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Calibration and accuracy determination of airdata system for a modern fighter

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An Air data system (ADS) is an essential avionics module found in modern fighter aircraft cockpits. It provides critical information about the aircraft to the pilot throughout the flight regime. Airdata system comprises of air data computer and their associated sensors. Sensors instrumented on aircraft normally measure pressures and flow angles in the local flow field using vanes and probes. However, aircraft requires the free stream parameters for flying. Therefore, forward lookup tables in Air Data Computer (ADC) are used to covert local parameters measured using airdata sensor to free stream parameters. In order to design flight controls, improved system performance, ADS should deliver accurate output. Accuracy of free stream parameters depends upon the accuracy of these tables in Air data computer. In this paper, the airdata system of a modern fighter aircraft is considered. This system carries airdata tables which are calibrated/updated using Maximum Likelihood Estimation (MLE) method. The accuracy of it needs to be determined by another independent technique. Hence an Extended Kalman Filter (EKF) is proposed to calibrate and describe the accuracy limits of airdata system. The technique is tested with flight data and the results demonstrate the strength of the technique for airdata calibration and accuracy determination.

Nomenclature

h = inertial altitude
P_s = static pressure
g = acceleration due to gravity
R = gas constant
T = ambient temperature
α = angle of attack
β = sideslip angle
P_{sn} = nose probe pressure measurement
P_{sp} = side probe static pressure
P_T = measured total pressure
p_g, q_g, r_g = gyro measurements
u, v, w = inertial velocities
a_x, a_y, a_z = acceleration measurements

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I. Introduction

Reliable and accurate airdata measurements are essential requirements to meet advancements in fly-by-wire and flight controls. An air data computer and their associated instrumentation are used to measure critical air mass properties from the aerodynamic flow field near the aircraft. Typical air data sensors are vanes and probes for flow angles, pitot probes, static pressure probes and air temperature probes. Air data computers are used by aircraft to acquire and process data from sensors to obtain key air data parameters such as altitude, airspeed, Angle of Attack (AOA, α), Angle of Side Slip (AOSS, β), Mach number, rate of climb and temperature.

Airdata parameters are the most important piece of information the pilot needs for safe and accurate flight. Each phase of flight is conducted based on these parameters. Vanes are used to measure angle of attack and side slip angle. Further, forward table in ADC are used to convert local measurement to free stream measurements. Vane alpha table is a function of local alpha and mach. This table gives a free stream alpha for a measured local alpha and mach. whereas vane sideslip table is function of free stream alpha obtained using alpha table, local sideslip angle and Mach number. Pressures measured using static and pitot probes are converted to indicate altitude, vertical speed, true air speed and Mach number. Similarly, differential pressure measurements on the airdata probes are also used to compute the flow angles such as angle of attack and side slip angle. The corrections to pressures and flow angles are normally implemented in the airdata computer in the form of look up tables as functions of mach, angle of attack and side slip angle. Accuracy of free stream parameters depends upon these tables. Therefore, these table values need to be verified and updated using flight test techniques for airdata calibration.

Airdata calibration using flight data is often performed using flight path reconstruction (FPR) techniques based on Maximum Likelihood Estimation (MLE) [2]. For the high performance aircraft discussed in this paper, initial airdata calibration was performed using FPR techniques [3]. The calibration was carried out using specific airdata calibration maneuvers. For certification of the airdata system, it has been found necessary to develop an alternate technique to define the accuracy of the airdata measurements using almost all the flight data gathered till date. For this purpose, an EKF based data fusion technique is implemented which will be used offline to define accuracy of calibrated airdata measurements. further, proposed EKF will be used for giving updates to the airdata tables as well.

Accuracy determination of airdata system is carried for entire envelope using 220 flights. Regions which need to be updated in an envelope are highlighted. Further, error statistics obtained from the filter is used to update the ADS tables. This paper is divided into sections. Section II, gives a brief introduction about proposed filter. Accuracy determination using EKF filter is discussed in section III followed by results and discussion in section IV.

II. Filter Implementation

The aircraft equations of motion form the basis [1] for the estimation of air data parameters such as airspeed, AOA, AOSS and altitude. The winds are estimated using a constant wind model that can adapt to changes in flight conditions. Similarly a constant bias model is used for estimating the gyro biases (p_b, q_b, r_b), accelerometer biases (a_{xb}, a_{yb}, a_{zb}), AOA (α_b) and AOSS (β_b) biases. The other measurements such as vehicle rates, accelerations and attitudes are not estimated; instead measurements from Digital Flight Control Computer (DFCC) and Inertial Navigation System (INS) are directly used. The idea is to use available inertial measurements to calibrate the airdata parameters. The state model for the proposed EKF is as follows

$$\mathbf{x} = \begin{bmatrix} u & v & w & h & w_{ni} & w_{ei} & p_b & q_b & r_b & a_{xb} & a_{yb} & a_{zb} & \alpha_b & \beta_b & P_s \end{bmatrix}^T \qquad (1)$$

$$\begin{aligned} \dot{u} &= rv - qw - g\sin\theta + a_x - a_{xb} + \mu_u \\ \dot{v} &= -ru + pw + g\sin\phi\cos\theta + a_y - a_{yb} + \mu_v \qquad (2) \\ \dot{w} &= qu - pv + g\cos\phi\cos\theta + a_z - a_{zb} + \mu_w \end{aligned}$$

and

$$\dot{h} = u\sin\theta - v\sin\phi\cos\theta - w\cos\phi\cos\theta + \mu_h \qquad (3)$$

where, $p = p_g - p_b$, $q = q_g - q_b$ and $r = r_g - r_b$ are bias corrected gyro measurements. a_y and a_z are lateral and normal accelerations (not bias corrected) from DFCC sensors. a_x is forward acceleration (Not bias corrected) from INS. u, v, w are the inertial velocities in the aircraft body frame. θ, ϕ are the aircraft pitch and roll attitudes used from the INS of the aircraft. Further, w_{ni}, w_{ei}, w_{di} are the north, east and down components of inertial winds.

$$\dot{w}_{ni} = \dot{w}_{ei} = \dot{w}_{di} = 0 \tag{4}$$

$$\dot{p}_b = \dot{q}_b = \dot{r}_b = 0 \tag{5}$$

$$\dot{a}_{xb} = \dot{a}_{yb} = \dot{a}_{zb} = 0 \tag{6}$$

$$\dot{\alpha}_b = \dot{\beta}_b = 0 \tag{7}$$

$$\dot{P}_s = -\frac{P_s g h}{RT} + \mu_p \tag{8}$$

α_b, β_b are the estimated AOA and AOSS biases. In Equations (1-8), μ represents a process noise. Detail on implementation of Extended Kalman filter can be found in [4] .

Measurement model

The measurement vector $\mathbf{z}$ is

$$\mathbf{z} = \begin{bmatrix} V_{rel\_meas} & \alpha_{meas} & \beta_{meas} & h_{meas} & P_{sn} \end{bmatrix}^T \tag{9}$$

The sensors used are modelled as follows:

$$V_{rel\_meas} = \sqrt{(u-u_{wb})^2 + (v-v_{wb})^2 + (w-w_{wb})^2} + \varepsilon_V \tag{10}$$

where V_{rel_meas} is the true air speed from the ADS. u_{wb}, v_{wb}, w_{wb} are the components of winds in the aircraft body frame.

$$\begin{bmatrix} u_{wb} \\ v_{wb} \\ w_{wb} \end{bmatrix} = C_n^b \begin{bmatrix} w_{ni} \\ w_{ei} \\ w_{di} \end{bmatrix} \tag{11}$$

C_b^n is the Direction Cosine Matrix (DCM). DCM is written in terms of rotation matrix that describes the orientation of the body coordinates frame ‘b’ with respect to the inertial/navigation frame ‘n’. Rotation matrix can be expressed as

$$C_n^b = C_b^{nT} = \begin{bmatrix} \cos\theta\cos\psi & -\cos\phi\sin\psi + \sin\phi\sin\theta\cos\psi & \sin\phi\sin\psi + \cos\phi\sin\theta\cos\psi \\ \cos\theta\sin\psi & \cos\phi\cos\psi + \sin\phi\sin\theta\sin\psi & -\sin\phi\cos\psi + \cos\phi\sin\theta\sin\psi \\ -\sin\theta & \sin\phi\cos\theta & \cos\phi\cos\theta \end{bmatrix}^T \tag{12}$$

ψ is the heading angle from INS.

$$\alpha_{meas} = \tan^{-1}\left(\frac{w-w_{wb}}{u-u_{wb}}\right) + \alpha_b + \varepsilon_\alpha \tag{13}$$

α_{meas} is the calibrated AOA measurement after passing vane measured AOA through the calibration tables implemented in ADS.

$$\beta_{meas} = \sin^{-1}\left(\frac{v-v_{wb}}{V_{rel\_meas}}\right) + \beta_b + \varepsilon_\beta \tag{14}$$

β_{meas} is the AOSS obtained after correcting the vane measured AOSS through the calibration tables implemented in ADS.

$$h_{meas} = h + \varepsilon_h \tag{15}$$

h_{meas} is the pressure altitude from ADS

$$P_{sn} = P_s + \varepsilon_{pn} \tag{16}$$

Using above measurements, filtering is performed on the flight data. ε represts a measurement noise. Estimates of the EKF are considered as true. Using this filter, accuracy of the existing tables will be defined.

III. Method for Accuracy determination

Aircraft has several forward tables in Air Data Computer (ADC). Brief detail on each table is as follows

Vane AOA: This is a function of Local AOA and Mach. i.e., it is a 2D look up table. X dimension is local alpha and Y dimension is Mach number. The output of the table is free stream AOA.

Vane AOSS: This is a function of free stream AOA, local AOSS and Mach number. The output is free stream AOSS.

Side probe AOA**:** The probes measure only pressures. So it is a two step process.

Step 1: Table given by manufacturer for converting local pressure to local AOA.

Step 2: Probe AOA: This is a function of average of local AOA (left, right), difference of local AOA (left, right) and Mach number. The output of this table is true AOA.

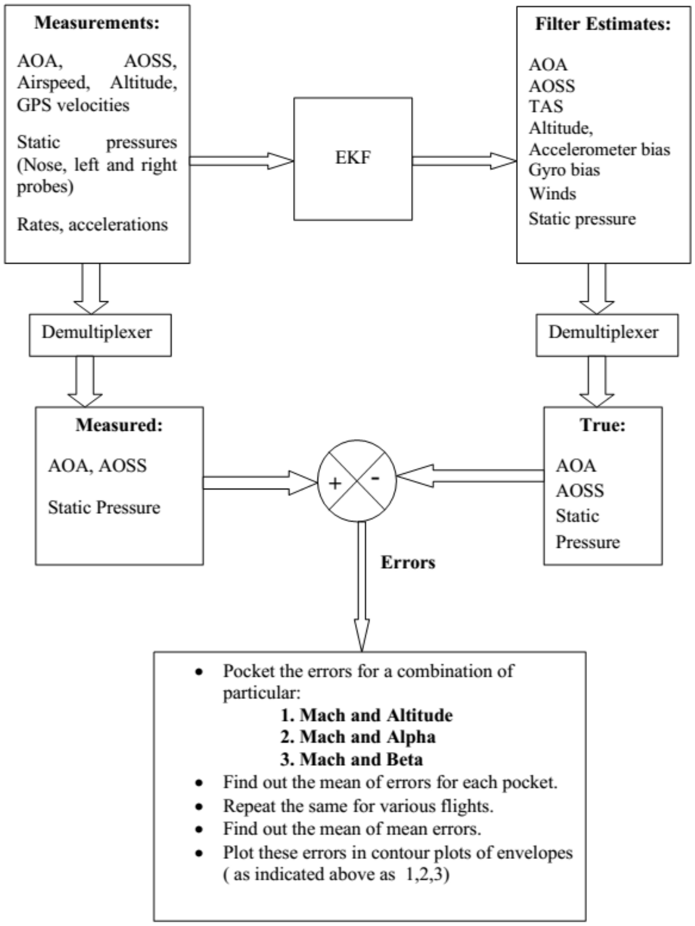
Side probe AOSS: The side probe AOSS table is similar to side probe AOA.

Pressure coefficient Cp table**:** Cp tables are function of free stream AOA, AOSS and local Mach number. The local Mach number is calculated based upon local total and static pressure.

Nose probe AOA: This is a function of (difference of two port pressures (vertical)/dynamic pressure) and local Mach number.

Nose probe AOSS: This is a function of (difference of two port pressures (side)/dynamic pressure) and local Mach number.

The ADS tables are already calibrated using Maximum Likelihood Estimation (MLE) based Estima (MLE) software. The goal of this work to ascribe accuracy limits for these calibrated tables. The accuracy of AOA, AOSS, and static pressures are determined. The detailed procedure of accuracy determination using Extended Kalman Filter is shown in Fig 1. Measurements obtained from ADS system is compared with EKF estimates. Flight data is segmented into pockets (Mach,altitude/Mach,alpha/Mach,beta). Mean of errors for each pocket is calculated from individual flight sorties. Subsequently, mean of mean errors for all flight sorties (220 total) are calculated. This mean of mean error for each pocket is plotted in contour formats for ascribing accuracy. Results are discussed in the following section.



- Pocket the errors for a combination of particular:
  1. **Mach and Altitude**
  2. **Mach and Alpha**
  3. **Mach and Beta**
- Find out the mean of errors for each pocket.
- Repeat the same for various flights.
- Find out the mean of mean errors.
- Plot these errors in contour plots of envelopes (as indicated above as 1,2,3)

Figure 1. Accuracy determination using

IV. Results & Discussion

In this section, Sorties with several high AOA and steep dives are considered to perform airdata calibration. Most of the maneuvers considered are typical wind up-turn maneuvers. The motivation behind ascribing accuracy of ADS table obtained from MLE/Estima is that it could not compute accurate AOA for wind-up turn maneuvers with huge variations in winds due to large altitude variations. AOA measured by vane sensors and corrected using onboard correction tables for a high AOA wind up turn maneuver is shown in Fig 12. Corrected AOA is obtained from MLE and EKF respectively. It can be seen MLE estimated AOA shows variations that are not seen by the vane sensors on the aircraft. EKF estimated AOA captures the measured AOA trends more appropriately. In most plots the Y axis ticks are not shown as the data is classified and there is no permission to publish them. However the errors are presented in most cases for comparison.

Further, calibration and accuracy of parameters such as AOA from vanes, AOSS from ADS and static pressure from side probe for different envelopes are discussed in detail as they are the primary sources of airdata system. Accuracy for other sensors such as AOA (left and right vane) and pressure probes (nose) are detremined but results are not presented in the paper. It is noted that the calibration of static pressure is carried out using Pressure coefficient (C_p) tables. The relationship between static pressure and C_p is as follows

$$C_p = \frac{P_{sp} - P_s}{P_T - P_{sp}}$$

P_s is obtained from filter (Estima/EKF). Side probe static pressure (P_{sp}) and total pressure (P_T) are the measurements.

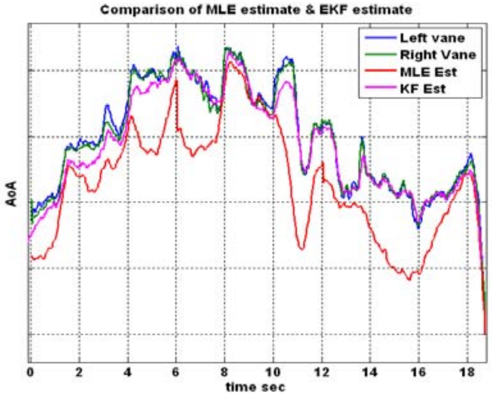
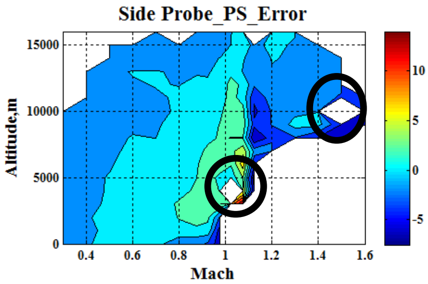
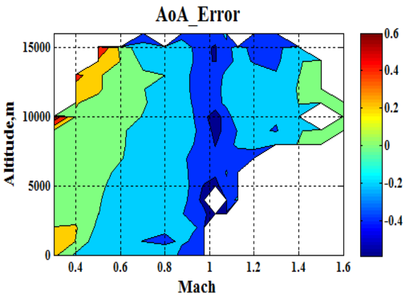
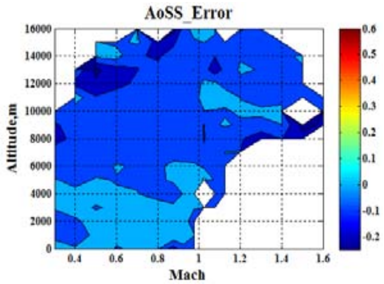
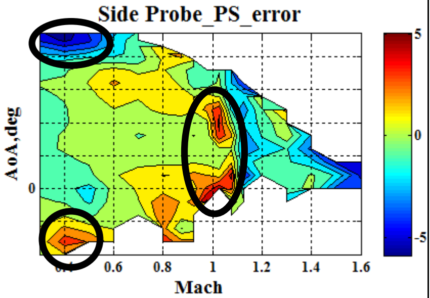
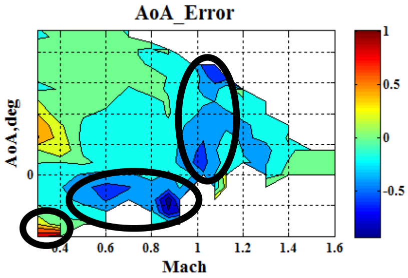
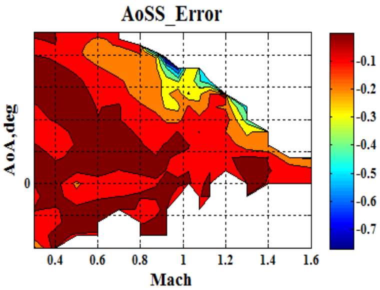


Figure 12. Comparison of AOA estimation

Results are presented below for diffrenet envelopes as discussed in section III:

Envelopes:

Static pressure	***Angle of attack***	***Sideslip angle***
 **Figure 2. Altitude-Mach Envelope** **Remarks:** Typically the accuracy expected is within ±5 millibar. Transonic and supersonic Encircled mach region has more errors.This is obvious due to transonic jumps seen in the sensor measurements.	 **Figure 5. Altitude-Mach Envelope** **Remarks:** Typically the accuracy expected is within ± 0.5 degree. Alpha is accurate in altitude-mach envelope. Error lies within the expected accuracy range.	 **Figure 8. Altitude-Mach Envelope** **Remarks:** Typically the accuracy expected is within ± 1 degree. Sideslip angle is accurate in altitude-mach envelope and error lies within the expected range.
 **Figure 3. Alpha-Mach envelope** **Remarks:** Error lies within ± 2 millibar for most of the envelope except encircled region shown in figure 3. In subsonic mach region for negative alpha and higher alpha region as well as transonic mach region update is required.	 **Figure 6. Alpha-Mach envelope** **Remarks:** Most of the alpha-mach envelope is accurate with error lies within ± 0.5 degree except encircled region for negative alpha at subsonic and transonic mach region.	 **Figure 9. Alpha-Mach envelope** **Remarks:** Typically the accuracy expected is within ± 1 degree. Sideslip is accurate in alpha-mach envelope. Error lies within the expected accuracy range.

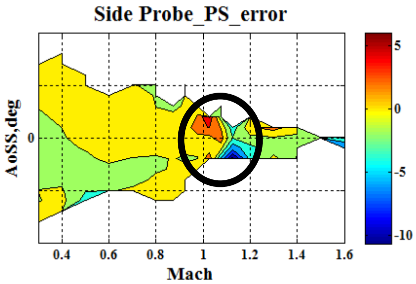

Side Probe_PS_error

Figure 4. Beta-Mach envelope

Remarks: Most of the envelope region error lies within ± 5 millibar. Encircled transonic region in figure 4 is erroneous and needs the update.

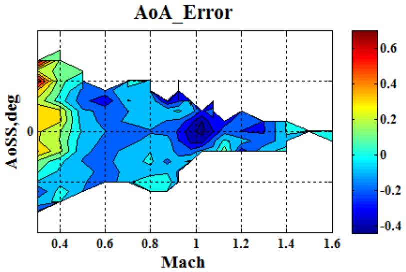

AoA_Error

Figure 7. Beta-Mach envelope

Remarks: Typically the accuracy expected is within ± 0.5 degree. Alpha is accurate in beta-mach envelope. Error lies within the expected accuracy range.

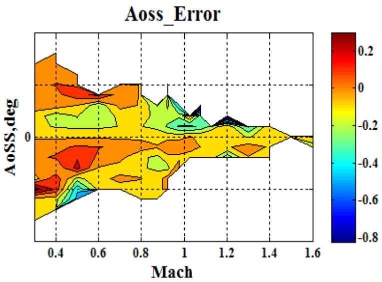

Aoss_Error

Figure 10. Beta-Mach envelope

Remarks: Error in the envelope lies within ± 1 degree as shown in figure 10.

Regions which need to be updated in an envelope are circled in Fig. 2-10. Error statistics obtained from EKF as discussed in section III is used to update the tables. A procedure to update table with error statistics is shown in Fig. 11.

Vane AOA and pressure coefficients tables are updated using EKF. Results of static pressure and AoA using calibrated tables obtained from Estima software (old tables) and proposed EKF (Updated table) are compared and are presented in Table 1.

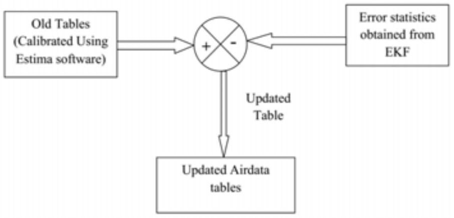
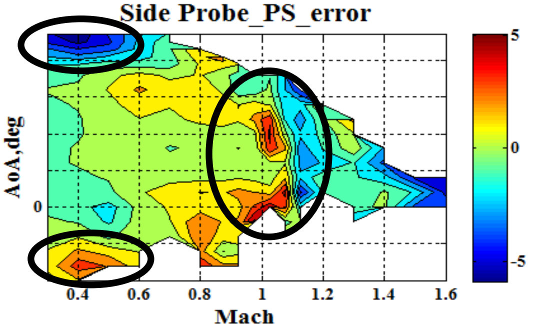
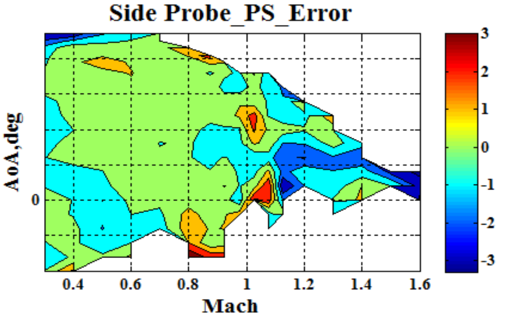
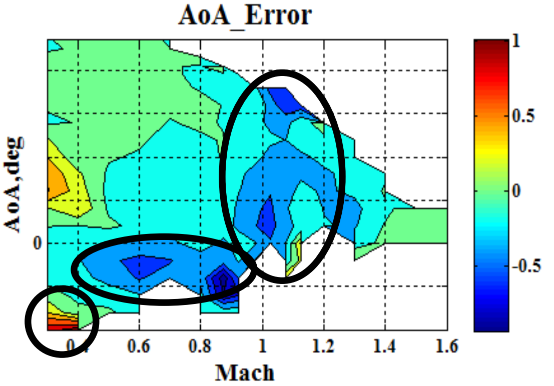
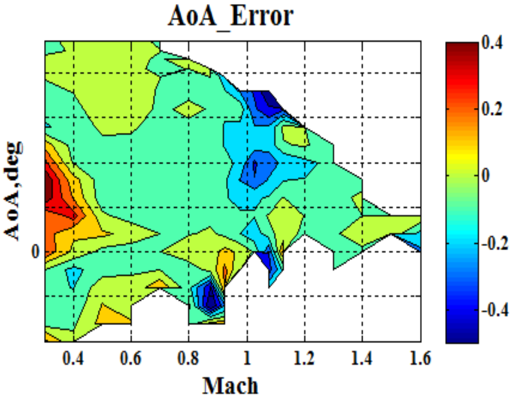
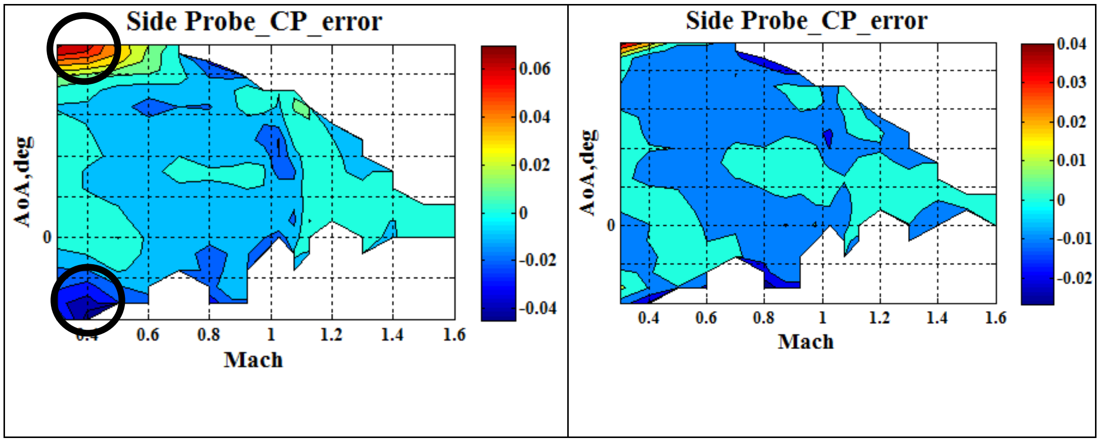


Figure 11. Airdata table update using EKF

Table 1: Comparison of Results with Estima vs. Up[dated table with EKF

Old table Results (Estima)	Updated table Results (EKF)
 Side Probe_PS_error 	 Side Probe_PS_Error
 AoA_Error 	 AoA_Error



Improvements brought by EKF in the calibration can be seen clearly from the contour plots compared in Table 1. Further, time histories are presented to show the difference between old and updated table results in figure 13. EKF based Updated ADS tables produce lesser errors as compared to old tables updated with Estima.

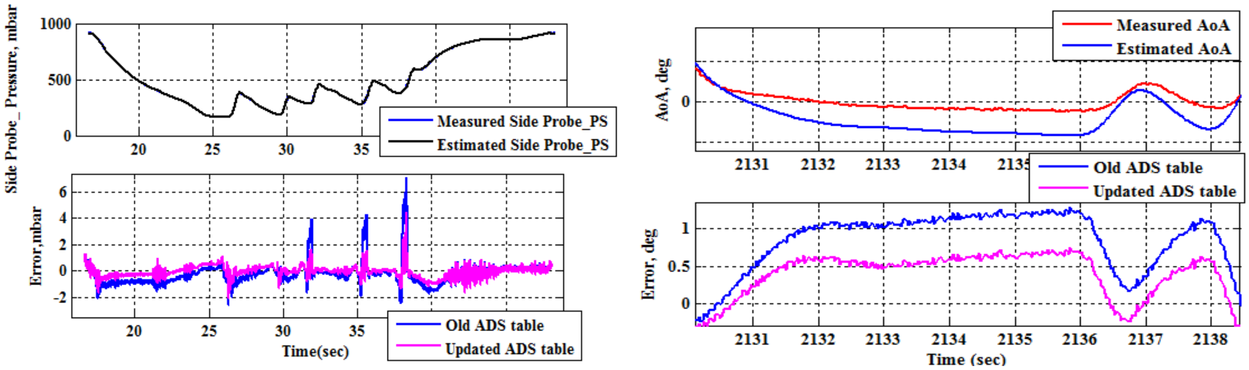


Figure 13. Time histories of airdata parameters

V. Conclusion

Accuracy determination and calibration of airdata system using EKF is presented. The technique is used to ascribe accuracy of calibrated ADS tables obtained from Estima software. It is further used to obtain improved calibrated ADS tables over Estima. The ADS tables calibrated using EKF will be implemented onboard the aircraft.

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