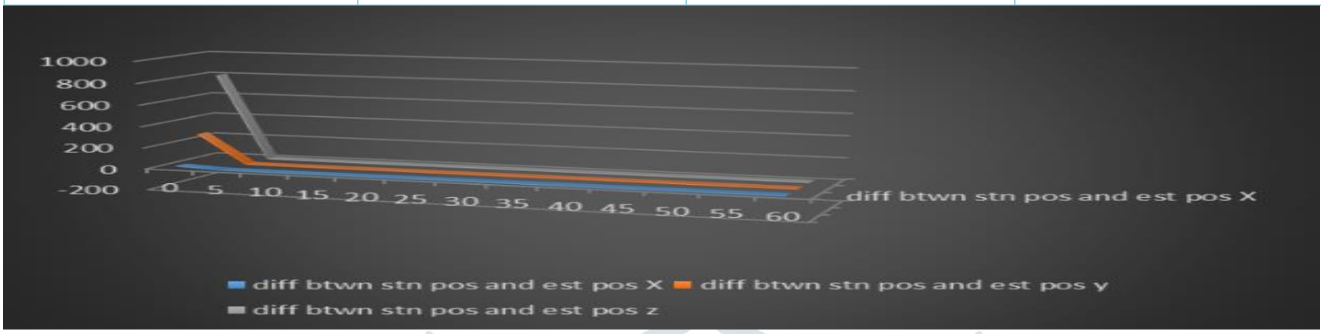


Figure 6: Error in estimating receiver position

Figure 6 and table 2 shows error in estimating receiver position which is obtained from the difference between estimated receiver position and receiver position obtained from the NavIC receiver. It is seen from the above graph the error in estimating receiver position is nearly zero after some iteration as kalman filter takes some iteration for converge. Thus when satellite clock correction is considered it is estimating correctly.

Iterative least square (ILS) with and without satellite clock correction:

In this case EKF is considered for position estimation with satellite clock correction and without satellite clock correction.

Case1: ILS without satellite clock correction

Pseudo range = NavIC pseudo range – ionosphere delay – troposphere delay

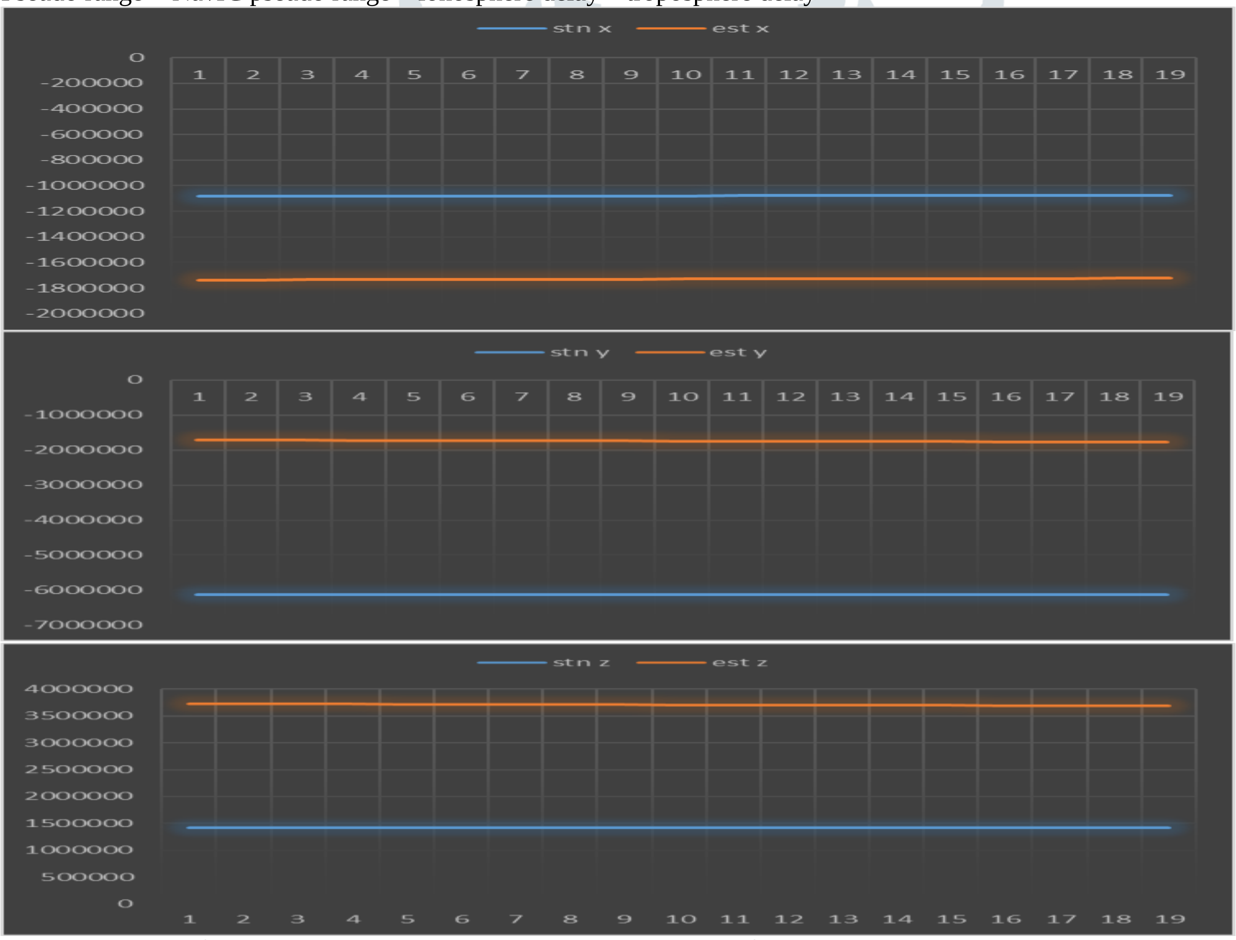


Figure 7: comparison of estimated receiver position with the receiver position obtained from the NavIC receiver

As shown in the above figure we can see the large variation in the estimated receiver position in comparison with the receiver position observed from the NavIC receiver when satellite clock correction is not considered.

Table 3: Error in receiver position estimation

Time(min)	Error in receiver position estimation without satellite clock correction		
	X	Y	z
0	653417	4409505	2312880
5	586175	3679224	1788635
10	555967.3	3225299	1462343
15	545391.9	2915856	1239862
20	546546.5	2691027	1078557
25	555293.7	2519673	956313.1
30	569249.1	2384013	860548.8
35	586898.4	2273080	783520.7
40	607223.6	2179784	720245
45	629511.9	2099325	667373.5
50	653200.8	2028302	622525.5
55	677864.4	1964289	584016.9
60	703055	1905659	550690.1

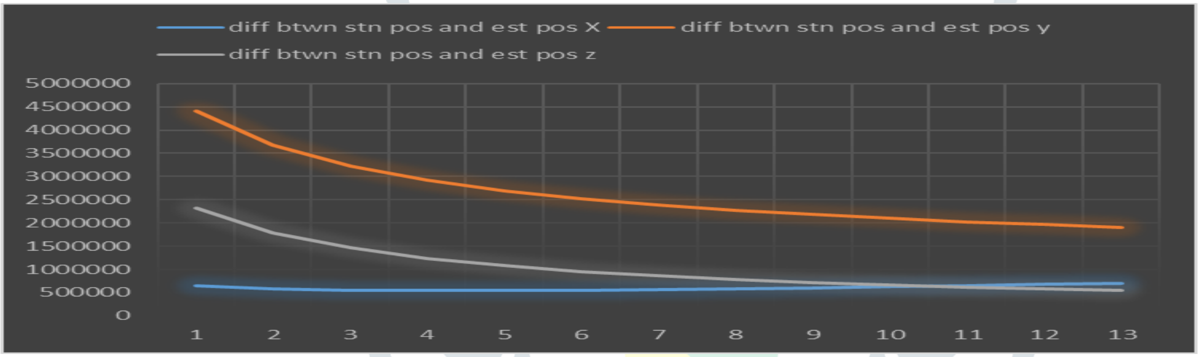
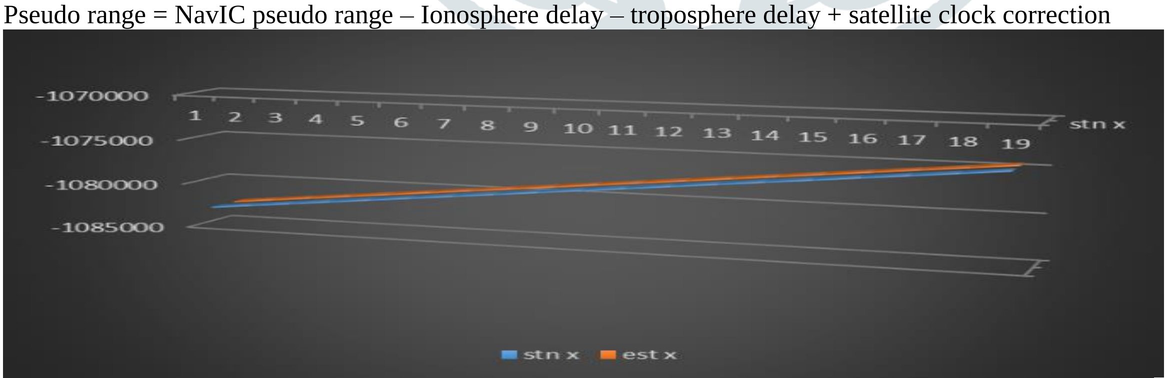


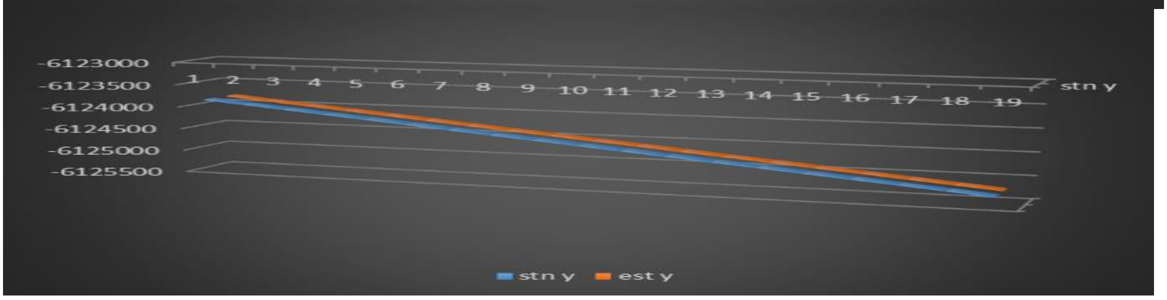
Figure 8: Error in receiver position estimation

Figure 8 and table 3 shows the error in receiver position that is difference between estimated receiver position and receiver position observed from the NavIC receiver. It is clearly seen from the above graph the error in receiver position is large.

Case 2: ILS with satellite correction

Pseudo range = NavIC pseudo range – Ionosphere delay – troposphere delay + satellite clock correction





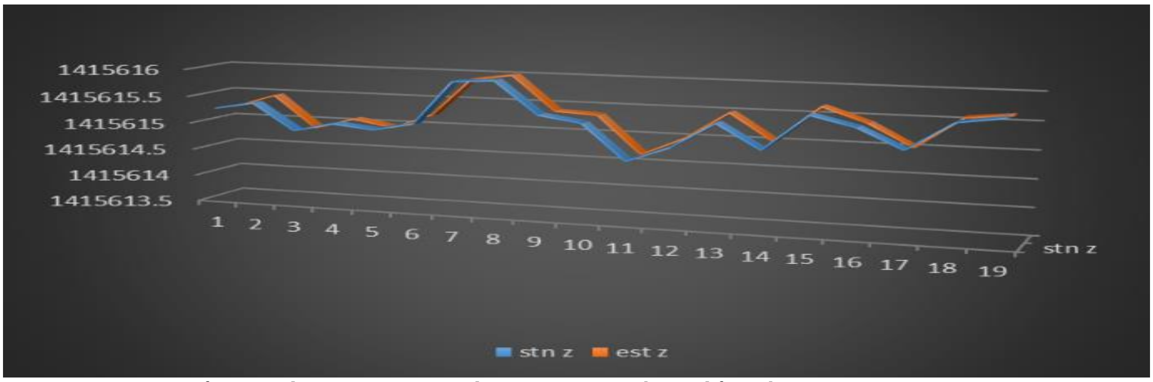


Figure 9: comparison of estimated receiver position and receiver position observed from the NavIC receiver

As seen from the above graph the estimated and observed receiver position are almost equal when satellite clock correction is considered.

Table 4: Error in receiver position estimation

Time(min)	Error in receiver position estimation with satellite clock correction		
	X	Y	Z
0	0.007301	0.08187	0.033851
5	0.004732	0.002614	0.018065
10	0.016629	0.031627	0.032979
15	0.017462	0.078197	0.053045
20	0.00151	0.024749	0.013981
25	0.006761	0.011671	0.023153
30	0.013728	0.016596	0.014195
35	0.010947	0.00681	0.017396
40	0.002608	0.009564	0.006295
45	0.004873	0.020041	0.004431
50	0.003369	0.016987	7.31E-05
55	0.002573	0.00483	0.014877
60	0.001659	0.025304	0.003298

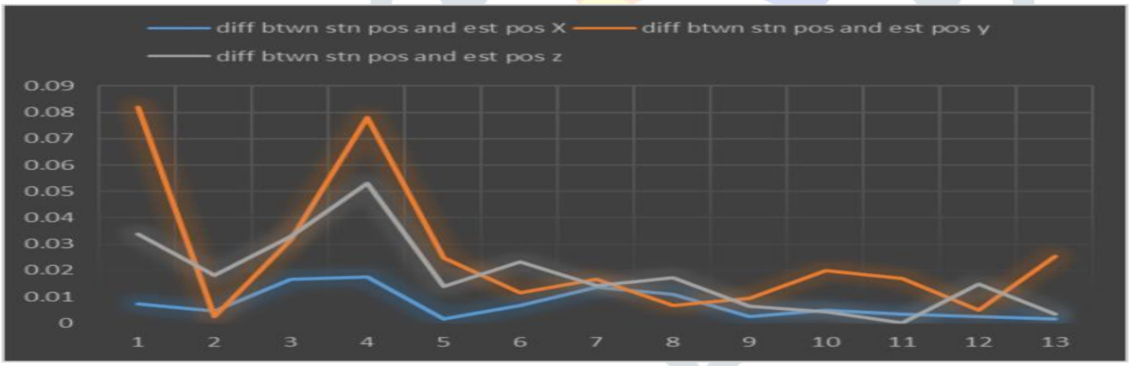


Figure 10: Error in receiver position estimation

Figure 10 and table 4 shows error in receiver position that is difference between estimated receiver position and observed receiver position from the NavIC receiver. It is clearly seen from the above graph there is improvement in position accuracy when satellite clock correction is considered.

Batch least square (BLS) with and without satellite clock correction

Table 5: Error in receiver position estimation

	Error in receiver position		
	X	Y	Z
when no satelliete clock correction	370023.9	-1523822.917	-463094.6252
when satellite clock correction	-5.21E-06	1.89E-05	1.32E-05

As seen from the table when no satellite clock correction is made the error in position estimation is less as compared with error when no satellite clock correction is not considered in estimation

Comparison of EKF, ILS and BLS estimation algorithms

Table 6: Comparison of different estimation algorithms

	Algorithm used for estimation	Error in receiver position estimation		
		X	Y	Z

when no satellite clock correction is considered	EKF	605498.3	2510024	956758.9
	ILS	605368.8	2636541	1048270
	BLS	370023.9	-1523823	-463095
when satellite clock correction is considered	EKF	0.247429	1.041245	0.485633
	ILS	0.007242	0.025451	0.018126
	BLS	-5.21E-06	1.89E-05	1.32E-05

The above table shows the comparison of EKF, ILS and BLS algorithms for finding error in receiver position estimation. It is seen from the above table the BLS algorithm is giving better result compared to EKF and ILS estimation algorithm.

VI. CONCLUSION

In this paper Extended kalman filter (EKF), iterative least square (ILS) and Batch least square algorithms have been implemented and results are discussed. The receiver position is estimated using EKF, ILS and BLS with and without satellite clock correction. Thus when satellite clock correction is considered estimation leads to more accuracy in compared with when satellite clock correction is not considered. The comparison of three estimation algorithms is also discussed.

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