

Measurement Data Inversion and Fidelity Assessment for Design and Development of Air Data System for Aerospace Vehicles

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Abstract - The measurements obtained from the Air Data System (ADS) are used for feedback to the safety critical fly-by-wire flight control system as well as for navigation on the aerospace vehicles. Therefore, reliable, accurate, and precise air data measurements are very important under normal and various failure conditions. Various steps are followed in the design and development of the ADS algorithms which are complex and challenging. These algorithms embed the computations of free stream or corrected measurements from the raw or local measurements obtained from the on-board sensors based on their position on the aircraft. These position error corrections are generated at on-ground for free stream to local measurement however, they need to be carried on-board for functioning in opposite way, i.e., local to free stream measurements. This paper presents the data inversion procedures, complexities and challenges involved therein as part of the ADS design and development. The procedure for validation of the data inversion process is also presented along with the relevant results. Experiences gained at various stages of the development are shared in this paper.

Keywords: Air Data System (ADS), Inversion Process, Total Pressure (Pt), Static Pressure (Ps), Angle of Attack (AOA), Angle of Side Slip (AOSS), Mach No. (M), Position Error Correction (PEC), Fidelity Assessment, Inverse, Forward

Nomenclature

ADS	:	Air Data System
6-DOF	:	Six Degrees of Freedom
AAR	:	Air-To-Air Refueling
AARP	:	Air-To-Air Refueling Probe
ADC	:	Air Data Computer
Ai	:	Free Stream AOA with index $i=1, 2, \dots$
AIRDATS	:	ADS Test System
AOA / AOAFs / αfs	:	Angle of Attack or Free stream AOA
AOAFs_fwd	:	Free Stream AOA within the Forward Tables
AOSS / AOSSfs / βfs / SSA	:	Angle of Side Slip or Free stream AOSS
AOSSfs_fwd	:	Free Stream AOSS within the Forward Tables
Avg_loc_angle	:	Average of local angles
Bi	:	Free Stream AOSS with index $i=1, 2, \dots$
CAS	:	Calibrated Air Speed
CFD	:	Computational Fluid Dynamics

CLAW	: Control Laws or Flight Control Laws
CPs or Cps	: Correction coefficient for Static Pressure
CPt or Cpt	: Correction coefficient for Total Pressure
DFCC	: Digital Flight Control Computer
Diff_loc_angle	: Difference of local angles
ETS	: Engineers Test Stations
FBW	: Fly-By-Wire
FCS	: Flight Control System
FRM	: Failure Redundancy Management
fwd_avg_loc_angle /	: Grid vector of average of local angle for forward lookup
Fwd_avg_loc_angle_grid	: tables of AOA and AOSS
fwd_diff_loc_angle /	: Grid vector of difference of local angle for forward lookup
Fwd_diff_loc_angle_grid	: table of AOA and AOSS
HILS	: Hardware-In-Loop Simulator
IB	: Iron Bird
IRST	: Infra-Red Search and Track
LAi	: Local Angle with index i=1, 2, ...
Loc_angle	: Local Angle
loc_aoa_fwd_grid	: local angle grid for forward lookup table of AOA
Loc_left, Loc right	: Local angle from the left and right probe
Mach No. / Mfs	: Free Stream Mach No.
Machfs_Grid	: Grid of free stream Mach No. for lookup table
Mm	: Measured Mach No.
NDPm	: Nose Differential Pressure Measured
OEM	: Original Equipment Manufacturer
PEC	: Position Error Correction
Ps	: Static Pressure or Free Steam Ps
Psm	: Measured static pressure
Pt	: Total Pressure or Free Steam Pt
Ptm	: Measured total pressure
qcm	: Measured dynamic pressure
RTFDS / FDS	: Real Time Flight Dynamic Simulator
Tt or TAT	: Total Air Temperature
WT	: Wind Tunnel
Zp	: Pressure Altitude

1. INTRODUCTION

Air Data System (ADS) is an integral part of the safety critical Fly-By-Wire (FBW) Flight Control System (FCS). As shown in Figure 1, the ADS plays a crucial role for feedback and gain scheduling to the FBW-FCS as well as for navigation, many other functions [1]. It involves measurements of the following parameters relative to the air:

- 1) Pressures measurements by using pressure probes or pitot tubes. It includes measurements of the:
 - 1.1) Total pressure (Pt), and
 - 1.2) Static pressure (Ps),Derived parameters or flight condition parameters like Mach No. (Mach), Pressure altitude (Zp), Calibrated Air Speed (CAS) are computed from these pressures.
- 2) Flow Angles (Aircraft angles relative to the wind axis) measurements are carried out by using pressure probes and rotating vanes. The flow angle measurements include the followings:
 - 2.1) Angle of Attack (AOA), and
 - 2.2) Angle of side Slip (AOSS).
- 3) Temperature (Tt or TAT) by using TAT probe

Refer to [1, 2] for detailed components of the ADS and relevant aspects. Figure 2 shows the role of ADS for the FBW-FCS. The measurement of the flow angles, pressures, and temperature obtained from the sensors get processed through the electronics hardware and then made as digital raw measurements inside the ADC. The ADS computational algorithms residing inside the ADC software perform the following critical tasks:

- 1) Corrections to the measurements. It includes various types of corrections, like sensor Position Error Correction (PEC), kinematic correction etc.
- 2) Failure Redundancy Management (FRM) for the measurements obtained from multiple sensors. The FRM includes computations of the failure thresholds or limits, identification of failed signal, and selection of healthy signal,
- 3) Computations of derived parameters or flight condition parameters,
- 4) Additional signal processing to mitigate the effects of the external turbulences, etc.

Thus, the accuracy of the complete system depends on the accuracy of each and every element, and the process adopted for measurement and corrections. The system can have the total minimum inaccuracy based on the acceptable inaccuracies of the system elements physical hardware (sensor, electronic hardware etc.), software, and sensor installation tolerance. Hardware decides the kind of minimum inaccuracy system shall have forever and it may likely increase due to aging or drift if it happens so. The other part of the inaccuracy is corrected through software / algorithms [3,4]. These algorithms embed the computations of free stream or corrected measurements from the raw or local measurements obtained from the on-board sensors based on their position on the aircraft. These position error corrections (PEC) are generated at on-ground for free stream to local measurements based on either CFD estimate or wind tunnel experiments or blend of both. Therefore, they need to be inverted for functioning in opposite way at on-board, i.e. applying PEC for converting local to free stream measurements. However, there are various challenges involved in the data inversion process. Significant literature on the ADS is available, especially on the position error corrections and calibration. However, the basics of the data inversions are not detailed anywhere. Thus, this article shall also aid in encouraging to understand this subject, especially beginners. This article presents the data inversion procedures, complexities and challenges involved therein as part of the ADS design and development. The procedure for validation of the data inversion process is also presented along with the relevant results. Experiences gained at various stages of the development of high-performance combat aircraft are shared in this paper.

The paper is organised as follows: Section 2 presents various challenges and the complexities involved in the design and development of the computational algorithms or process for the ADS. Section 3 broadly elaborates the need for applying PEC to on-board ADS measurement, data inversion process and relevant aspects. Section 4 presents on the evaluation of FBW-FCS involving ADS at Hardware-In-Loop Simulator (HILS) which is also referred to Iron Bird. Section 5 presents process for formatting the data prior to data inversion and analysis thereof. Section 6 presents the typical characteristics of the ADS measurements

illustrating the complexities. Section 7 presents the data inversion procedures for flow angles and pressures. Section 8 presents the fidelity assessment process for inverted data, and Section 9 concludes the paper.

2. ADS ALGORITHMS DEVELOPMENT COMPLEXITIES AND CHALLENGES

The complexities and challenges involved in the design and development of ADS are shown in Figure 3 [1] and the relevant details are given below:

- 1) Measurements get perturbed in presence of aircraft despite being installed at the least sensitive location. Therefore, the need for applying PEC to the measurement arises.

Pressure distribution of the air flow changes along the body of the aircraft depending upon the aerodynamic shape and flight condition defined in terms of Mach No., (speed), Altitude, and flow angles (AOA and AOSS: representing orientation with respect to wind direction). See the diagram at the left-top corner of Figure 3 [5]. The laminar flow becomes turbulent at some locations or the aircraft body itself masks the sensor measurement which and ultimately leads to have perturbed (noisy) and inaccurate measurements. Therefore, ADS sensors are required to be mounted at the locations on the aircraft where flow disturbances are least. For example, at the location numbers 1 to 6 shown in Figure 3 where the pressure distribution along the body of a typical aircraft is least affected. However, it is not possible to find a fixed set of locations for mounting the ADS sensors that satisfy the requirement of low disturbance levels for all orientations of the aircraft over the entire flight envelope. Further, the decided location may not permit the mounting of the sensor due to the presence of internal structural elements of the aircraft (structural issues) and therefore additional compensation to be accounted for it. Thus, the air data measurements done by the sensors at a specific location are local to the place where they are mounted and need to be corrected for that position error. Even though the sensors are installed at the optimal locations where measurements are least affected due to local flow, still they are sensitive and pick up unwanted effects during maneuvering or different orientation of the aircraft. Hence, on-board local air data measurements need PEC.

- 2) PEC data generated based on analytical estimates (CFD) or Wind Tunnel (WT) data or blend thereof as shown in Figure 4.

The PEC data tables generated at on-ground are referred here as **inverse tables**. The inverse tables are functions of free stream Angle of Attack (AOA or α or AOAs), Angle of Side Slip (SSA or AOSS or β or AOSSs), and Mach No. (Mfs). They need to be inverted for functioning in opposite way at on-board, i.e. applying PEC for converting local measurements to free stream as shown in Figure 5. The inverted tables (more precisely inverted inverse tables) are referred as **forward tables** for porting them on-board computer. The inverse tables contain correction coefficients and local flow angles for pressure (Pt, Ps) and flow angle (AOA and AOSS), respectively. Thus, they provide the amount of correction to be applied to the on-board pressures and local angles measured by the sensors to have free stream signals at the given flight condition [6]. The process for validation of the inverted tables is shown in Figure 6.

However, the data inversion process is highly complex due to nonlinear nature of multi-inputs data, and few of them possess multi-valued nature also. In the later section, the typical nature of ADS measurements from different types of sensors is given.

- 3) Calibration possible only in flight.

The calibration of ADS is valid for the specific aircraft. Therefore, *significant efforts* are required to optimize the flight testing for overall development of the aircraft. It involves considerations of various aspects such as aircraft instrumentation, supporting resources and infrastructure development, evolving safety procedures, conduct of flight tests, development of procedures and tools for correction updates. Extensive efforts are being devoted for the ADS calibration [6-12].

- 4) Parameter interdependency.

The computational algorithms are parameter interdependent and recursive in nature as can be seen in the left-bottom side diagram of Figure 3. Therefore, rate of computations, sequence of execution, and initialization need to be appropriately done in order to ensure the convergence (numerical stability) of the algorithms.

- 5) Effects of external devices mounted on the aircraft and specific flight operations [2, 13-14].
The shock emanating in the presence of Air-To-Air Refueling Probe (AARP), Infra-Red Search and Track (IRST) sensor etc. which are mounted ahead of the ADS sensors may affect the measurements. Further, the ADS measurements also get affected during the specific flight operations such as wake encounter, Air-To-Air Refueling (AAR), drogue movements during AAR etc. Thus, it demands to have *novel features for reconfigurations and robust redundancy management (failure threshold design, failure detection, isolation and selection)*.

3. EVALUATION OF FBW-FCS INVOLVING ADS ON HARDWARE-IN-LOOP SIMULATOR

Figure 7 shows the block schematic of the Iron Bird or Hardware-In-Loop Simulator (HILS) setup, elements and process thereof used for evaluation of FBW-FCS including ADS. Experiences on the clearance of FCS software on HILS are detailed in [15]. The on-board devices to be evaluated include the followings:

- 1) Digital Flight Control Computer (DFCC) wherein Flight Control Laws (CLAW) reside, and
- 2) Air Data Computers (ADC) wherein ADS computational algorithms reside.

As part of the ground test rig, a Real Time Flight Dynamic Simulator (RTFDS or FDS in short), Engineers Test Stations (ETS), and AIRDATSs, and cockpit are shown in Figure 7 [16]. Aircraft motions are simulated through a six-Degrees-Of-Freedom (6-DOF) simulation for this fixed base test rig. The 6-DOF model / software thereof is residing inside the FDS. The FDS includes various sensor models like rate, acceleration, 'inverse ADS model', etc. The 'inverse ADS model' computes the local measurements for the given free stream condition based on the inverse ADS tables / data.

ETS and AIRDATS are elements of test rig and they are used for:

- 1) Accessing the data for complete system evaluation and analysis, and
- 2) making the signals compatible for interface within the on-board and off-board (test rig) elements.

The local measurements obtained from the inverse ADS model residing inside the FDS are passed through AIRDATS to the on-board ADCs. ADCs have been provisioned with the followings for operational use and on-ground testing, respectively:

- 1) **Real / Actual Pressurization Path:** Actual / real pressure can be given to the pneumatic port available. The pneumatic pressure sensed by the transducers gets converted to frequency [17]. This path is used on the aircraft for actual operation, and it is a fail-safe or default setting. However, it would be challenging to meet the required bandwidth by the real pressurization unit during closed loop evaluation at on-ground test rig.
- 2) **Synthetic Path for injecting equivalent Frequency:** ADCs have provision for injecting the frequency signal in lieu of pneumatic pressure for evaluation of the overall FBW-FCS at on-ground. The value of the required frequency can be computed based on the inverse characteristics of the transducer. The inverse computation model of the transducers (for converting digital pressure to frequency) resides inside the FDS. Thus, this synthetic path aids overcoming the issue of bandwidth limitation of the real pressurization unit during on-ground evaluation.

Thus, the inverse and forward PEC models broadly work in complementary mode during on-ground evaluation. The injected signals get processed in the following order:

1) Inside the on-ground FDS:

Process A: The digital values of free stream signals (Mach No., AOA, AOSS) are given to the inverse ADS model residing inside the FDS. It computes the raw digital local pressures and angles (equivalent to pneumatic pressures and angles that would be actually measured by the sensor mounted on the aircraft at their location),

2) Inside on-board ADC:

Process A⁻¹: The raw digital pressures and angles received from the transducers are corrected for PEC (inverted PEC) to have free stream digital values of Mach No., AOA, and AOSS.

The free stream signals pass through the processes A and A^{-1} in series. Mathematically it indicates the passing of the signals through the product of $A \cdot A^{-1}$, which results in becoming Identity, i.e., $I = A \cdot A^{-1}$. Thus, the free stream outputs obtained in ADCs are expected to be same as the free stream inputs to the FDS. Thus, the entire closed loop evaluation is carried out.

4. PEC DATA FORMATTING AND INVERSE TABLE CREATION

As part of the design and development of ADS, the inverse tables are used for:

- 1) Analysis of the nature ADS measurements, finalization of the sensor locations on the aircraft, and summarizing the magnitude of the PECs that are tolerable for safe and reliable operation of closed loop FBW-FCS,
- 2) Development of the computational model of inverse ADS which is used for evaluation and clearance of FBW-FCS at HILS as explained in the prior section, and
- 3) Creation of the forward tables (on-board PEC data tables) by using inversion process as elaborated in the subsequent section,

However, the inverse ADS data (PEC) generated based on the CFD estimates or wind tunnel experiments may not be completely filled with required cells of the matrix or data tables due to singularity in solutions or insensitivities / certain limitations they arise during the experiments. Therefore, significant efforts are devoted to format the data for further processing and tackle the issues of the portion where data not generated. This formatted data then conveniently aids in carrying out follow up procedures.

The inverse tables are functions of free stream Angle of Attack (AOA or α or AOAs), Angle of Side Slip (SSA or AOSS or β or AOSSfs) and Mach No. (Mfs). A schematic 3D table is shown in Figure 8(a), wherein each slice of a particular Mach No. has got the data containing values for AOA vs SSA grid points.

The following steps given below are carried out for formatting the inverse data tables, especially data for the grid points:

- 1) Which are not required but given may be eliminated or preserved,
- 2) which are required and not given are created by interpolation or by freezing across row / column (by repeating the same data for the remaining rows / columns) depending upon the trend and sensitivity, to make each slice of the table of the same size for AOA vs SSA grid points,
- 3) for few cases, data is generated by extrapolation.

Figure 8(b) illustrates the schematic process of formatting of the data tables for a particular Mach number. Thus, the steps used for populating the data tables broadly include:

- (i) Filling up the empty cells (for which data is not provided) in each slice of a Mach No., and
- (ii) Values for the remaining required grid points are obtained by interpolation or by freezing across columns / rows.

Data formatting is considered as the first step for each category of data inversion as brought out in the subsequent subsections.

5. TYPICAL CHARACTERISTICS OF MEASUREMENTS

Figures 9 to 14 show the data plots of various parameters as obtained from the CFD/Wind tunnel / blend thereof.

Figure 9 shows local angle ($\pm LA_i$) vs free stream AOA ($\pm A_i$) measurement from the rotating vane. The 'i' in the symbol indicates the index for the values represented in the plots along the y and x axis. The data appears to be linear over the entire range of free stream AOA, and across all speed regimes designated by the M1 to M9 values of the Mach No. However, at the large -ve AOA ($-A_2$ to $-A_3$), a clear bifurcation in the bunch of measurements seen.

Figure 10 shows the nature of measurement between local angle with respect to the plane formed by the combination of free stream AOA ($-A_3$ to A_6) & AOSS ($-B_3$ to B_3) as obtained from the side mounted pressure probes for a specific speed or Mach No. The intersection of the contours of the left and right probe

local angles aid in inference of the corresponding free stream AOA and AOSS. However, these intersecting contours become non-intersecting at certain combinations of AOA, AOSS, and Mach No. (not shown), and thus results in indeterminacy or singularity.

Figure 11 shows the nature of measurement between local AOSS obtained from the vane mounted below the fuselage and the plane formed by the combination of free stream AOSS (-B3 to B3) and AOA (-A3 to A6). There is not much variation in the local AOSS at high value of free stream AOA (along x-axis), despite the large change in free stream AOSS (along y-axis). It shows poor sensitivity in the measurement of AOSS at large AOA.

Figure 12 shows the nature of measurement between local AOSS from the Nose mounted pressure probe ($\pm\text{NDPi}$) and free stream AOSS ($\pm\text{B1}$ to $\pm\text{B5}$). The data plots are shown for different values of free stream AOA (A1 to A6). For measurement of NDPm (Nose Probe local angle or Differential Pressure measured) at $\text{AOA}=\text{A6}$ deg, the inferred AOSS could have three values along the x-axis. It results in indeterminacy in the computation or signal selection. Therefore, an appropriate intelligence or guidance needs to be incorporated in the on-board computational algorithms for selection of an appropriate value in real time.

Figure 13 shows the nature of measurement between local and free stream Static Pressure at the front of the nose cone mounted pressure probe for $\text{AOSS}=0$ deg. The x-axis shows the Measured Mach No. (Mm) from Mm0 to Mm2. The Mm is computed from the measured total and static pressure by the probe or sensor. The y-axis shows the normalized static pressure correction coefficient (CPs) for $\pm\text{CP0}$, $\pm\text{CP1}$ to $\pm\text{CP5}$. CPs curves for different values of free stream $\text{AOA} = \text{A1}$ to A8 deg are shown. CPs stands for PEC quantified in terms of dimensionless correction coefficients as defined below:

$$\left\{ \begin{array}{l} \text{Cpt} = (\text{Ptm} - \text{Pt}) / (\text{Ptm} - \text{Psm}), \text{ and} \\ \text{Cps} = (\text{Psm} - \text{Ps}) / (\text{Ptm} - \text{Psm}) \end{array} \right\} \quad \text{Eq (1)}$$

Where

Cpt = Correction coefficient for total pressure

Cps = Correction coefficient for static pressure

Ptm = Measured total pressure

Psm = Measured static pressure

Pt = Corrected or free stream total pressure

Ps = Corrected or free stream static pressure

The Cpt and Cps data base 3D tables are made up as a function of AOA_{fs} , AOSS_{fs} , and Mach_{fs} . In transonic Mach regime at around Mm1, the sharp change in the CPs indicates the effects of shock (a sharp change in the measured pressure), It is highly sensitive in this Mach regime.

Figure 14 shows the nature of measurement between local and free stream Static Pressure at the side of the fuselage mounted pressure probe (side probe) for $\text{AOSS}=0$ deg. The plots of CPs for the side probe is shown here. The nature of the shock in transonic Mach regime is slightly different than that of the Figure 13 (of nose probe). It is due to the fact that the air flow over the side probe in presence of the aircraft body get disturbed more as compared to nose probe (being ahead of the aircraft) and also the nature of the disturbance is different. In either case, ideally it is expected that the CPs should be minimal. Likewise, data for the CPt also generated and analysed. However, measurements of Pt is less sensitive as compared to Ps measurement.

Summarizing, the prominent characteristics or required PECs as part of the inverse ADS tables / data seen in the ADS measurements include the followings:

- 1) It is a function of multiple parameters (multi-input). There is data interdependency for the computations of output signals. Multiple outputs are computed from the specific set of measurements, and thus it acts as a multi-input multi-output system,
- 2) Highly nonlinear characteristics of the data,
- 3) Multi-valued characteristics for a few of them result in indeterminacy for inversion,
- 4) Highly sensitive: A sharp change in measurement for a small change in flight conditions or orientation at some situations reflects high sensitivity.

6. DATA INVERSION PROCEDURES

Data inversion procedures evolved and used for creating the forward tables from the set of inverse tables are given in this section. The free stream parameter computations at on-board can be done by using measurements from any of the followings based on the number of sensors and their position on the aircraft:

- 1) individual sensor, or
- 2) two sensors (relative measurements)

6.1 Generic steps for data inversion

The data inversion process involves the following generic steps:

- 1) Based on the sensitivity analysis, parameter which has got the least influence on the measurement can be identified.
- 2) Keep the common grid value of this least sensitive parameter in both sides of data inversion (inverse and forward tables). Data inversion for the remaining parameters of that grid value (a least sensitive parameter) can be carried out.
- 3) The negligible effect or correction on the least sensitive parameter is worked as a 1D correction table.

Data inversion procedures for the following measurements are given in the subsections:

- 1) Flow Angles (AOA and AOSS) from 'local angle' to 'free stream AoA', and
- 2) Total and Static pressures

6.2 Data inversion of individual sensor for flow angle computations

The measurement from individual sensor / probe can be directly used for correction to have free stream signal, if the airflow over the sensor does not get obstructed significantly under all manoeuvring conditions in the entire flight envelope. The elaborated generic steps are given below along with the illustration shown in Figure 15. In this illustration, it is assumed that the local angle measurement from the sensor is not much affected in the presence of Angle of Side Slip: AoSS (β_{fs}) on the aircraft.

- 1) Data formatting and processing / populating by interpolating within range and freezing or extrapolating for out of range as described in the prior section. In the present scenario, the 3-Dimensional inverse table (3D inverse table) of a sensor for measurement of local angle (Loc_angle) is a function of free stream AOA (α_{fs}), AOSS (β_{fs}) and Mach No. (M_{fs}).

Forward correction tables for AOA are planned to be a function of Loc_angle, M_{fs} , and β_{fs} . The local angle measurement is less affected in the presence of AOSS as compared to Mach No.

- 2) Hence, for each slice of AOSS (indicated by the index $AOSS_{fs,i}$), the 2D table of local angle (Loc_angle) as a function of α_{fs} and M_{fs} is extracted from the given 3D tables and used for further processing.
- 3) The im^{th} column (of $Mach_{fs}$ grid point) of 2D Tables of **Loc_angle** from Step 2 and Input AOAFs grid vectors are done with 1D interpolation for the required forward local angle grid (loc_aoa_fwd_grid). The resulting column of computed AOA shall be for the Required Forward Grid of Local Angle (loc_aoa_fwd_grid) for each column of $Mach_{fs}$.
- 4) Thus, the 2D tables (slices) for each **AOSS_{fs,i}** filled with free stream AOA are collated.
- 5) The resultant forward 3D table filled with the free stream AOA (AOAFs_fwd) as a function of Local angle (loc_aoa_fwd_grid), Mach No. ($Mach_{fs_Grid}$), and AOSS (AOSS_{fs_grid}) is made. It is used in on board computer (in the aircraft) for applying correction to the measured local angle to have the computed value of the free stream AoA.

Note that the correction effect for AOSS (being least sensitive in the preset example) is not detailed herein due to simplistic nature of 1D lookup table as compared to the above prominent process.

6.3 Data inversion of relative measurements from two sensors for flow angle computations

If the sensors are mounted on both the side of the aircraft, then they become significantly less sensitive at mid to large value of AOSS. When there is a wind from one side (AOSS build up), the measurement from the sensor on the other side becomes insensitive to AOSS. Similarly, if the sensors are mounted on top and bottom side of the aircraft, then they become significantly less sensitive at mid to large value of AOA. Likewise, at in-between location on either side, the combined effectiveness of AOA and AOSS affects the measurements. Therefore, need for use of relative measurements from multiple sensors (at least two) arises to compute the free stream values of AOA and AOSS together.

Usually, the Original Equipment Manufacturer (OEM) of the Air Data Sensor provides the complete data sheet of the measurements obtained from the standalone sensor. Such measurements are blend of the CFD estimates and validated through wind tunnel experiment.

Refer to the data sheets of the various types of ADS sensors available from different OEMs. In case of differential pressure-based flow angle computations, the values of the measured pressure AOA1 (Pa1), measured pressure AOA2 (Pa2), measured total pressure (Ptm), measured static pressure (Psm), and the measured local angle (Loc_angle) are provided in the data sheet for the given free stream values of Mach No, AOA, and AOSS. The values of measured pressure AOSS1 (Pb1), measured pressure AOSS2 (Pb2) are also included in the data sheet, if the sensor is provisioned for such measurements. Thus, the relation between the loc_angle and normalized pressure $((Pa1-Pa2)/(Ptm-Psm))$ can be made for further usage. Note that the normalized pressure is differential pressure of AOAs over the measured dynamic pressure designated by the letter qcm ($qcm = Ptm-Psm$).

The 3D inverse table of a sensor for measurement of local angle (Loc_angle) is a function of free stream AOA (α_{fs}), AOSS (β_{fs}) and Mach No. (M_{fs}). The second inverse table stands for the normalized pressure $((Pa1-Pa2)/(Ptm-Psm))$ as a function of local angle and measured Mach No. (M_m). This data is purely based on the OEM data sheet and therefore inversion of the same for use at on-board can be done. Hence, data inversion for the OEM data sheet-based tables is not given here.

Therefore, data inversion process for relative local angle measurements to free stream value computations only is given in this section as illustrated in Figure 16 and elaborated in the following steps. In this illustration, it is assumed that the local angle measurement from the sensor is not much affected in the presence of Mach No. (M_{fs}) on the aircraft.

- 1) Data formatting and processing / populating by interpolating within range and freezing or extrapolating for out of range as described in the prior section. In the present scenario, the 3D inverse table of a sensor for measurement of local angle (Loc_angle) from individual sensor (as an example Loc_left and Loc_right) is a function of free stream AOA (α_{fs}), AOSS (β_{fs}) and Mach No. (M_{fs}).

Forward correction tables for AOA and AOSS are planned to be a function of Average and Difference of local angles (Avg_loc_angle and Diff_loc_angle) from both the sensors, and third dimension as free stream Mach No. (M_{fs}). The local angle measurement is less affected in the presence of Mach No.

- 2) The 3D tables of average and difference of local angles (Avg_loc_angle and Diff_loc_angle) as a function of free stream AOA, AOSS, and Mach No. are computed and used for further processing.
- 3) For each slice of Mach No. (indicated by the index $Mach_{fs,i}$), the 2D table of average and difference of local angles (Avg_loc_angle and Diff_loc_angle) as a function of AOA and AOSS are extracted from the given 3D tables and used for further processing.
- 4) Find the nearest Avg_loc and Diff_loc that satisfy the common AOSSfs and AOAs in both the slices for the present values of Local angles for the given free stream Mach No., AOA, and AOSS. This shall aid in making the 2D Tables of AOA and AOSS.
- 5) Collate 2D tables (slices) for each $Mach_{fs,i}$ filled up with AOA and AOSS: These are for the required forward grid vector of Average and Difference of Local angles (fwd_avg_loc_angle and fwd_diff_loc_angle)
- 6) Collate the Final Forward 3D Tables of AOA_fwd and AOSS_fwd. The resultant forward 3D tables filled with the free stream AOA (AOAfs_fwd) and AOSS (AOSSfs_fwd) as a function of Fwd_avg_loc_angle_grid, Fwd_diff_loc_angle_grid, and, Machfs_grid are made. They are used in on board computer (in the aircraft) for applying correction to the measured local angle (obtained from

OEM data sheet for the measured values of various pressures from the sensor at on-board, i.e., Pa1, Pa2, Pb1, Pb2, Ptm, Psm) to have the computed value of the free stream AOA and AOSS.

6.4 Data inversion of individual sensors for computation of total and static pressures

The measurement of total or static pressure alone or blend thereof from the probes is done through available ports (whole) thereon. The PEC is required on the measured total pressure (Ptm) and measured static pressure (Psm) from the probes to have free stream or corrected total pressure (Pt) and static pressure (Ps). The required PEC is quantified in terms of dimensionless correction coefficients (Cpt and Cps) as defined in Eq(1). The Cpt and Cps are made up as a function of free stream AOA (α_{fs}), AOSS (β_{fs}), and Mach No. (M_{fs}).

Similar to the flow angle measurements, the individual sensor pressure measurements can be directly corrected if both the measurements of Pt and Ps are available thereon. Further, measurements of total and static pressures from the different sensors (located at different places on the aircraft) can also be possible to correct by making the Cpt and Cps database accordingly, however it increases the complexity, especially under sensor failure scenarios. Anyhow, the process of data inversion for pressure measurement in either case remains same as illustrated in Figure 17 and elaborated in the following steps. In this illustration, it is assumed that the measurement from the sensor is not much affected on the aircraft in the presence of AOSS (β_{fs}) as compared to the effects of AOA and Mach No. Note that Figure 17 is spanning over two pages as Figures 17(a) and (b):

- 1) Data formatting and processing / populating by interpolating within range and freezing or extrapolating for out of range as described in the prior section. The Cpt and Cps 3D inverse tables as a function of free stream AOA (α_{fs}), AOSS (β_{fs}) and Mach No. (M_{fs}) are made ready for further processing.

Forward correction tables of Cpt and Cps for computations of free stream total and static pressure (Pt and Ps) are planned to be a function of free stream AOA (α_{fs}), AOSS (β_{fs}) and Measured Mach No. (Mm) instead of free stream Mach No. (M_{fs}). The measured pressures from the sensor are used through the computed Measured Mach No. (Mm) for on-board corrections to have free stream Pt and Ps.

- 2) For each slice of AOSS (indicated by the index $\text{AOSS}_{fs,i}$), the 2D tables of Cpt and Cps as a function of AOA and AOSS are extracted together from the given 3D tables and used for further processing.
- 3) Reference or Atmospheric Total Pressure (Pta) and Static Pressure (Psa) are computed from the standard atmosphere model for the given Mach No. (M_{fs}) at sea level altitude ($Z_p = 0.0$ Km).
- 4) Rearranging and solving the two simultaneous relations of Cpt and Cps as given in Eq(1) above, the Measured Total Pressure (Ptm) and Static Pressure (Psm) for each probe is computed by using the following relation:

$$\begin{bmatrix} Ptm \\ Psm \end{bmatrix} = \begin{bmatrix} (1-CPt) & CPt \\ -CPs & (1+CPs) \end{bmatrix}^{-1} \times \begin{bmatrix} Pta \\ Psa \end{bmatrix} \quad \text{Eq (2)}$$

- 5) Measured Mach No. (Mm) for each probe is computed from the corresponding measured pressures, i.e., Ptm and Psm by using the standard equation [18] for each combination of AOAFs and Machfs.
- 6) A collated 2D table filled up with Mm for each combination of the grid points of α_{fs} and M_{fs} is prepared.
- 7) Compute CPt and CPs for the required forward grid of Measured Mach No. (Mm_fwd) for each row of AOAFs by 1D interpolation of Mm vs CPt, and Mm vs CP. Note that, the α_{fs} grid points for inverse and forward tables are same. Thus, the difference between the inverse and forward lookup tables is the use of Mach No. for lookup, i.e., in case of inverse tables it is M_{fs} while in case of forward tables it is Mm. Therefore, for each grid point of α_{fs} , the corresponding rows of the Mm, CPt and CPs from the respective 2D tables obtained in steps 6 and 2, are interpolated for the given Mm grid points of the forward table. Any non-monotonic behaviour in the CP (CPt and CPs) with respect to Mach No. needs to be accounted appropriately, before interpolation as illustrated in Figure 18.

- 8) Collate the rows of computed Cpt and Cps obtained in the prior step for each grid value of AOA under each slice of AOSS. The collation of all such rows results in the formation of 2D table or slice for each AOSS grid point.
- 9) Collate the 2D slices for each AOSS grid points as obtained in the prior step to have final Forward 3D Tables of CPt and CPs. The resultant forward 3D tables filled with the correction coefficients as a function of α_{fs} , Mm (Mm_fwd), and β_{fs} are used in on-board computations to have free stream pressures from the measured or raw pressured received from the sensors.

7. DATA ANALYSIS FOR FIDELITY ASSESSMENT

As illustrated in Figures 5 and 6, the fidelity assessment process on the generated forward tables and the corresponding inverse tables is carried out. In the fidelity assessment process, the following steps are carried out:

- 1) The set of free stream inputs (AOA, AOSS, and Mach No) are passed in to the set of inverse tables to compute the local measurements (local angles and measured pressures).
- 2) The local measurements are then passed through forward tables to compute the free stream measurements of pressures and angles.
- 3) The overall difference or errors between free stream outputs of forward tables and free stream inputs to the inverse tables are computed and analysed for acceptance of the forward tables. This error is referred to end-to-end (Output-Input) error.

The fidelity assessment process ensures that the aerodynamic characteristics of the measurement data generated through CFD and / or wind tunnel experiment at on-ground are retained while carrying out the data inversion. Thus, it ensures that the inverted tables (forward tables) are fit for porting / flying the aircraft with the prior know corrections.

Typical results of the fidelity assessments are shown in Figures 19 to 21 as end-to-end (Output-Input) error for various parameters. Figure 19 shows error plots for Mach No. with respect to Input Mach No., AOA, and AOSS or SSA.

The Mach No. error is well within ± 0.05 and transonic regime it is within ± 0.1 . Figure 20 shows the error plots for AOA from two different sensors (Vane and Probe) with respect to Input Mach No., AOA, and AOSS or SSA. AOA error from vane is within ± 1.5 deg normally and between -4 to 2 deg at transonic Mach regime at -ve AOA. The AOA error from probe is slightly higher and it requires removal of bias effects due to the droop in the front nose cone of the aircraft. Figure 21 shows the error plots for AOSS from two different sensors (Vane and Probe) with respect to Input Mach No., AOA, and AOSS or SSA. The AOSS error from the probe alone is ranging from 0.2 to 2.5 deg varying with Mach No. and local dispersion of about ± 0.5 deg. The combined error of AOSS from the two sensors is within ± 2.5 degree, and the slightly higher at large -ve AOA.

8. BIDIRECTIONAL DATA INVERSION

The ADS data inversion for inverse to forward table creation, there usage, data inversion procedures and validation thereof have been elaborated in the prior sections. All this would be required for the system development including initial bunch of test flights.

However, after flight tests, if any deviations in the ADS measurements found to be beyond the acceptable limits, then the forward tables residing inside the on-board ADC needs to be updated [19]. It is precisely, carried out as part of the ADS calibration process.

When the calibrated or updated forward tables are incorporated into the next version of the on-board software, the entire cycle of evaluation of the ADS repeats, which does include the on-ground evaluation on HILS. Therefore, it also demands to update the inverse ADS tables residing inside the inverse ADS model as part of the FDS in HILS. It may be noted that as described in the prior section, if the set of forward tables (designated as A^{-1}) are updated but the corresponding set of inverse tables (A) not updated, then the $A \cdot A^{-1}$ would not be an identity ($A \cdot A^{-1} \neq I$). It may unnecessarily result in declaring nuisance or unwanted failures and effects thereof during the on-ground evaluation. Occurrence of such nuisance failures may result in

compromising the system clearance. Therefore, process for data inversion in opposite way, i.e., forward to inverse tables creation arises.

Further, as a lesson learnt from the past experiences, the updated inverse tables are also used for the following purposes:

- (i) Verification and updating of the CFD estimation models and relevant procedures,
- (ii) Improvements in the wind tunnel experiments and associated aspects

In summary, the need for bi-directional data inversions is required in the ADS design and development. The bi-directional data inversion refers to the dual procedures of: (i) inverse to forward table creation, (ii) forward to inverse table creation. Due to the space paucity, the forward to inverse data inversion process is kept out of scope of the present article.

9. CONCLUSIONS

The process for inversion of the measurement data of the Air Data Sensor / System (ADS) for the aerospace vehicles is presented in this article. The process for validation which also referred to as fidelity assessment of the inverted measurement data is also presented in this article. The fidelity assessment process ensures that the aerodynamic characteristics of the measurements have been preserved while inverting the data and thus the inverted data is fit for flying on the aircraft. Various challenges come across during the data inversion process and relevant resolutions have also been illustrated in this article. The processes evolved and as presented in this article have been used for the design and development of the ADS for the high-performance combat aircraft having Fly-By-Wire (FBW) Flight Control System (FCS), and thus the efficacy of the same have been well established.

Acknowledgement

The interactions made with Dr. Girish S. Deodhare, former Director General (ADA) were very fruitful and encouraging to realise the work presented in this paper which is highly acknowledged.

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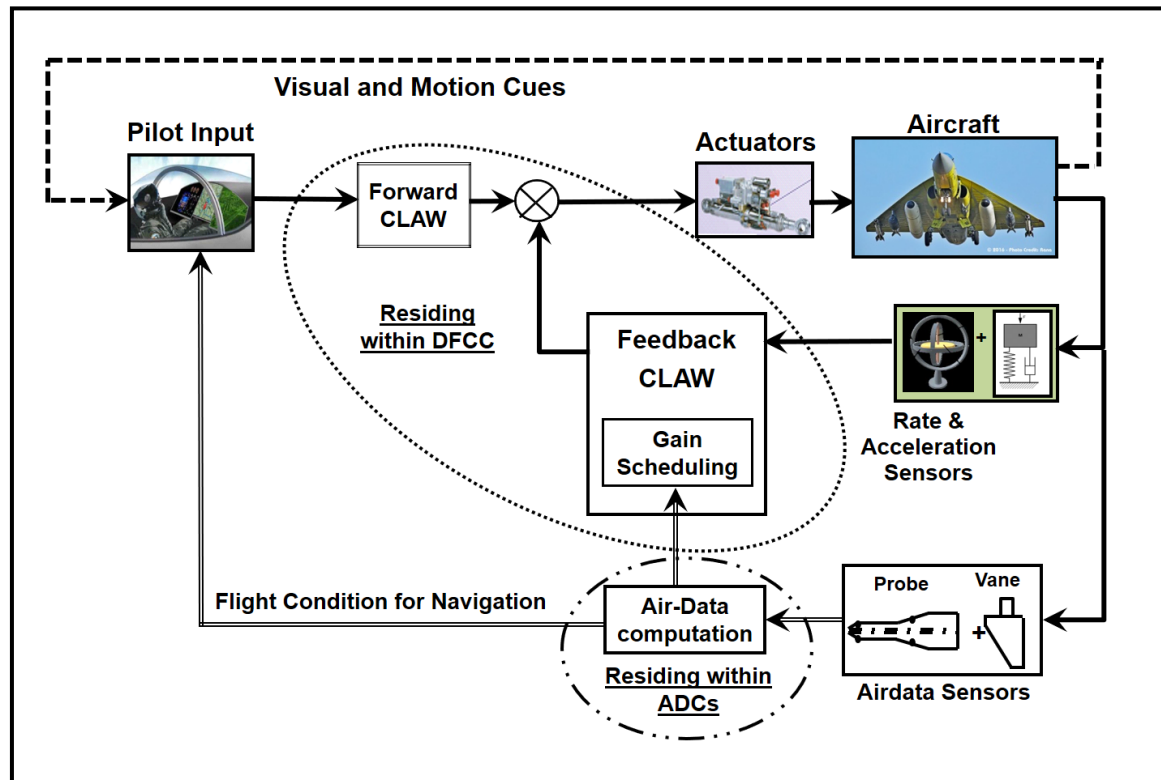


Figure 1: Flight Control System Structure

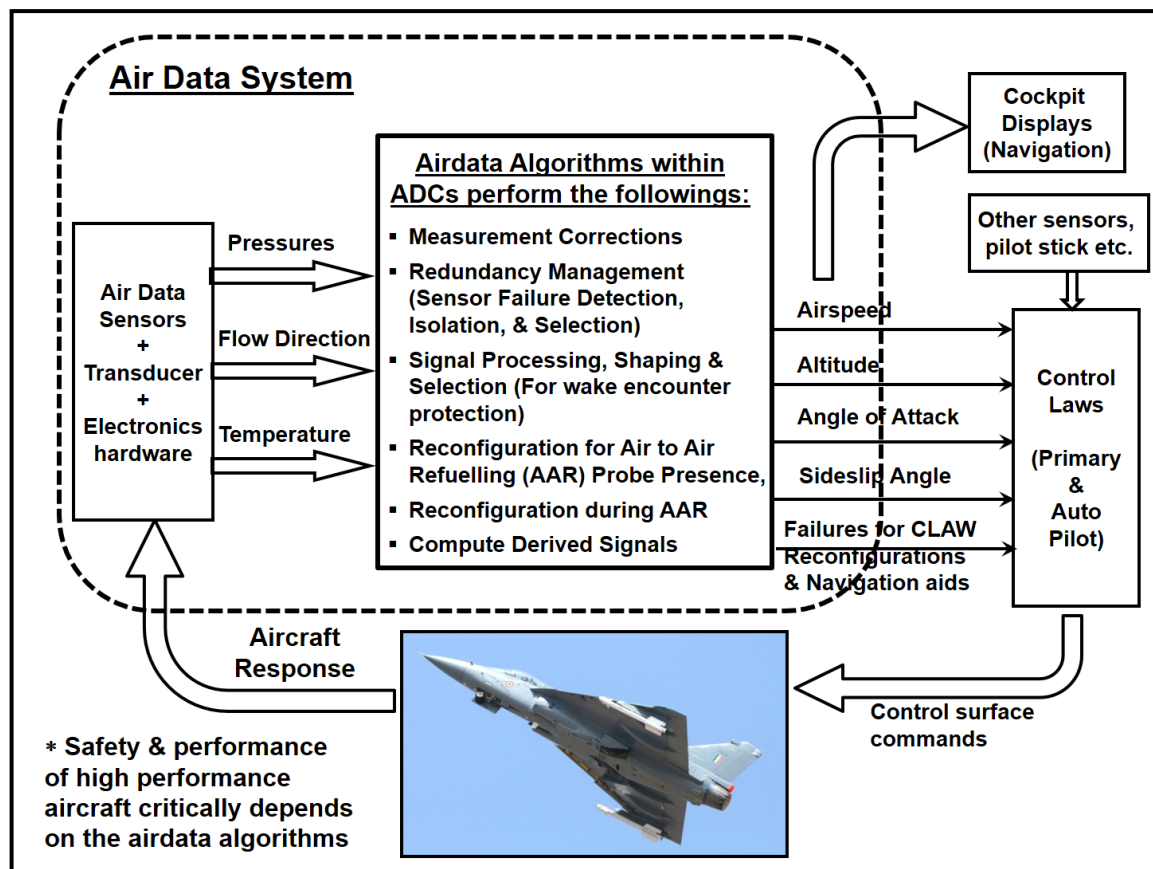


Figure 2: Role of ADS in closed loop Fly-By-Wire (FBW) Flight Control System (FCS)

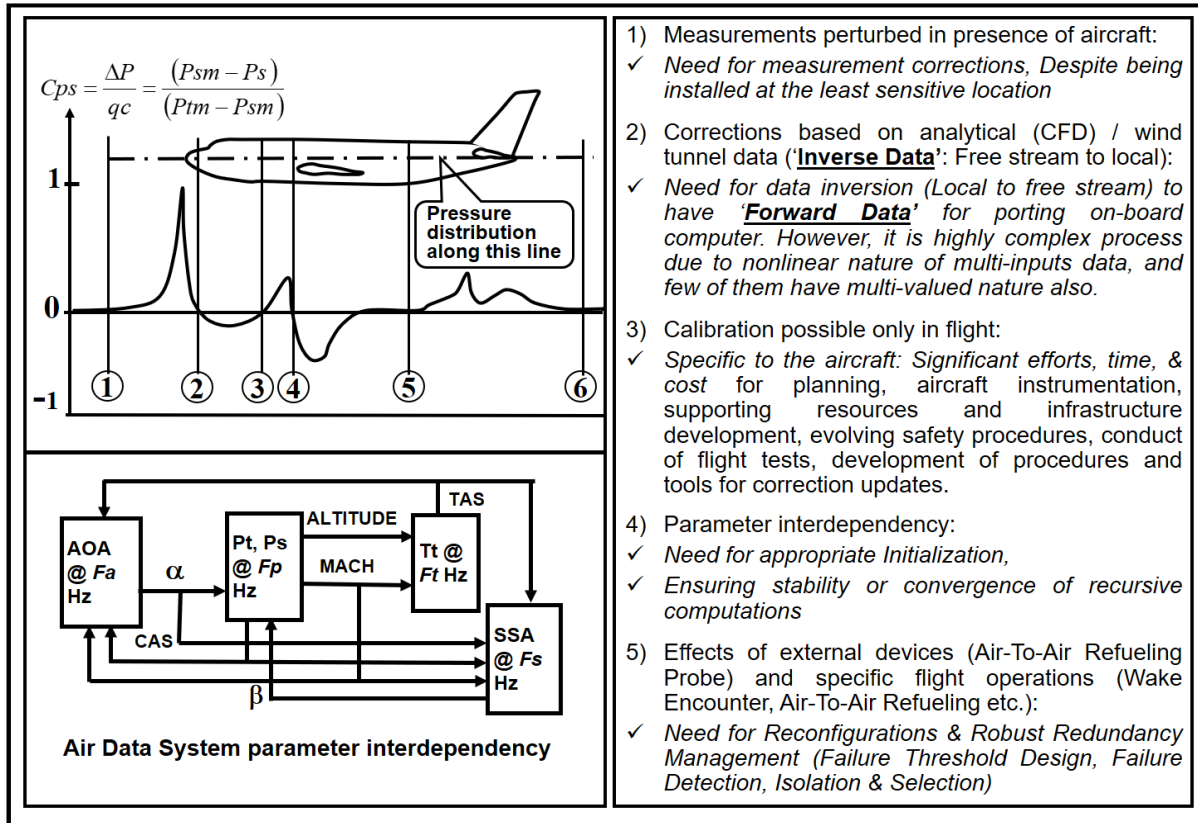


Figure 3 ADS algorithms Development Complexities and Challenges

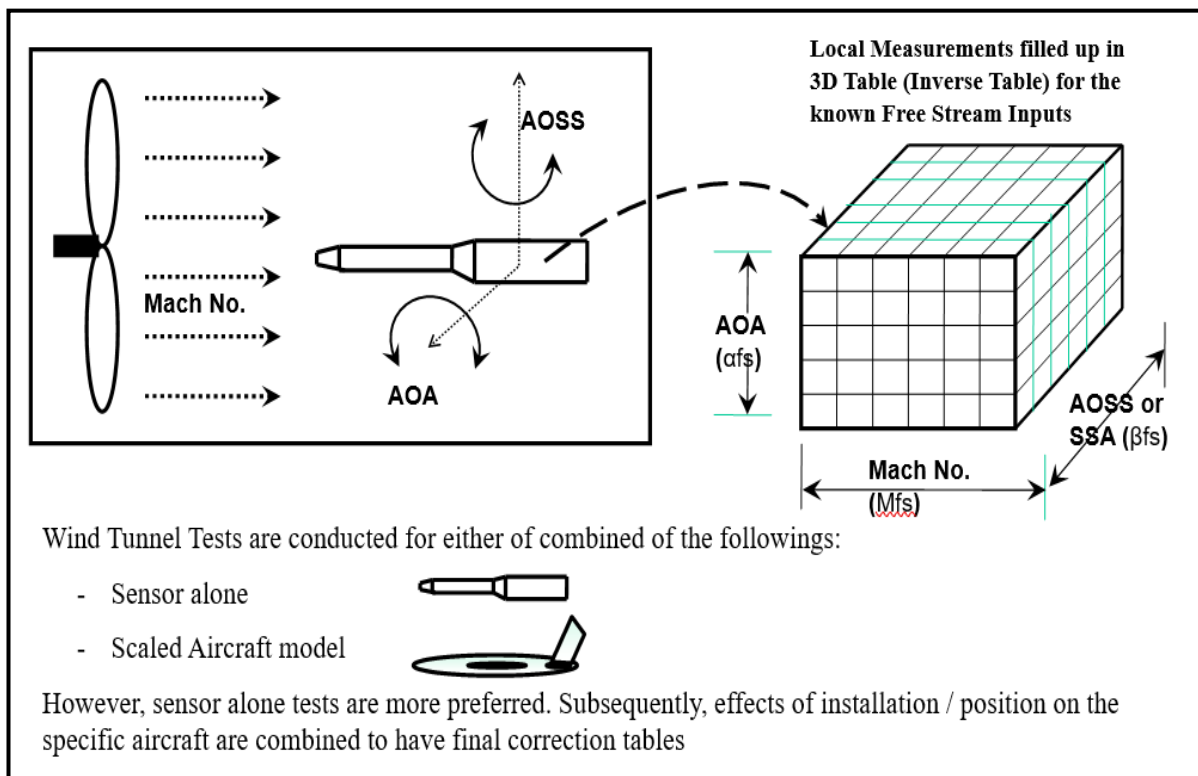


Figure 4: ADS data obtained by using Wind Tunnel Experiment / CFD Estimation

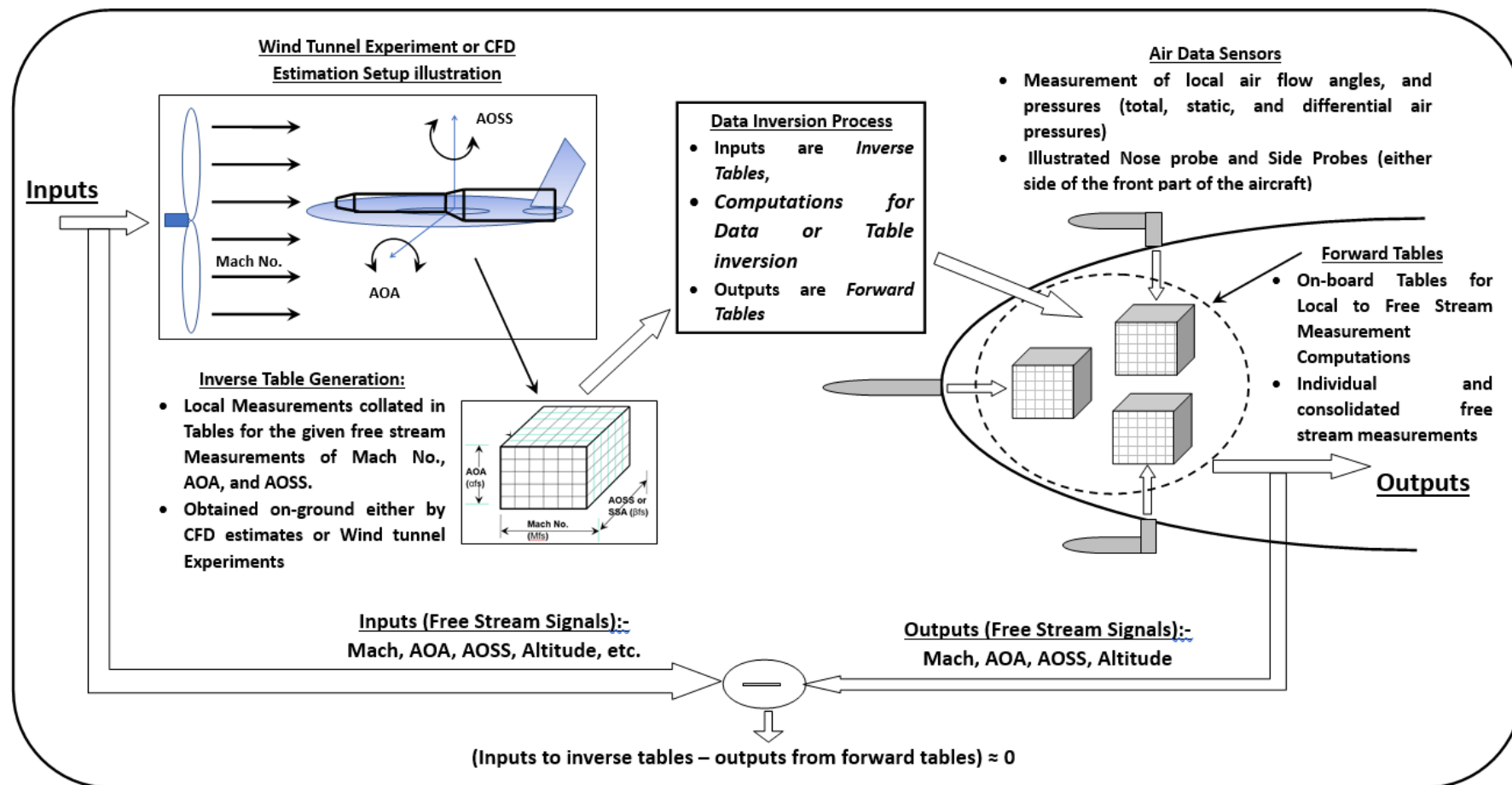


Figure 5: Illustration of process for obtaining Inverse and Forward ADS measurement, and validation of inverted data (This fidelity assessment ensures that the aerodynamic characteristics of the measurements have been preserved while inverting and thus the inverted data is fit for flying on-board)

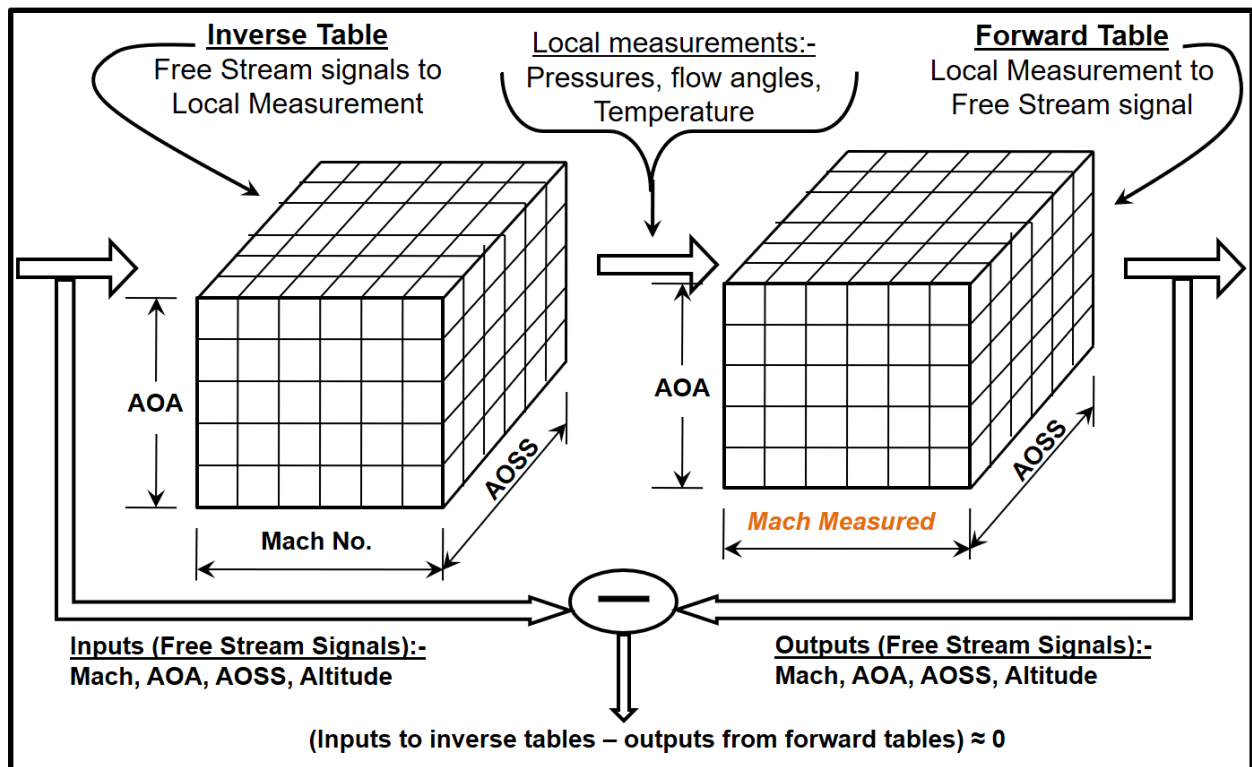


Figure 6: Validation Process for Inverted Data of ADS Sensors

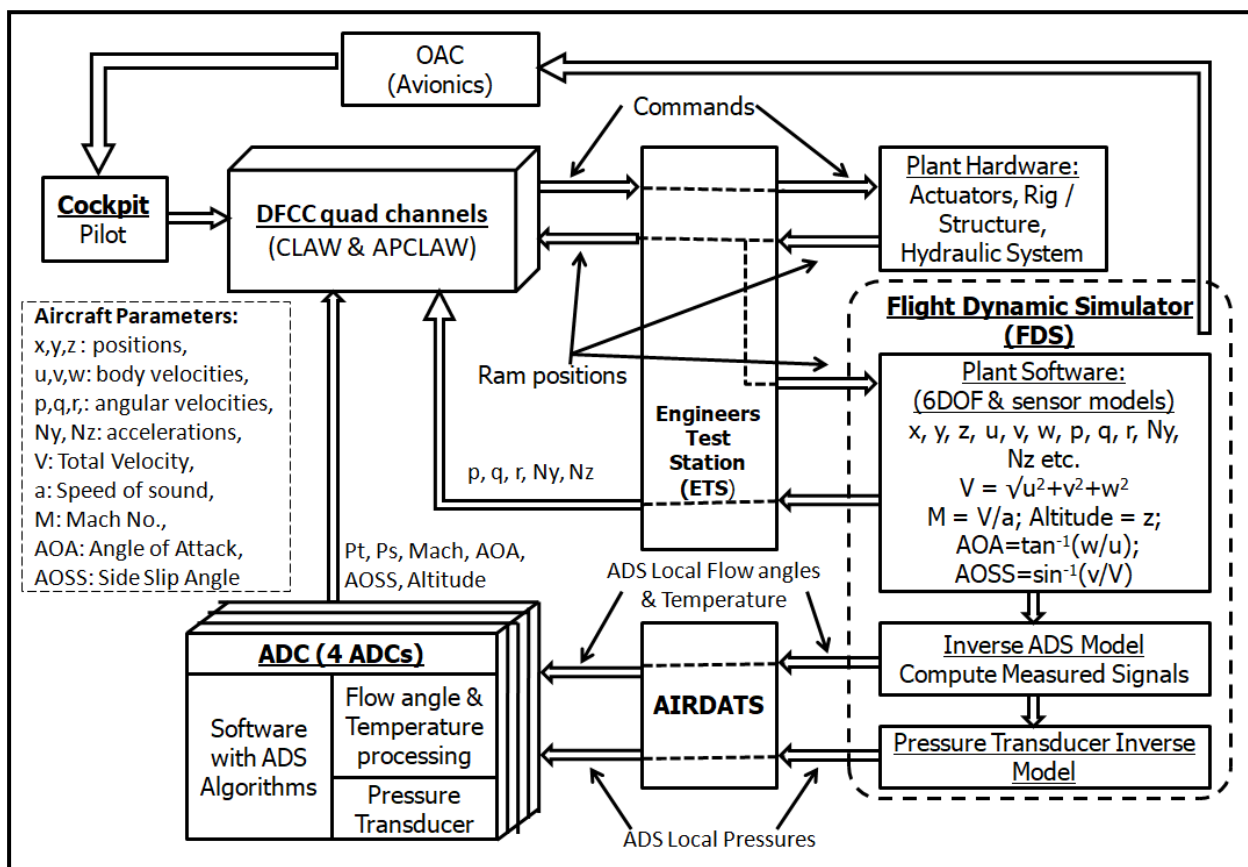


Figure 7: Iron Bird FCS Closed Loop Block Schematic

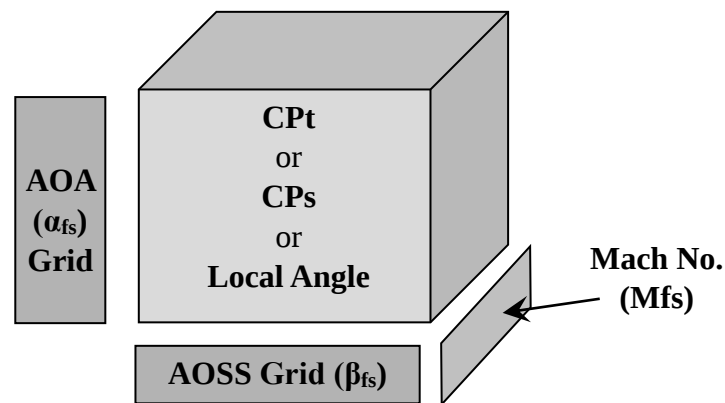


Figure 8 (a): A Schematic of 3-Dimensional (3D) Table having ADS measurements with aerodynamic effects as a function of free stream inputs

AOSS grid →	B1	B2	B3	B4
AOA grid ↓				
A1	√	↔	√	→
A2	↕	↔	↕	→
A3	↕	√	↕	√
A4	√	↕	√	↕
A5	↕	√	↕	√
A6	√	↔	√	→

Legend:

- √ Data available (Measurement data from CFD or Wind Tunnel)
- ↔ Data obtained by interpolation of the adjacent column cells
- ↕ Data obtained by interpolation of the adjacent row cells
- Data obtained by extrapolation of the previous column cells

Figure 8 (b): Schematic process of formatting and populating the measurement data

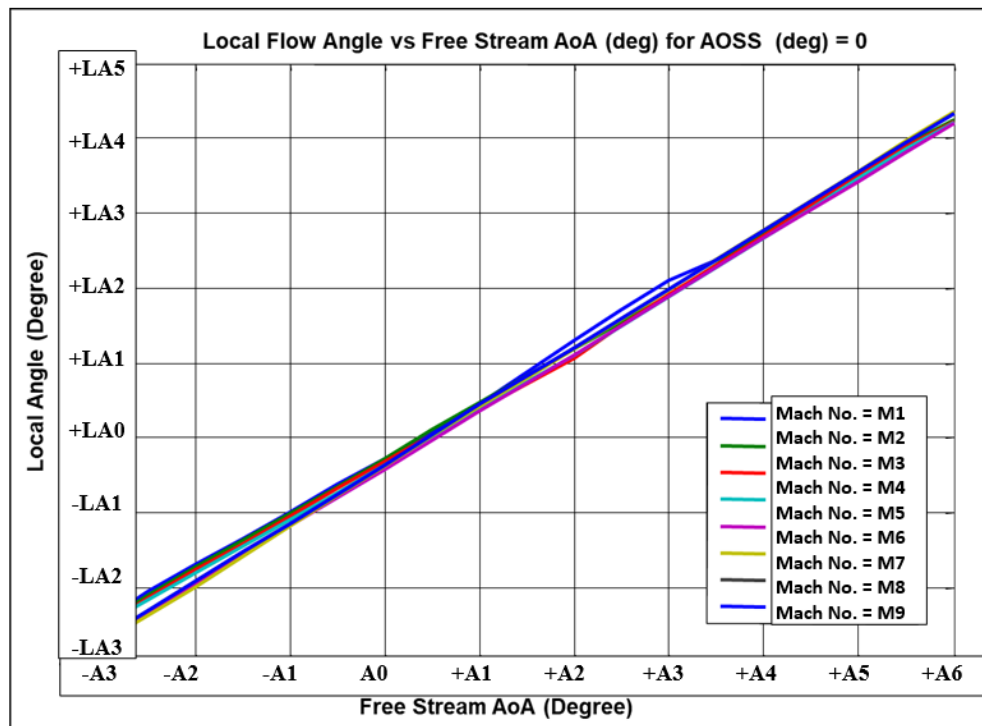


Figure 9: Typical nature of measurement between local angle and free stream AOA from rotating vane

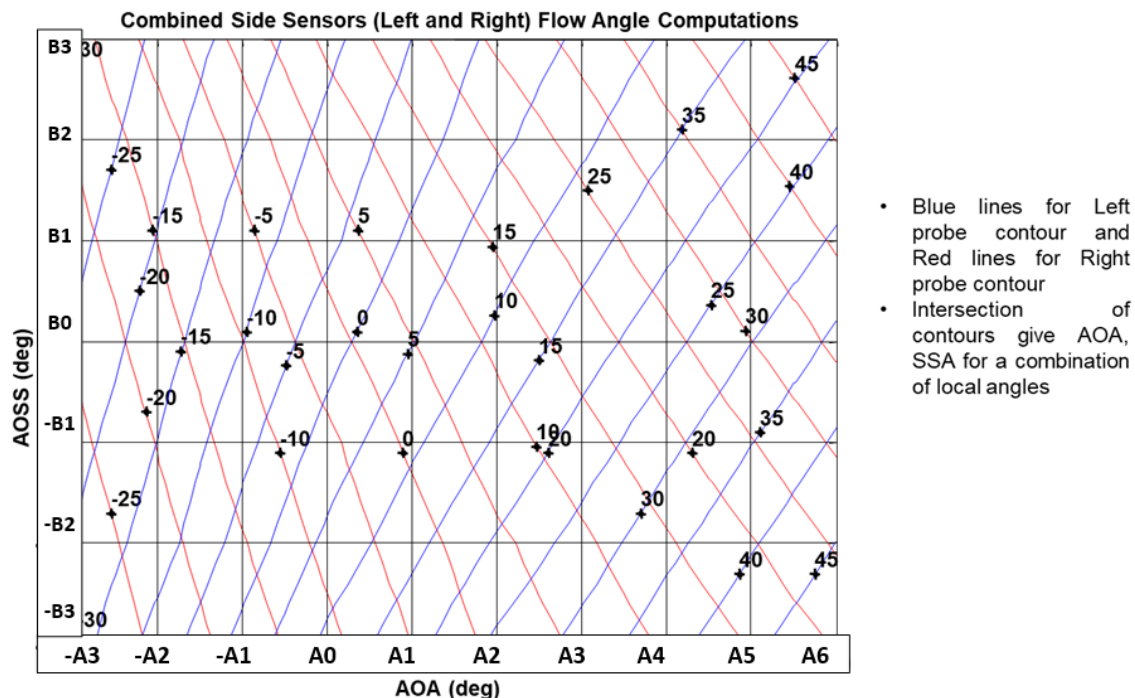


Figure 10: Typical nature of measurement between local and free stream AOA (-A3 to A6) & AOSS (-B3 to B3) obtained from the side mounted pressure probes

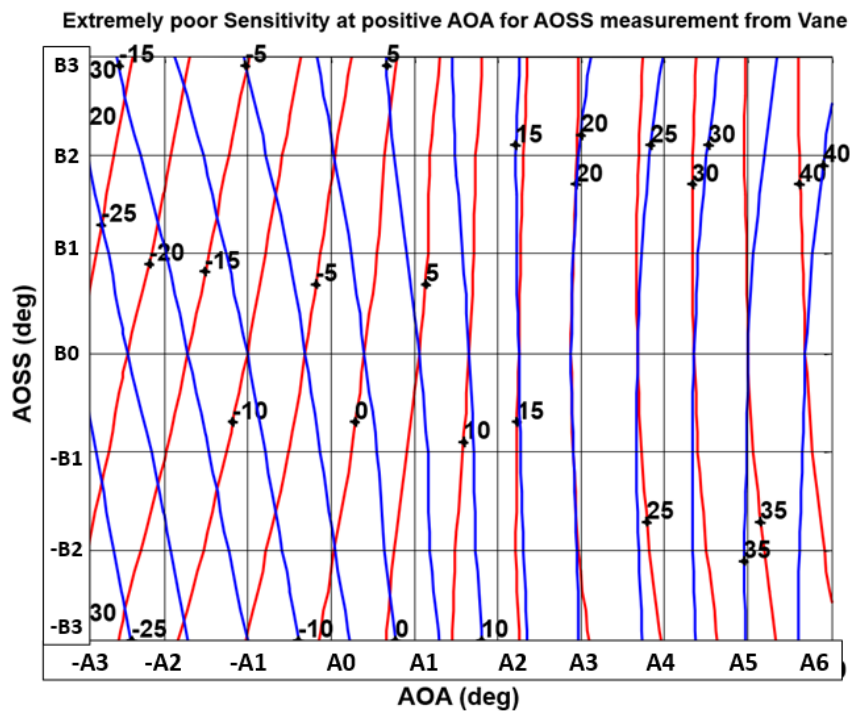


Figure 11: Typical nature of measurement between local AOSS and free stream AOSS for the free stream AOA mounted below the fuselage

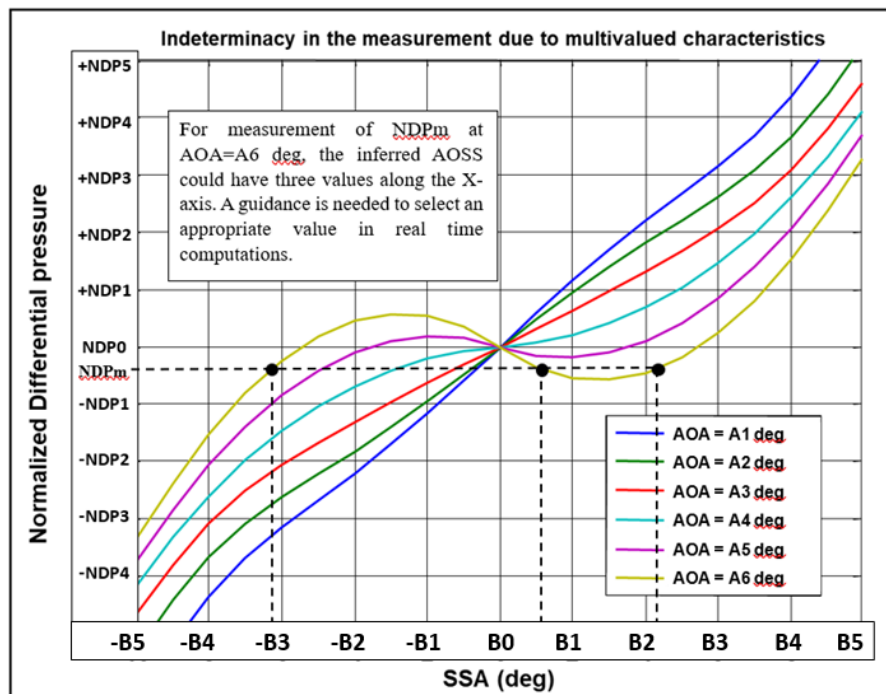


Figure 12: Typical nature of measurement between local AOSS and free stream AOSS at the front of nose cone or pressure probe mounted thereon

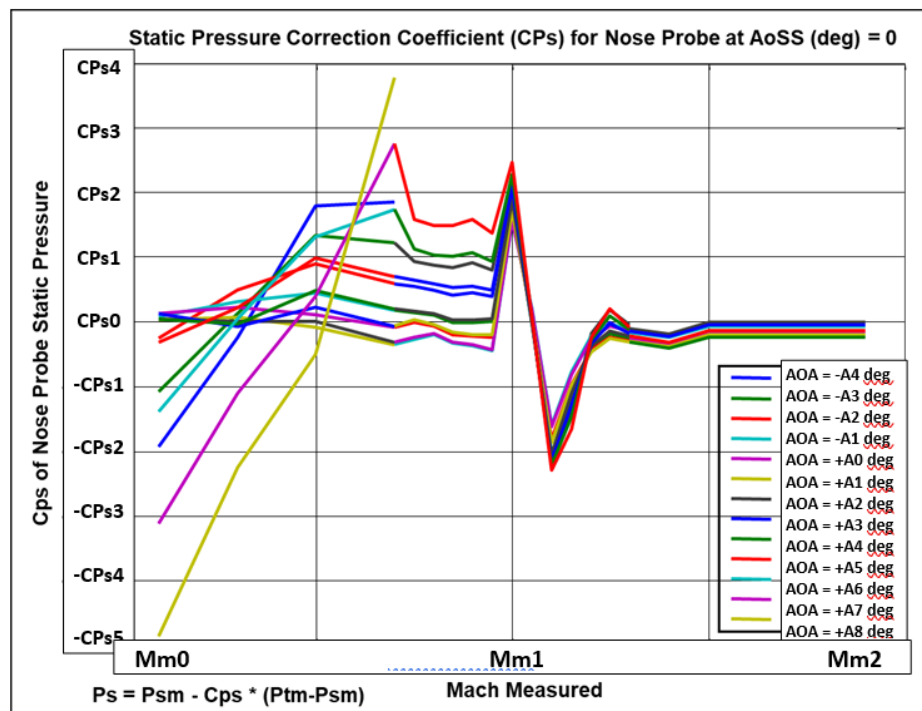


Figure 13: Typical nature of measurement between local and free stream Static Pressure at the front of nose cone or pressure probe mounted thereon

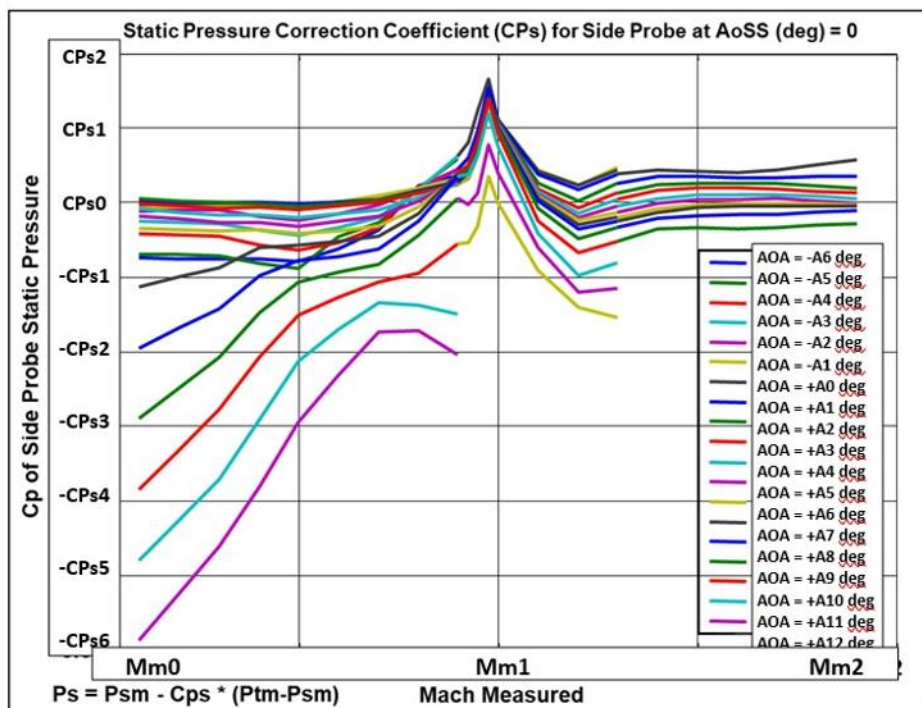


Figure 14: Typical nature of measurement between local and free stream Static Pressure at the side of the fuselage or pressure probe mounted thereon

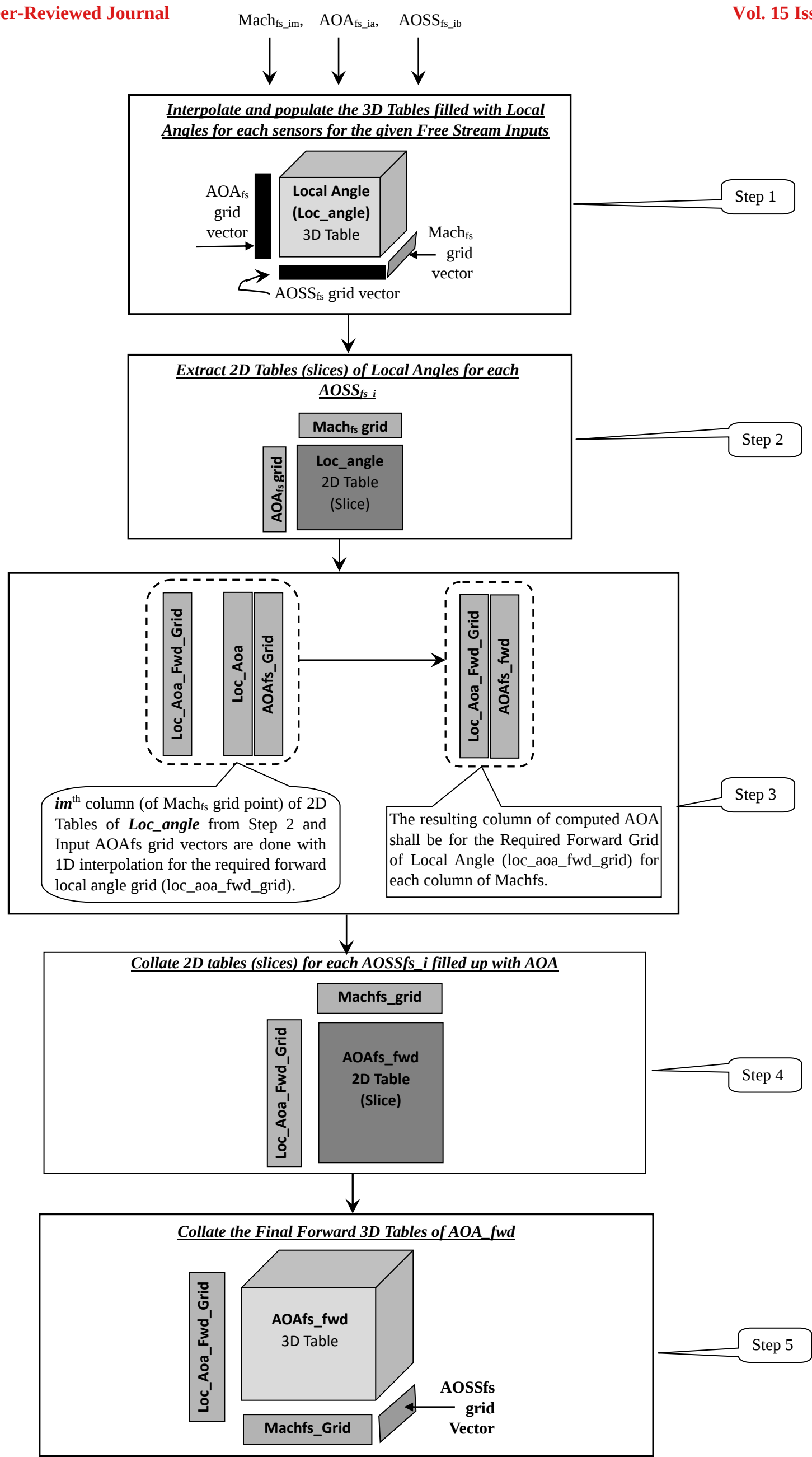


Figure 15: Schematic Process of Flow Angle (AOA and AOSS) table inversion to create the forward tables (Local angles to Free Stream measurements) from the given inverse tables (free stream to local measurements) with absolute measurements of individual sensors.

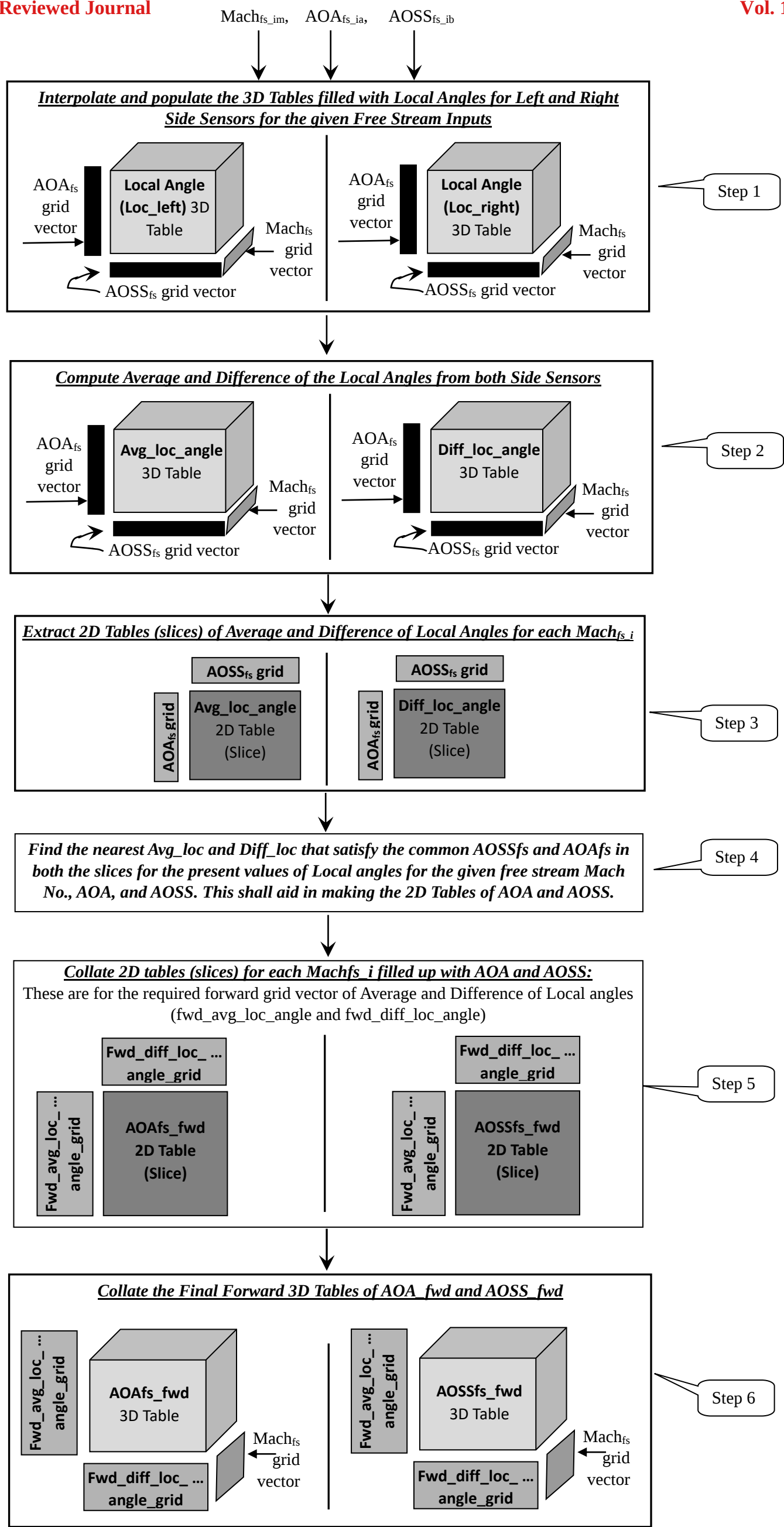


Figure 16: Schematic Process of Flow Angle (AOA and AOSS) table inversion to create the forward tables (Local angles to Free Stream measurements) from the given inverse tables (free stream to local measurements) with relative measurements of two sensors.

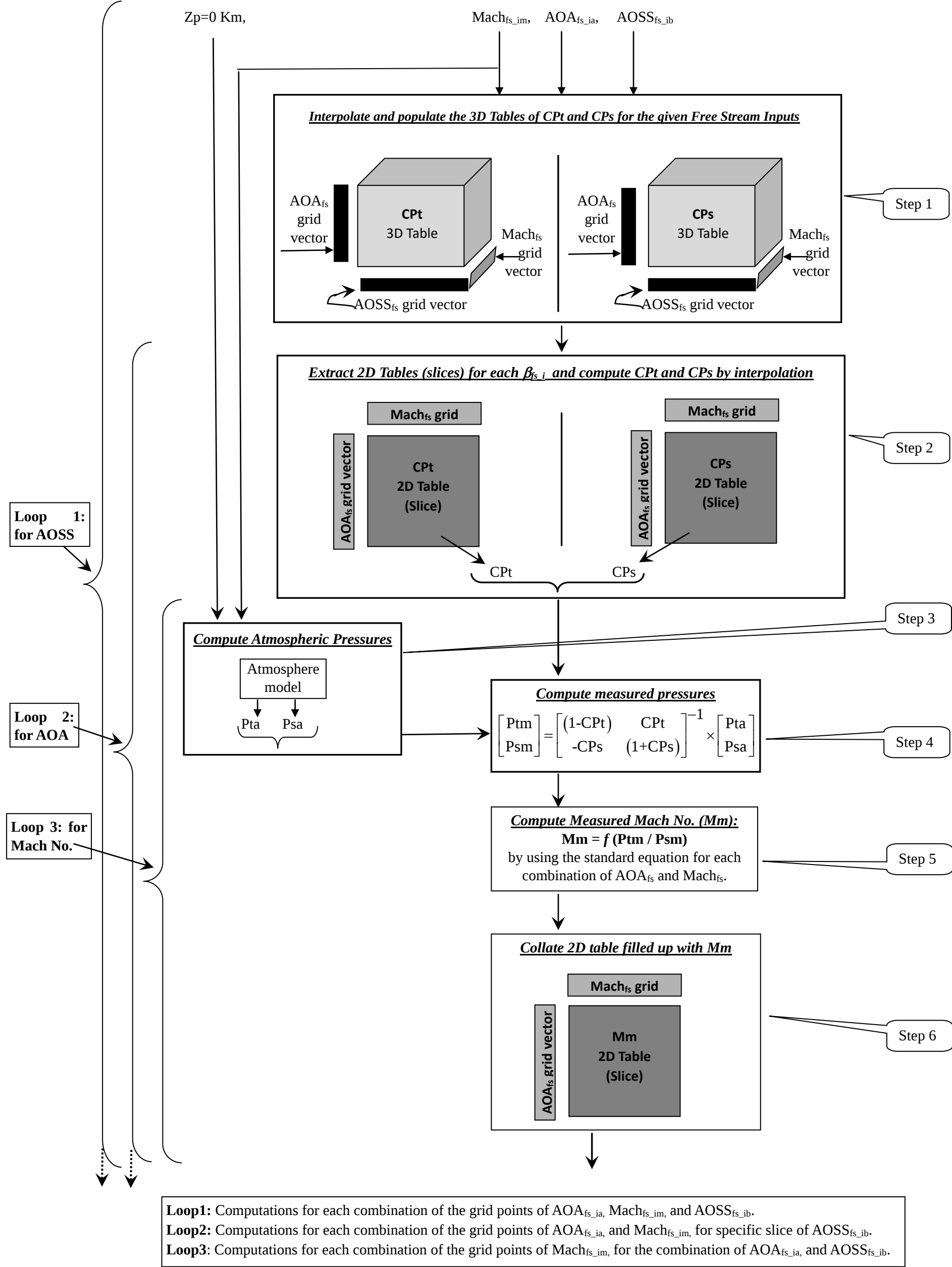


Figure 17 (a): Schematic Process of Measured Total and Static Pressure Correction Coefficients (CPt and CPs) table inversion to create the forward tables (Local to Free Stream measurements) from the given inverse tables (free stream to local measurements).

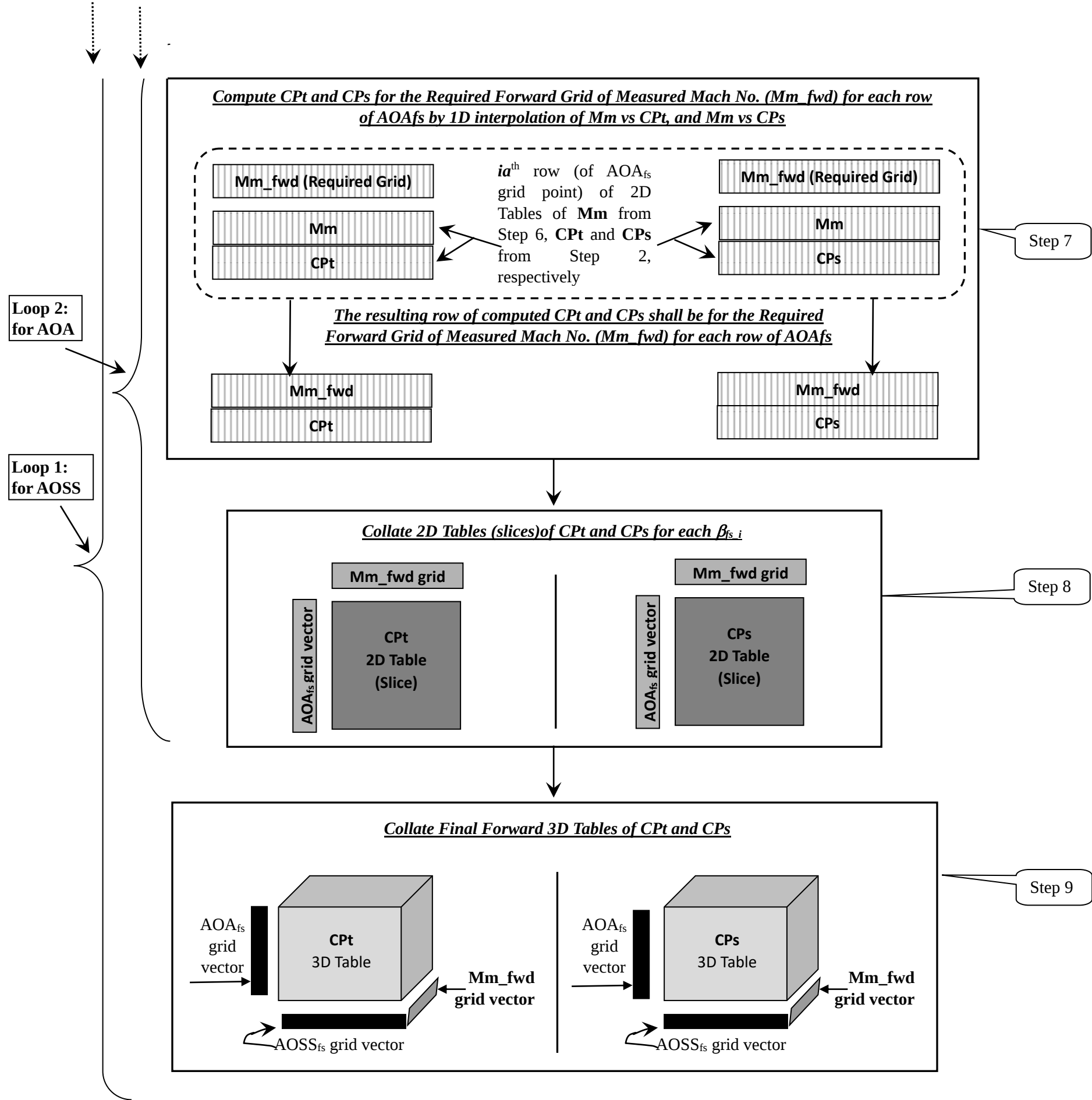


Figure 17 (b): Schematic Process of Measured Total and Static Pressure Correction Coefficients (CPT and CPs) table inversion to create the forward tables (Local to Free Stream measurements) from the given inverse tables (free stream to local measurements).

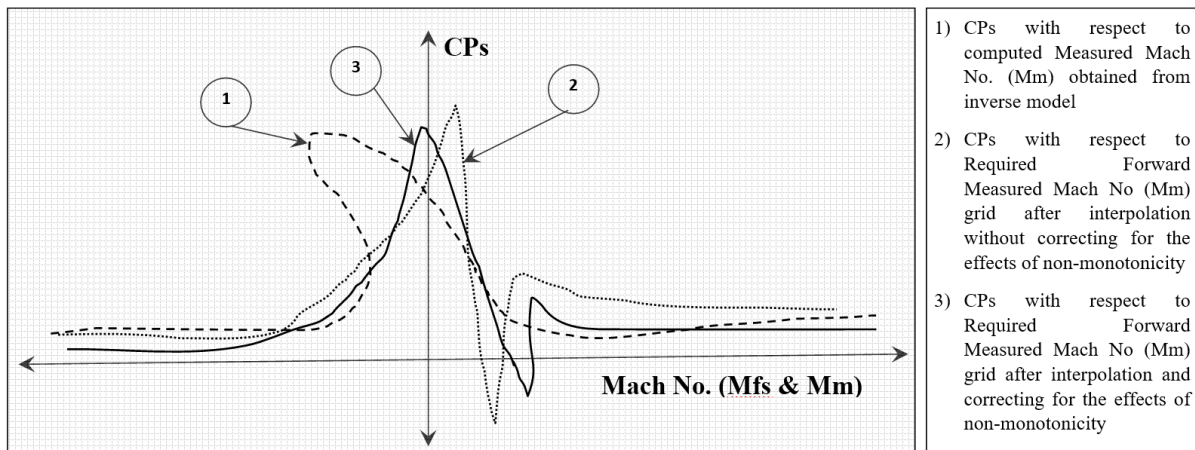


Figure 18: Illustration of occurrence of the shift in the curve of CPs in transonic Mach regime due to the non-monotonicity in the computed Measured Mach No., and the correction required to have consistency with respect to the required forward Measured Mach No. grid. The illustrated curves are for a one typical free stream AOA.

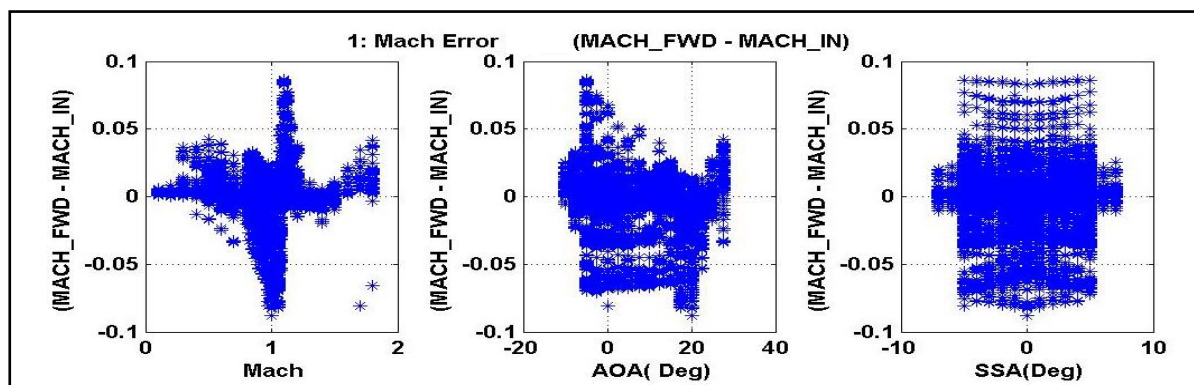


Figure 19: Data inversion process: End-to-end (Output-Input) error for Mach No. with respect to Input Mach No., AOA, and AOSS or SSA.

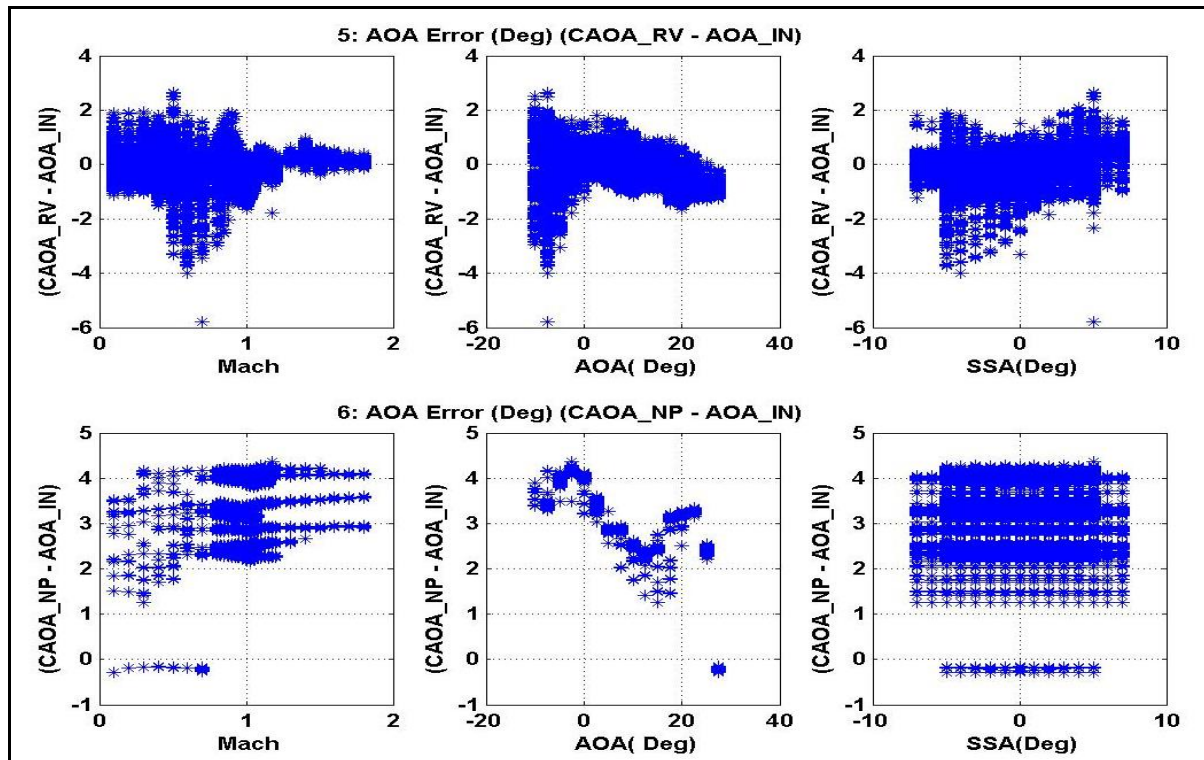


Figure 20: Data inversion process: End-to-end (Output-Input) error for AOA (from Vane and Probe) with respect to Input Mach No., AOA, and AOSS or SSA

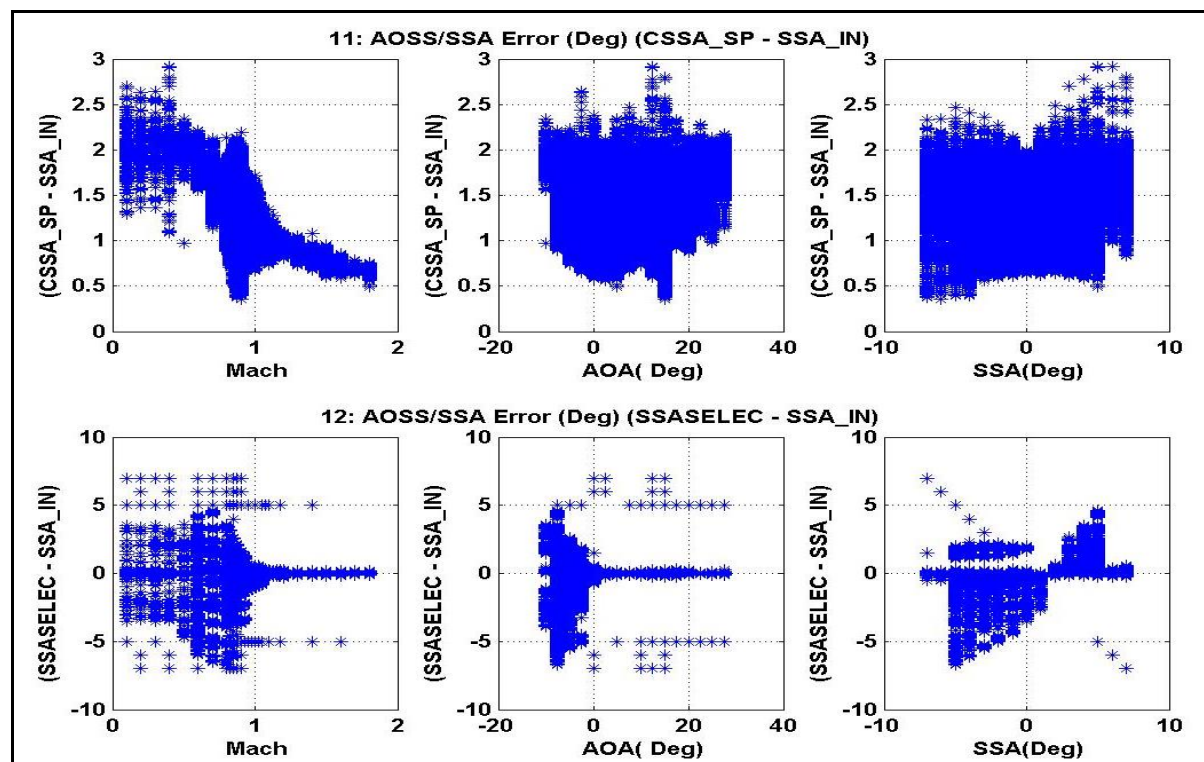


Figure 21: Data inversion process: End-to-end (Output-Input) error for AOSS (from Vane and Probe) with respect to Input Mach No., AOA, and AOSS or SSA