# REAL TIME ESTIMATE AND COMPUTATIONAL MODEL OF FIGHTER AIRCRAFT FUEL GAUGE SYSTEM

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## Abstract

*An onboard program for the fighter aircraft fuel gauge system is developed using a computational model resulting in to an optimal estimate of fuel gauge system. A fighter aircraft has several fuel tanks and the fuel quantity of the fuel tanks is required to be gauged reliably taking into account the various dynamic effects of flight maneuvers like aircraft pitch angle, roll angle and acceleration parameters for aircraft CG management. Real time estimation and computational modeling of fuel gauging system is realised by using the least square estimation numerical method with Microcontroller based Electronic unit. It was seen that the fluctuations in the fuel quantity estimation under the dynamic flight conditions are reduced and fuel gauging accuracy is improved.*

*Keywords : Fuel quantity, Fuel gauging probe, Least Square (LS) computational model, Automatic Net generation Tool for Structural Analysis (ANSA), Microcontroller, Time Processor Unit (TPU) channel*

## Introduction

The fuel content measurement in fighter aircraft with multiple fuel tanks is a complicated process due to dynamic effects of flight maneuvers. Fuel changes its position with respect to maneuvering conditions and thus affects the aircraft CG. Aircraft CG depends on the distribution of fuel quantity in individual tanks. So it is important to find out the fuel content of each tank accurately for aircraft CG management.

Known liquid gauging systems typically gauge liquid volume by attempting to determine the height and orientation of the liquid surface in the container. Once the liquid plane surface is defined and located, the information can be converted to a volume and then equivalent mass. Such systems typically use ultrasonic sensors or liquid height sensors such as cylindrical capacitance sensors to determine the height of the liquid in the container [1].

Fighter aircraft fuel gauging is a dynamic process during flight. The fluctuations are due to the effects of dynamic variations of aircraft pitch angle, roll angle and acceleration parameters. The problems associated with fuel gauging are further compounded by the fact that aircraft fuel tanks generally have complicated geometrical shapes and typically include number of internal structures.

Methods based on kalman filter, neural networks etc. are available and expert systems literature for fuel content measurement. However, an approach based on the least square estimation method which quantitatively estimates the trend of outcomes by curve fitting technique has the advantage since it is based on a rigorous method with a vast amount of known results. It involves simple arithmetic operations which can be realized in real time application. The best-fit curve of a given type is the curve that has minimal sum of the deviations squared (least square error) from a given set of data [2].

But least square estimation method requires a huge amount of data to cover the entire envelope of dynamic flight conditions and the fuel tank modeling [1] approach can be used for generation of huge database for the fuel gauging system considering dynamic flight conditions. An analytical method is required which estimates the fuel content using the database generated by the fuel tank modeling approach. Fuel tank model is integrated with the least square estimation analytical method for fuel content measurements, the hybrid technique should be able to meet all the demands of the fighter aircraft fuel gauging system.

The present work is aimed at the computational modeling of fuel gauging system and the real time estimate of the fuel gauging system considering all the dynamic effects of flight maneuvers. The work presented in this paper is an extension of the authors previous work [3] that deals with a simple least square estimation model.

In this paper, least square computational model is used to compute estimations of parameters and to fit data. It is required to fit linear mathematical model to given observations. Fuel tank model is developed to generate huge database which gives fuel height to fuel volume relationship for a fuel tank considering the dynamic flight conditions.

Section - Aircraft Fuel Gauge System, describes the fuel gauging system of fighter aircraft, section - Least Square Computational Model, provides the details of least square computational model of the fuel gauging system, section - Fuel Tank Modeling, deals with the fuel tank model approach, section - Real Time Fuel Content Estimation, provides the details of the real time estimate of fuel gauging system using microcontroller based electronic unit, section - Results and Discussion, presents the results of least square computational model. Finally section - Conclusion, contains some concluding remarks.

## Aircraft Fuel Gauge System

A typical schematic of aircraft fuel system is shown in Fig.1 with specific example of three fuel tanks. One fuel tank in fuselage, fuselage tank 1 (FT1) and two fuel tanks in wing, Left Hand side wing tank and Right Hand side wing tank (LHWT, RHWT). Fuel tanks are gauged by using cylindrical capacitance type gauging probes. Based on the capacity of the fuel tanks appropriate number of fuel probes with specified lengths are located in each tank. The probe consists of two concentric aluminium alloy tubes

insulated from each other to form capacitance plates. When tubes are not immersed in fuel, air occupies the space between the two tubes. The dielectric constant of air being the lowest, the probe exhibits low capacitance. Capacitance increases when probe is fully or partially immersed in fuel as dielectric of fuel is more than air. The sensing capacitance is converted in to frequency by an oscillator circuit.

A Microcontroller based Electronic unit (EU) acquires the fuel gauge probe signal [4], pitch angle, roll angle and acceleration parameters. EU processes the least square computational model using the data generated by fuel tank model (developed using ANSA simulation software) resulting into the improved fuel gauge estimate in real time.

## Least Square Computational Model

Field data is often accompanied by noise. Even though all control parameters (independent variables) remain constant, the resultant outcomes (dependent variables) vary. A process of quantitatively estimating the trend of the outcomes known as regression or curve fitting therefore becomes necessary.

Curve fitting, also called regression analysis is a process of fitting a function to a set of data points. The function can then be used as a mathematical model of the data [6]. For a given set of data, the fitting curves of a given type are generally not unique. Thus, a curve with a minimal deviation from all data points is desired. This best-fitting curve can be obtained by the method of least squares. The best-fit curve of a given type is the curve that has the minimal sum of the deviations squared (least square error) [2] from a given set of data.

Suppose that the data points are $(x1, y1), (x2, y2) \ldots (xn, yn)$, where x is the independent variable and y is the dependent variable. The fitting curve f(x) has the deviation (error) d from each data point, i.e., $d1 = y1 - f(x1)$, $d2 = y2 - f(x2)$, $dn = yn - f(xn)$. According to the method of least squares [2] [7], the best fitting curve has the property that

$$\sum_{i=1}^{n} d_i^2 \quad \text{should be a minimum}$$

Where $di = yi - f(xi)$ [8], a residual which is defined as the difference between the values of the dependent variable and the predicted values from the estimated model [9]

$$\sum_{i=1}^{n} \left[ y_i - f(x_i) \right]^2 = \text{a minimum}$$

The objective consists of adjusting the parameters of a model function so as to best fit a data set. The best fit is that instance of the model for which the sum of squared residuals has its least value.

A computational model shown in Fig.2 relates the fuel gauge probe values, pitch angle, roll angle and acceleration parameters to fuel quantity computed using a data base table (Look up table). For a simple least square computational model, previous flight data were used for obtaining the aircraft parameters required for computing the Least Square (LS) coefficients.

Since the accurate time history of fuel quantity is not available from the previous flight data, the fuel quantity time history was reconstructed using Look up table output for level flight condition and for other dynamic conditions flow meter output which gives the estimate of fuel consumed by the engine was used. This reconstructed fuel quantity was further filtered to obtain smooth trajectory. Least square coefficients were estimated using the reconstructed fuel quantity trajectory.

Least square model for a fuel tank is given by the equation [3].

$$\begin{Bmatrix} Y \\ . \\ . \\ . \end{Bmatrix} = \begin{pmatrix} 1 & \text{Probe} & \Phi & \Theta & Jx & Jz \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \end{pmatrix} \begin{Bmatrix} c1 \\ c2 \\ c3 \\ c4 \\ c5 \\ c6 \end{Bmatrix}$$
$$\text{N x 1} \qquad\qquad \text{N X 6} \qquad \text{6 x 1}$$

where c1, c2 ... and c6 are LS coefficients, $\Phi$ - pitch angle, $\Theta$ - roll angle, Jx - longitudinal acceleration, Jz - vertical acceleration and Y is the fuel quantity obtained from the reconstructed fuel quantity trajectory. The unknown coefficients in the above equation are estimated as given below [2]

$$C = (X^T X)^{-1} X^T Y$$

**Fuel Tank Modeling**

Real time computational model based on least squares (LS) technique was developed using previous flight data. Results are found to be consistent. However, since the LS coefficients are estimated using previous flight data with its inherent limitations, there is a need for generating accurate truth data relating the probe measurements and fuel content under various attitudes, for improving the model accuracies.

The problems associated with aircraft fuel gauging is complicated by the fact that aircraft fuel tanks generally have complicated geometrical shapes and typically include number of internal structures. In such cases fuel tank model is required to be developed, which helps in generation of relationship between height of the fuel surface and fuel volume for any combination of pitch and roll angles [1].

The basic principle for calculating fuel quantity in the fuel tank is by using a height to volume function 'V = h x A' where h is the height of the fuel surface at fuel gauge probe location in the tank and A is surface Area. It is easy to find out volume for simple geometry as above but for the complicated tank profile it is necessary to develop fuel tank model. CATIA is used to produce a solid model computer database of the fuel tank. This solid model database is based on the CAD drawings of the tank. Thus the solid model database is defined by the geometric coordinates of the various surfaces and internal structures of the tank in terms of the local x,y,z coordinate system [10].

The solid model database is used as an input database to an analytical tool ANSA to build fuel tank analytical model. ANSA software is used to slice the fuel tank model with gauging planes at different heights along the length of the fuel gauging probe considering the aircraft pitch and roll angles. By incrementally slicing the entire tank for each incremental change in pitch and roll angles, a large database is generated which defines all the relationships of fuel height to volume across all combinations of pitch and roll angles [1].

Suppose 'θ', and 'φ' are the aircraft pitch and roll, the height to volume relationship can be derived from ANSA Fuel Tank Tool. Volume = f (θ, φ, h) [10] where h is the fuel plane height above the origin of the arbitrary local coordinate system, φ is the roll data value and θ is the pitch data value. ANSA considers the immersed structure, com-

ponents inside the fuel tank and displaces the liquid column accordingly.

ANSA is a CAE tool for Finite Element Analysis. Finite element method is used to find approximate solutions for partial differential equations [11]. ANSA maintains the association between CAD geometry and the FE mesh. It carries several proprietary algorithms for meshing which is suitable for fuel tank model.

### Real Time Fuel Content Estimation

Fuel content measurement in real time is estimated using Microcontroller based Electronic unit. Electronic unit acquires the fuel gauge probe signal using Microcontrollers Time Processor Unit (TPU) channel [5]. It is a 32 bit Micro controller running at 16 MHZ clock speed. It has 16 independent TPU channels and two timer counters. TPU channel is configured in Programmable Time Accumulator (PTA) mode [4].

The fuel gauge probe signal is measured by TPU channel for a specified number of periods. After the elapse of specified number of periods, TPU updates the result in terms of 32-bit count. An interrupt signal is generated to the Microcontroller and the measurement process is restarted. Each 32-bit count corresponds to 250ns period by selecting the Timer counter 1 (250ns period) as the time base for the TPU channel [4].

Moving average of eight samples of the acquired fuel gauge probe signal is done by the Electronic unit in order to filter out the noise. The fuel gauge probe signal is validated by checking for its range. If the signal is found to be out of its range for more than the specified persistence time, it will not be used for fuel quantity estimation.

The fuel quantity in the fuel tank is estimated by using the estimated LS coefficients, probe outputs, pitch angle, roll angle and aircraft accelerations as shown below [2].

$$Y = (X^T X)^{-1} XC$$

For a fuel tank :

$$Y_{Nx1} = A_{NxP} \, C_{Px1}$$

Where
     Y : tank fuel quantity in Kgs
     C : estimated LS coefficients
     A : fuel guage probe data, angles and accelerations
     N : number of data points and

P : number of estimated LS coefficients

$$Y = c1 + c2* \text{ probe} + c3* \text{ pitch angle} + c4* \\ \text{roll angle} + c5* \text{ longitudinal acceleration} + c6 * \\ \text{vertical acceleration}$$

(1)

c1, c2 ... and c6 are estimated LS coefficients and Y is the fuel quantity to be computed. The computation is done for every 80 milliseconds in a continuous loop.

The fuel quantity is gauged as shown in Fig.4 from the estimated LS coefficients, fuel gauge probe data, angles and accelerations parameters when the probe signal is in the gauging zone i.e within Twet and Tdry limits. Twet and Tdry limits correspond to the fuel gauge probe frequency signals when the probe is fully immersed and fully dry. The fully immersed and dry condition of the probe indicates the fuel tank capacity as full or empty. The estimated LS coefficients are used to gauge the fuel when the fuel gauge probe is in the gauging zone.

When the fuel probe is in gauging zone and not failed, the equation (1) is used to estimate the fuel quantity for each probe. The average of the fuel quantity estimated for the probes is computed to gauge the fuel quantity of a fuel tank. Any upward fluctuation or downward fluctuation by more than the rate of maximum fuel consumption by the engine in the fuel quantity estimation is filtered.

Fuel tank model (developed using ANSA simulation software) generates huge database which relates the fuel volume of a fuel tank for a specified fuel probe height, pitch angle and roll angle parameters. Using a truth table (frequency Vs fuel probe height), fuel gauge probe frequency is obtained for a specified fuel gauge probe height. LS coefficients are estimated using the data generated by fuel tank model using the equation.

$$C = (X^T X)^{-1} X^T Y$$

### Results and Discussion

Least Square coefficients estimated for each probe of fuselage tank 1, left hand side wing tank and right hand side wing tank are listed in Table-1, 2 and 3 respectively.

Least square computational model implemented in Electronic unit is tested at Test Rig which has dynamic flight test environment facility. The performance is verified with the previous flight data and the results are presented for fuel Tanks in Fig.5 to 7. The results indicate that

the estimation by least square model is more consistent and accurate.

Least Square estimate is also found closer to the total fuel remaining (detotaliser-DTOT) estimate of the aircraft which gives redundant fuel quantity information in terms of the remaining fuel in the aircraft after engine consumption. Total fuel remaining estimate is done using flow meter data. Initially total fuel remaining parameter is initialized to the sum of the all internal fuel tanks quantity. When the fuel is consumed by the engine, the total fuel remaining is updated by subtracting the fuel consumed by

the engine using flow rate data from the initialized value. The results are presented in Fig.8.

A comparison study of real time fuel quantity estimation and the aircraft data obtained by filling the fuel tank, measuring the unknown fuel gauge probe signal for the known quantity of fuel and draining the fuel tank for subsequent measurements for fuselage tank 1 (for 3 deg pitch angle and 0 deg roll angle) is given in Table-4. There was an offset of around 30mm found with the fuel tank model results due to the deviation in the fuel gauging probe mounting in the fuel tank.

The fuel gauge probe is mounted in a fuel tank in such a way that around twenty five kgs of fuel quantity in the bottom of the fuel tank is ungaugeable which leads to an offset in the fuel probe height data with the fuel tank model.

The results of fuel quantity estimation for fuselage tank 1 (for 3 deg pitch angle and 0 deg roll angle) are presented in Fig.9. It indicates that the fuel quantity estimated is almost closer to the actual aircraft data results.

### Table-1 : Least Square Coefficients for Fuselage Tank 1

| Sl. No. | LS Coeff. | Probe 1 |
|---------|-----------|---------|
| 1 | C1 | -589.5196 |
| 2 | C2 | 5.4711 |
| 3 | C3 | 17.9582 |
| 4 | C4 | 1.6905 |
| 5 | C5 | 0.0378 |
| 6 | C6 | 0.4895 |

### Table-2 : Least Square Coefficients for Left Hand Side Wing Tank

| Sl. No. | LS Coefficients | Probe 1 | Probe 2 | Probe 3 | Probe 4 |
|---------|-----------------|---------|---------|---------|---------|
| 1 | C1 | -210.7296 | -200.9358 | -444.7123 | 389.9668 |
| 2 | C2 | 3.8693 | 2.8047 | 4.1951 | 1.3319 |
| 3 | C3 | 3.6897 | 40.7260 | -12.8687 | 0.4235 |
| 4 | C4 | -4.7924 | -5.2318 | 0.9046 | 0.2365 |
| 5 | C5 | 0.5645 | 1.1569 | -0.4190 | 0.1841 |
| 6 | C6 | 3.3433 | 1.4888 | 2.9844 | -0.1271 |

### Table-3 : Least Square Coefficients for Right Hand Side Wing Tank

| Sl. No. | LS Coefficients | Probe 1 | Probe 2 | Probe 3 | Probe 4 |
|---------|-----------------|---------|---------|---------|---------|
| 1 | C1 | 66.4696 | -118.7423 | -543.6729 | 387.7067 |
| 2 | C2 | 1.8456 | 3.1491 | 4.9725 | 1.3787 |
| 3 | C3 | 15.6367 | 43.8742 | 4.0312 | -0.2041 |
| 4 | C4 | -0.0635 | 3.3495 | -0.3959 | 0.9080 |
| 5 | C5 | 0.2117 | -0.0619 | -0.1742 | 0.7038 |
| 6 | C6 | 6.0663 | 1.4888 | -0.5463 | -0.5777 |

| Table-4 : Comparison Study of Fuel Quantity Estimation of Fuselage Tank 1 Between Aircraft Data and Computational Model | | | |
|---|---|---|---|
| | | Probe Height (mm) Corresponding to Fuel Quantity | |
| Sl. No. | Fuel Quantity (Kgs) | Aircraft Data | Real Time Model (without offset) |
| 1 | 60 | 62.27 | 65 |
| 2 | 85 | 97.7 | 97.5 |
| 3 | 110 | 131.88 | 133.2 |
| 4 | 160 | 197.7 | 199.7 |
| 5 | 210 | 262.34 | 266.1 |
| 6 | 235 | 294.32 | 296.8 |
| 7 | 260 | 325.97 | 330.8 |
| 8 | 310 | 389.18 | 397.3 |
| 9 | 385 | 482.27 | 492.6 |
| 10 | 423 | 534.2 | 538 |

## Conclusion

It is seen that the fuel gauging system performance is well improved by using the least square computational model. Least square computational model caters for various dynamic effects of flight maneuvers of fighter aircraft.

A real time computational model based on fuel tank model method is developed successfully. It can be used for modeling any irregular shape of fuel tank and it is practically demonstrated that the fuel quantity estimated by this method matches well with the actual aircraft data.

An onboard program was developed using Microcontroller based Electronic unit and tested at test rig which has dynamic flight test environment facility. The results obtained are found to be more accurate and reliable.

Further refinements to the fuel gauging system logic can be done and robustness of least square computational model can be increased by rebuilding the model with more data.

The fuel tank can be modeled more precisely by considering all the internal structures and components of fuel tank. The real time computational model onboard program can be improvised further by catering for all the dynamic flight conditions of aircraft for better accuracy of fuel quantity estimate.

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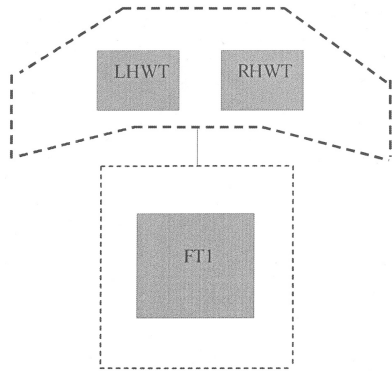11. Seshu, P., Text Book of "Finite Element Analysis", Prentice Hall of India, 2003.
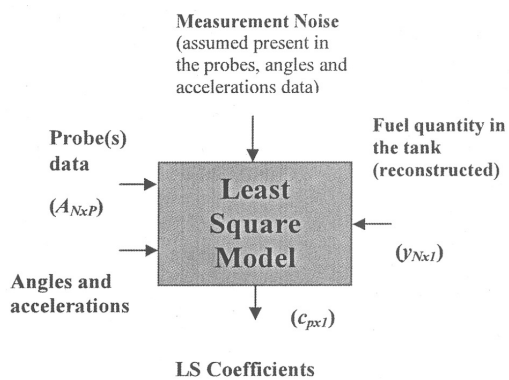
*Fig.1 Schematic of Aircraft Fuel System*

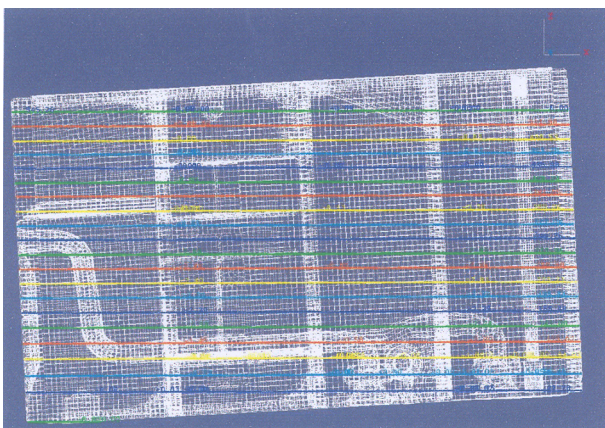

*Fig.2 Least Square Computational Model*



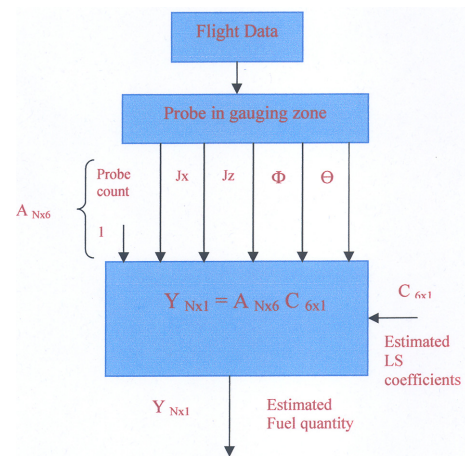*Fig.3 Fuel Quantity Estimation Using Fuel Tank Model*
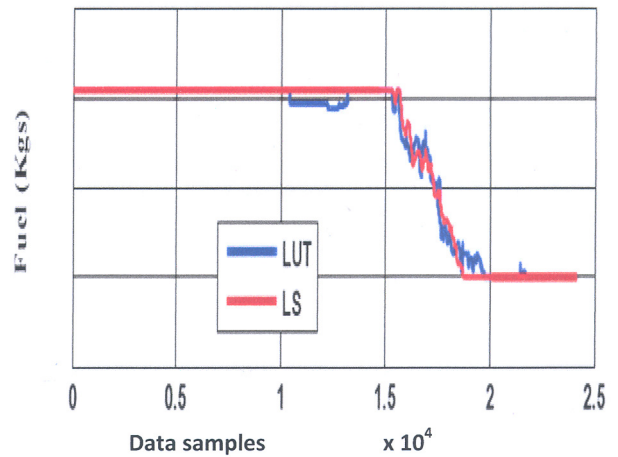


*Fig.4 Fuel Quantity Estimation Using LS Model*
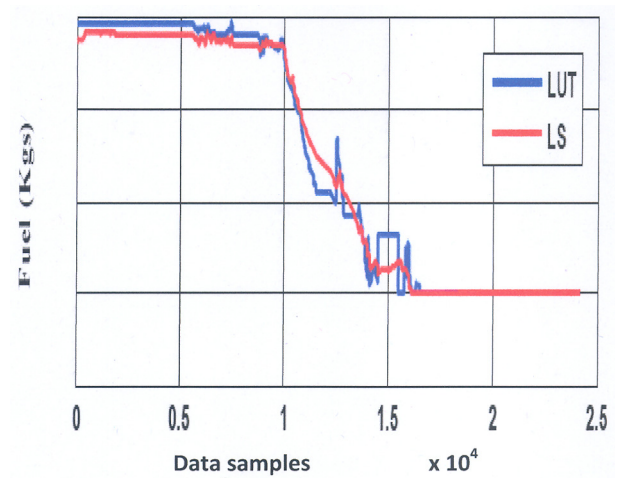


*Fig.5 Fuel Quantity Estimation of Fuselage Tank 1*
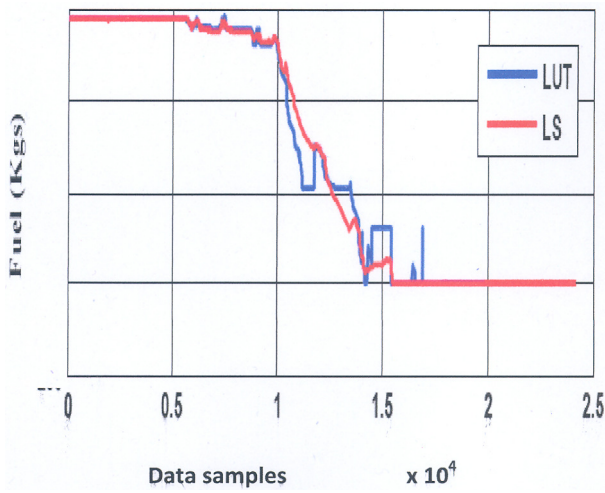


*Fig.6 Fuel Quantity Estimation of Left Hand Side Wing Tank*

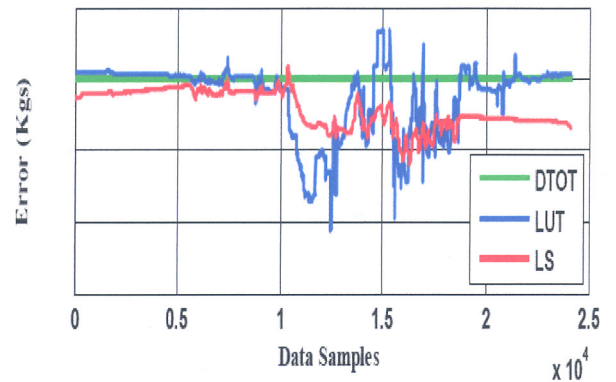*Fig.7 Fuel Quantity Estimation of Right Hand Side Wing Tank*



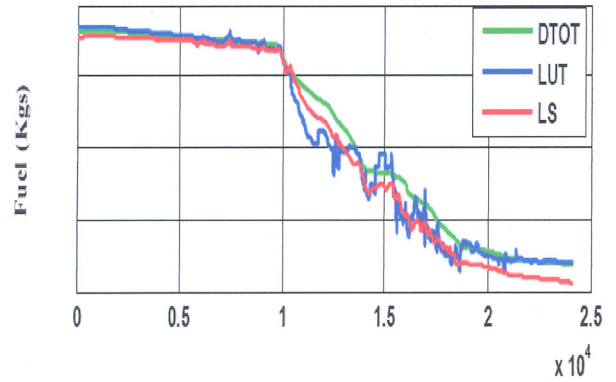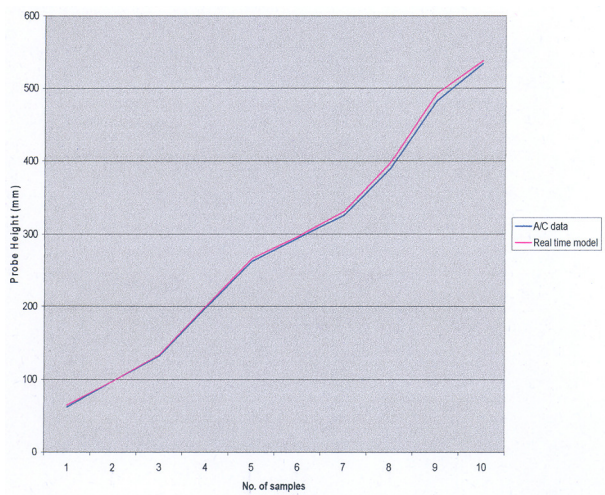*Fig.9 Fuel Quantity Estimation of Fuselage Tank 1*



*Fig.8 Fuel Quantity Estimation of all Fuel Tanks*