



HYBRID AIR DATA SYSTEM ARCHITECTURE: FROM DESIGN TO FLIGHT TEST VERIFICATION

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Abstract

The Air Data System (ADS) of an aircraft is of paramount importance for a variety of aspects including safety and situational awareness. Traditionally, the architecture of the ADS is based on physical sensors installed on the outside surface of the aircraft in order to detect the primary air data, namely pressures and flow angles. Many research efforts have been made in the direction of synthetic reconstruction of the air data as a potential replacement for such sensors. However, only a few of those examples reached the certification step to become actually part of an aircraft. This paper provides an overview of the design, integration and test of a Hybrid ADS architecture that relies on both sensors and synthetic estimator specifically designed to solve a calibration problem occurring during high AOA manoeuvres on an already existing architecture. The implementation of such system has been achieved in a multidisciplinary framework involving the aerodynamic, flight control system, avionics, and safety departments. The proposed design and integration solution have been verified in a laboratory environment. Flight-testing has been used to validate the performance of the ADS and to provide information useful for further improvements through a design iterative process. The whole process aims to achieve the desired accuracy in the whole envelope and to provide the compliance evidence to the certification authority.

Keywords: Air Data System, Synthetic Estimation, Flight Test, Airworthiness, Analytical Redundancy

List of Acronyms and Symbols

Acronym/Symbol	Meaning
A/C	Aircraft
ADC	Air Data Computer
ADM	Air Data Module
ADS	Air Data System
AoA / α	Angle of attack
AWB	Airworthiness Basis requirements
AoS	Angle of Sideslip

Acronym/Symbol	Meaning
CAS	Calibrated Air Speed
C_{L0}	Lift coefficient at null angle of attack
C_{Lα}	Lift coefficient slope
COTS	Commercial Off The Shelf
ΔPs/Ps	Static pressure correction
DAL	Design Assurance Level
DCU	Data Concentrator Unit
f_{PROBE}	Probe model function
FDAL	Functional Design Assurance Level
FTI	Flight Test Instrumentation
g	Gravity acceleration
HADS	Hybrid Air Data System
HW	Hardware
Hp	Pressure altitude
m	Aircraft mass
M	Mach number
MC	Mission Computer
MoC	Means of Compliance
n_z	Normal load factor
NB	Nose Boom
p	Roll rate
P_s	Static pressure
P_{S,corr}	Corrected static pressure
PDI	Parameter Data Items
q	Roll rate
q_c	Impact pressure
r	Yaw rate
S	Reference surface
SSEC	Static Source Error Correction
SW	Software

1. Introduction

The knowledge of Air Data during flight has always been of interest since the dawn of flying. With aircraft speed and performance increasing during time and the birth of commercial aviation, Air Data Systems (ADS) have become increasingly complex to guarantee satisfactory levels of flight safety and situational awareness. Air data computation have been historically relying on physical probes installed on the outside surface of the aircraft for the estimation of the primary air data, namely pressures and flow angles. With the advent of Air Data Computers (ADCs) in the 1950s, such probes have been coupled with electronics to drive a much faster, reliable and compact way of computing

Air Data. The use of synthetic estimators for flow angles has been investigated since 1950s to reach higher redundancy levels.

In the last 70 years, many research efforts have been made in this direction to develop different type of estimators. It is possible to classify Air Data estimators in three different categories, as proposed in [1]:

- *Estimator based on classical aerodynamic coefficients*: flight parameters are evaluated by inversion of the dynamic model of the aircraft. The first estimator was provided by Freeman [2] using data from the inertial platform. Later on, different estimators based on similar principles were derived ([3],[4]);
- *Model-based data fusion*: estimation with a Kalman filter based on dynamic identification of the aircraft ([5], [6], [7], [8], [9]) ;
- *Model-learned estimation*: methods in which the dynamic model is determined through an algorithm. In brief, every data-driven method based on Machine Learning that learns how to estimate the desired flight parameters falls in this category ([10], [11], [12], [13]).

The present work starts from an already existing ADS with traditional architecture installed on a Trainer Aircraft. This system was based on pitot-static probes and one fin-type Angle of Attack (AoA) probe. Two pitot-static probes are used in order to allow the required redundancy level. In order to read the data coming from the probes, an ADC has been selected. All the components are Commercial Off The Shelf (COTS) with little to none possibility of modifications. The selected COTS pressure probe is pretty robust to variations in AoA and AoS by design, when considered as an isolated object. It was successfully certified to meet the airworthiness requirements, with altitude and airspeed errors compliant to the international regulations. However, when installed on-board the A/C, some influence of AoA and AoS arise due to A/C probe interference. In particular, in dynamic manoeuvres, where high AoA excursions are achieved, the calibration implemented into the ADC was not accurate enough since it depended only on the indicated Mach number. Therefore, a new calibration needs to be developed taking into account the effect of AoA. This step however is not straightforward since it requires an architecture modification due to the presence of only one AoA probe. The new architecture will be called Hybrid Air Data System (HADS) and consists in the addition of a new software layer called Air Data Module (ADM), as shown in **Figure 1**.

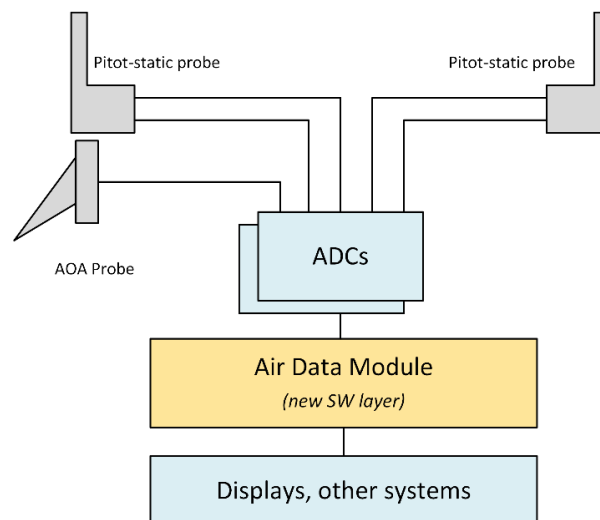


Figure 1 - High level schematic

It is a Hybrid system because it exploits a synthetic reconstruction of the AoA within the ADM to monitor the data provided by the AoA probe in addition to the traditional ADS. The AoA estimator developed in this work belongs to the first category presented above (namely *estimator based on classical aerodynamic coefficients*) and it is developed with a simpler yet reliable architecture than

the ones found in literature. One of the main design requirements comes from the classification of the hazard associated to the ADS. The functionality of providing air data has been associated with a Design Assurance Level (DAL) A and must have sufficient degree of redundancy to minimize to probability of critical failures during flight. Since only one AoA probe is available, redundancy is provided by the synthetic AoA reconstruction implemented in the ADM.

The main goals of this architecture modification is to satisfy the requirements on accuracy in terms of pressure altitude, dynamic pressure and Calibrated Airspeed (CAS), over the entire A/C envelope including high AoA excursion manoeuvres.

The paper provides details about the Software (SW) development and integration of the proposed HADS, which has been achieved in a multidisciplinary framework involving aerodynamic, flight control system, avionics and safety departments. It also provides information about the extensive validation performed in a laboratory environment followed by flight testing. Apart from safety and redundancy requirements, additional airworthiness requirements on accuracy must be satisfied. Therefore, the development process followed an iterative procedure in order to apply corrections based on laboratory and flight tests results. A focus on the development, verification, integration and validation of the AoA estimator is provided.

The present paper is organised as follows:

- *Introduction*: problem definition and literature review
- *Methodology*: definition of the main tools and method used for the development and testing of the HADS
- *Results and discussion*: description of the SW architecture, probes calibration and main results
- *Conclusions*: main outcome and limitations of the HADS

2. Methodology

This section provides a brief view of the process implemented during this project in order to design, validate and verify the entire system starting from a pre-existing traditional system.

As above-mentioned, the development of the HADS is carried out starting from already existing traditional ADS. The Hardware (HW) components are selected as COTS products and they are integrated with each other to reach the required performance and to meet the safety requirements.

The chosen ADC only allows calibrating the probes as a function of the indicated Mach number. In order to consider also the effect of AoA on probes calibration, an additional module, called ADM needs to be introduced in the ADS architecture. However, only one AoA probe is available, due to limited space availability and structural constraints on the aircraft. Therefore, the opportunity of implementing an analytical estimator of the AoA arises.

2.1 Synthetic AOA estimator

The synthetic AoA estimator is used to provide an analytical redundancy on AoA value coming from the physical probe. In this way, the AoA value can be used to apply corrections to the static pressure signal, guaranteeing the required DAL level. More in detail, the AoA estimator is applied as a monitor over the measured AoA and it is not provided to pilot during the flight.

Starting from the literature review presented in Section 1 and from the available signals on-board the aircraft, it has been decided to design an analytical estimator based on inertial measurements and complete A/C aerodynamic model, falling into the first category of analytical estimators (namely *estimator based on classical aerodynamic coefficients*). It is defined as:

$$\alpha_{est} = - \frac{-mn_z g + q_c S C_{L0}}{q_c S C_{L\alpha}}$$

where n_z is the vertical unbiased acceleration, m is the A/C mass, g is the gravity acceleration, q_c is the impact pressure, S is the reference surface, C_{L0} and $C_{L\alpha}$ are the lift curve coefficients of the A/C. Note that the lift coefficient data are referred to the A/C in cruise configuration (landing gear up, flap up). This will lead to limitations in flapped configurations, as shown in Section 3.2.

2.2 Software architecture

To meet the DAL A requirement, considering the avionic system structure, two dissimilar SW applications meeting DAL B requirement are needed. Hence, two separated development processes have been defined for SW, even if both of them foresee model-based activities, with different architecture and by different teams. In one case, modelling acts as a support to design activity, while in the other the detailed design activity is completely model-based. The two processes are based on RTCA DO178C [14] and DO331 [15] guidelines respectively. With the adoption of these approaches, it is possible to handle the criticalities posed by the implementation of dissimilar ADM applications and to guarantee the consistence of the resulting designs with the applicable system requirements.

The two dissimilar Software Applications have been designed to run in parallel on two different computing platforms that are available on the A/C called respectively Data Concentrator Unit (DCU) and Mission Computer (MC).

2.3 Probes aerodynamic calibration

The current ADS architecture implements a static pressure correction based on indicated Mach number alone. The development of a new calibration to take into account the effect of AoA, requires probes aerodynamic characterization and modelling. To do so, a probe model has been first developed in Simulink [17] by regression of a database of flight data coming from previous flight test campaigns. The probe model is then exploited to develop the new correction matrix to be applied on probes static pressure signals in order to minimize the difference between the computed and reference data over the entire A/C envelope. Such reference data comes from the calibrated Nose Boom (NB), which is a reliable air data source since it is located upstream of the nose in order to minimize any possible influence on the pressure and flow angles readings. A complete workflow is then developed in Simulink in order to preliminary evaluate the performance of the ADS based on a wide flight library before proceeding to the laboratory verification phase.

Regarding the AoA probe signal, since it remains unchanged from the already existing ADS, no further calibration actions are performed and its signal remains valid in the new HADS architecture.

2.4 ADS RIG Testing

The previous sections covered the methodology for system definition and verification in a simulated environment, leading to the release of a SW baseline. Once the baseline is released, the SW components need to be integrated into the existing avionic system in a laboratory environment, called RIG hereafter.

This phase is called laboratory verification and it is part of the system design process conducted to meet all the airworthiness requirements. This phase provides a Means of Compliance (MoC) for the system at hand, representing the verification that requirements have been implemented as intended. Additionally, the effect of hardware-software integration on ADS behavior and performance is assessed along with the interaction with other A/C systems.

2.5 ADS Flight Testing

As a last step, the ADS is integrated on board a prototype aircraft and flight-testing is performed in order to assess ADS performance in its real operating environment. This phase is called in-flight validation and it is one of the fundamental aspects of the engineering process because it allows assessing the real performance of the designed feature with respect to project requirements and the collection of experimental data useful for further improvement.

In this work, the validation is provided in terms of both synthetic AoA accuracy and overall ADS performance. To do so, a direct comparison between the in-flight acquired data and the reference NB data is performed. The validation was performed both during stabilized flight and through a wide range of dedicated maneuvers, aimed at covering the entire authorized aircraft envelope in terms of altitude, airspeed and angle of attack.

Moreover, additional stabilized flight tests are conducted in order to assess more accurately the ADS performance to be compared with airworthiness requirements. To do so, the tower-fly-by methodology

[16] is applied by comparing measured air data and GPS reference altitude/speed values. This comparison provides the ADS absolute errors to be compared with A/C requirements.

The data processing activity is performed off-line by recording aircraft parameters using an on-board Flight Test Instrumentation (FTI).

3. Results and Discussion

This section provides an overview of the results obtained following the process detailed in **Section 2**. The results are intended as both the final SW architecture and the performance of the HADS. Moreover, a focus on the performance of the AoA analytical estimator is provided.

3.1 SW architecture

As introduced in **Section 2.2**, in order to meet a Functional Design Assurance Level (FDAL) A for the overall air data system, dissimilarity is applied. Indeed, according to SAE ARP-4754A: DCU_ADM and CMDP_ADM, two dissimilar applications qualified as DAL B running on two dissimilar DAL B hardware platforms (MC and DCU) of the avionic system have been implemented. For these reasons, each ADM software application have been developed by different working teams and qualified in accordance to a DAL equal to B.

The two applications provide redundant capabilities and output data cross-check, with the exception of Synthetic AoA Estimation, that is implemented on DCU only. The value of synthetic AOA is compared with the measured AoA, received by the two different ADC connected to two different transducers. If both applications agree, the AoA signal can be applied for the static pressure correction. However, in case one of the applications reports a failure, the ADMs shall move to a degraded mode where a single variable data correction is applied based on Mach number only.

For the application to be loaded on the DCU the DO178C guidelines has been applied for both the development and verification paths: a SysML model has been built in order to support the definition of software requirements, software architecture and detailed design. The application code, to be loaded on DCU platform, has been completely generated from the SysML model itself.

The DCU SW application model has been structured, as shown in **Figure 2**. The implemented architecture foresees the possibility to configure the algorithm's behavior by means of a set of Parameter Data Items (PDIs) to be loaded during software initialization phase.

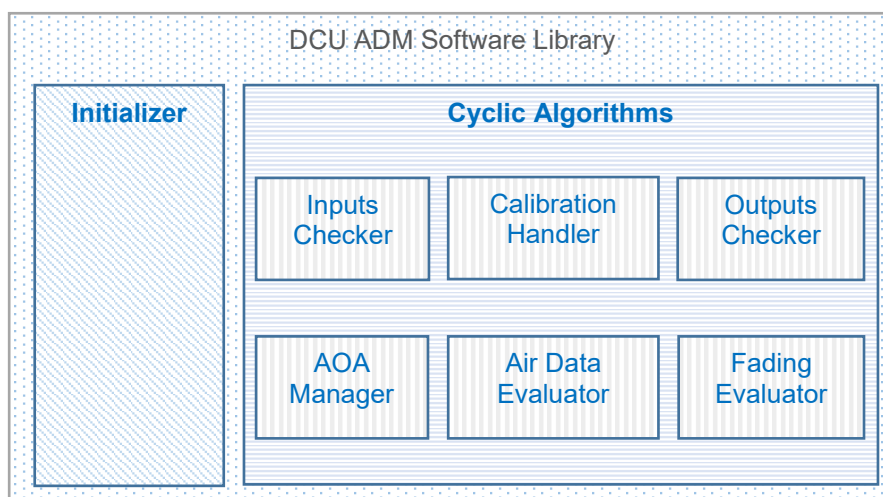


Figure 2 – DCU ADM Software Library

On the other hand, for the application to be loaded on the MC, the DO331 supplement to DO178C guidelines has been applied to the development path. As a first step, an architecture and functional requirements specification has been defined with the support of SysML semantic. This specification extends the relevant system high-level capabilities identified as applicable for the ADM application.

As a second step, the Software application has been completely defined as described in **Figure 3**. Its definition has been carried out by means of a MATLAB/Simulink [17] design model specifying the software low-level requirements as required by DO331 guidelines. From this model, the code to be loaded on MC platform has been completely generated.

Also for the MC, the implemented architecture supports the algorithm's configuration by means of a set of PDIs to be loaded during software initialization.

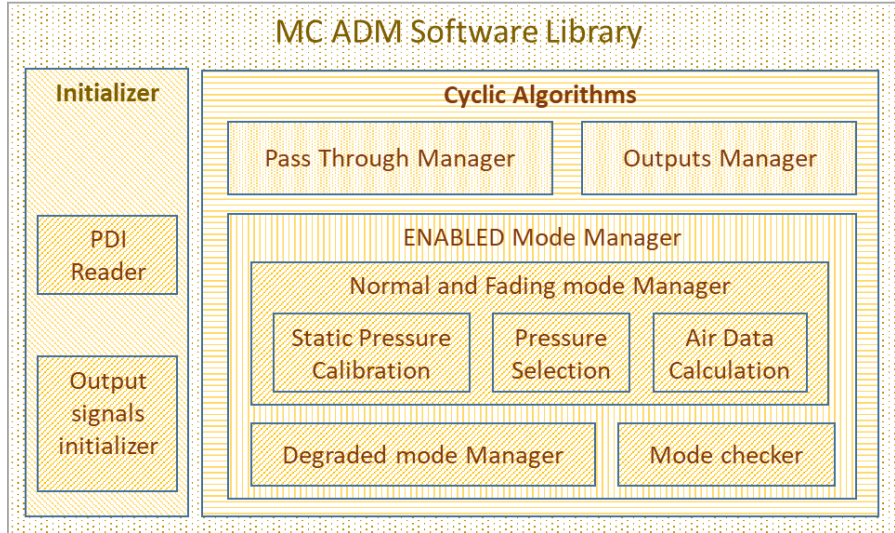


Figure 3 – MC ADM Software Library

3.2 Aerodynamic calibration definition

The introduction of the ADM allows to take into account both the effects of indicated Mach number and AoA on pressure probes calibration. Therefore, a new calibration matrix is developed and it is called Static Source Error Correction (SSEC) 3D.

As seen in **Section 2.1**, the synthetic AoA is a value derived from a force balance involving the aircraft CL-AoA value in cruise configuration. This would result in a bias of the calculated value when flaps are extracted, since their extraction implies the use of a different CL-AoA curve. However, since the DAL level of the flap signal is not compliant with the requirements, such signal cannot be used to switch different CL-AoA curves. For this reason, the synthetic AoA estimation cannot be used to monitor the AoA status when flying within the flapped configuration A/C envelope. Therefore, ADM is forced to use the ADC calibration, taking into account only the indicated Mach number, neglecting the AoA contribution to static pressure correction. Moreover, should the AoA probe fail during flight, the same single parameter ADC calibration is used to provide back-up air data to the pilot. This single-parameter calibration matrix is called SSEC.

Each of the two calibrations is defined in terms of variation of static pressure over the probe static pressure ($\Delta P_s/P_s$), and the correction is applied as follows:

$$P_{s,corr} = \left(1 + \frac{\Delta P_s}{P_s}\right) P_s$$

Where P_s is the raw static pressure provided by the probe, $\Delta P_s/P_s$ is the correction to be applied that may be associated either with SSEC or SSEC3D, $P_{s,corr}$ is the corrected static pressure.

In order to define the SSEC3D, it is necessary to build a probe model (f_{PROBE}) capable of representing the probes¹ behavior starting from reference air data values coming from Nose Boom (NB) data recorded on previous flight test campaigns. The probe can be considered as an input/output system where the Nose Boom signals represent the inputs and the processed probe signals represent the outputs, as show in **Figure 4**.

¹ Both AoA and pressure probes

The equation describing such model is the following:

$$[P_t, P_s, AoA] = f_{PROBE}(AoA_{NB}, H_{p_{NB}}, M_{NB}, AoS_{NB}, p, q, r)$$

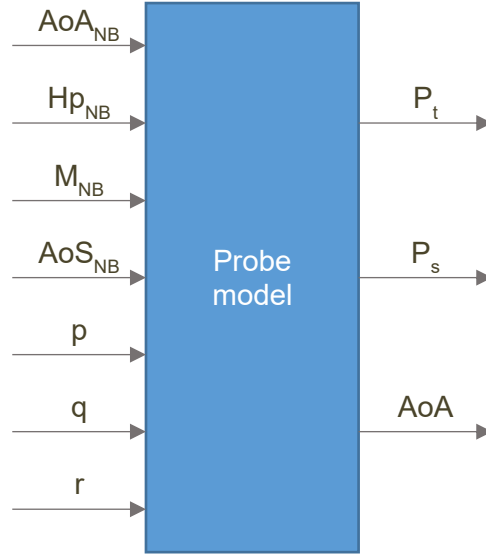


Figure 4 - Probe model

Where, AoA_{NB} , $H_{p_{NB}}$, M_{NB} and AoS_{NB} are the Nose Boom signal considered as “true”; and p , q , r are the rotational velocities about the body axes derived from the inertial platform. f_{PROBE} represents the probe model, which is an arbitrary fitting function to be derived based on the available flight data².

In particular, flight data are fitted by the least square method using two different approaches: a brute-force approach and a physics-based one. The brute-force approach is a straightforward method for solving the problem in which the entire set of variables is used disregard of their physical relevance. The physics-based approach takes into account only the input parameters directly correlated to the probe behaviour neglecting any cross-correlation contribution. Consequently, in the latter scenario, the f_{PROBE} function consists in a longitudinal term based on longitudinal manoeuvres and a directional term based on directional manoeuvres.

Therefore, two different definitions of f_{PROB} are derived and the selection between them is made by comparing the prediction of the probe model with the real flight data. Such comparison led to the selection of the brute-force model for AoA estimation and physics-based model for pressure estimation.

Once the probe model is obtained, it can be exploited to generate a set of input data used to drive the SSEC3D definition process, defined as:

$$\frac{\Delta P_s}{P_s} = f_{SSEC3D}(AoA_{probe}, M_{probe})$$

The f_{SSEC3D} function is defined with the aim of minimizing the difference between the static pressure signal coming from the probe model and the NB reference value. The obtained SSEC3D calibration, shown in **Figure 5**, is then preliminary tested as shown in the following section.

An additional application of the probe model, to be considered as a future development, could be its implementation within a flight simulator environment in order to replicate the probe behaviour throughout the flight.

² Approximately 120 flight data coming previous flight test campaigns

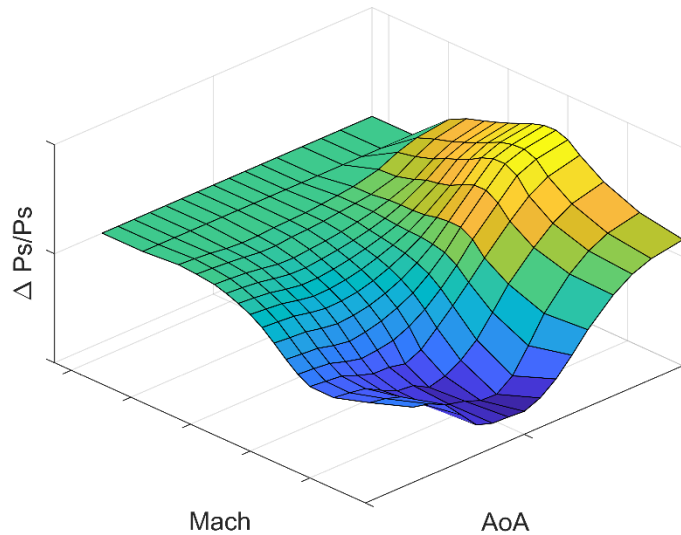


Figure 5 - SSEC3D calibration matrix

3.3 Aerodynamic calibration preliminary off-line testing

Following the definition of the new calibration matrix, a workflow for the preliminary evaluation of ADS performance is proposed, as shown in **Figure 6**. Starting from a flight library, the reference data coming from the NB are compared with the ADS Air Data computed offline by either using SSEC3D or SSEC, depending on where the flight point lies in the A/C envelope, as discussed in **Section 3.2**. An additional function called *Atmos* is here introduced in order to compute the relevant primary air data (such as altitude, CAS and Mach number) starting from the static and total pressure values.

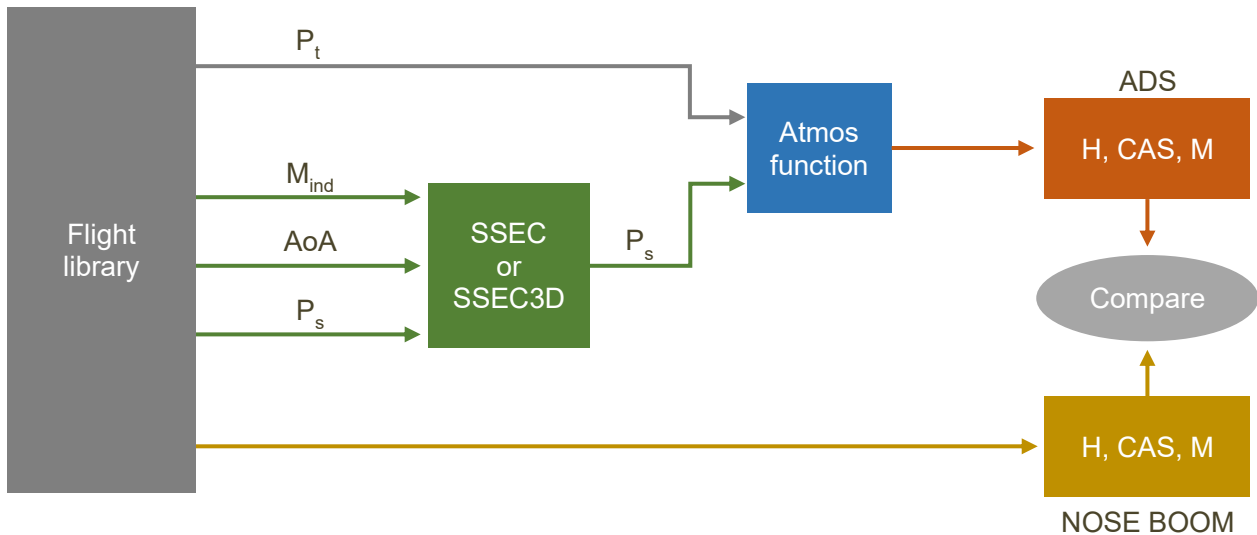


Figure 6 - Workflow for preliminary evaluation of ADS performance

A comparison between the results obtained from this analysis and the A/C requirements is achieved in order to preliminarily evaluate the system compliance with Airworthiness Basis Requirements (AWB). Such requirements need to be satisfied over the entire operative envelope, therefore both using the SSEC and SSEC3D calibrations. The comparison between the new ADS performance with respect to AWB is shown in **Figure 7** for both pressure altitude and airspeed. Preliminary compliance is therefore verified. The final compliance will be provided after the in-flight validation, as shown in **Section 3.5**.

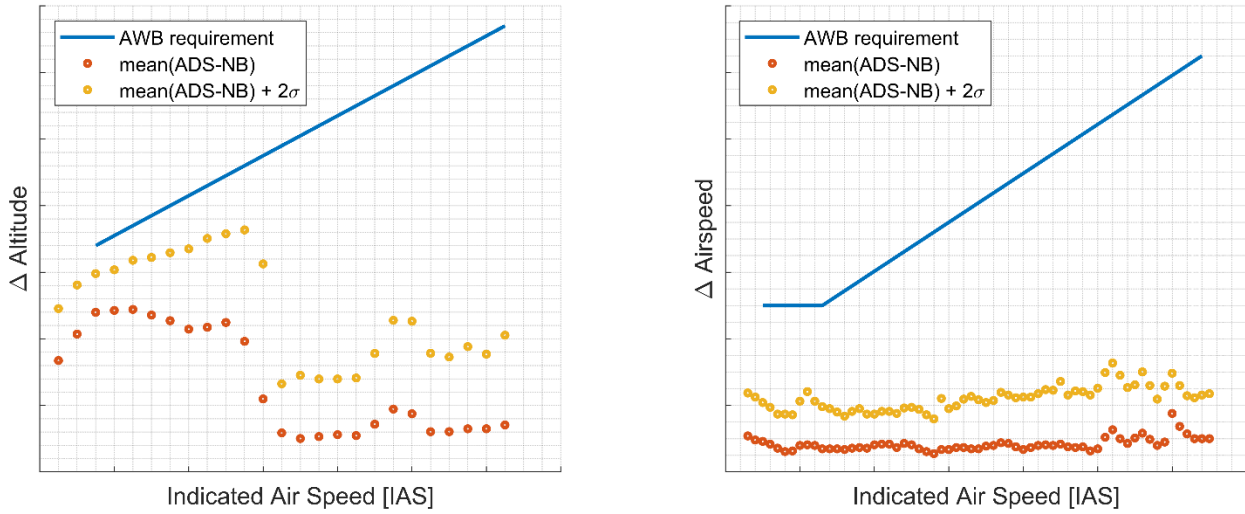


Figure 7 - ADS off-line performance compared to AWB requirements on altitude and airspeed

3.4 ADS RIG Testing results

The RIG testing allows the verification of the project requirements as explained in Section 2.4. The main outcome of this phase is that all the required airworthiness requirements have been implemented correctly and no HW-SW integration issues have been highlighted.

Therefore, the verification of HADS in the simulated environment has led to the successful issue of the required MoC allowing the execution of the in-flight validation phase safely.

Some of the tests for the verification procedure include:

- ADS transition between SSEC and SSEC3D
- Comparison of air data output with high precision input values
- ADS integrity checks and signal persistence
- Cautions callout, acknowledge and reset
- Stress tests

3.5 ADS Flight Testing results

The in-flight testing allows for the final validation of the designed system. Therefore, the HADS has been integrated on a prototype aircraft and an in-depth flight activity has been conducted on spring 2023. The flight test campaign provided results about the accuracy of the analytical AoA estimation and the HADS overall performance in terms of air data evaluation.

Regarding the analytical AoA estimator, it is in good agreement with the reference AoA coming from the NB. Two different analysis has been carried out in order to examine the synthetic estimator behavior both in steady flight conditions and during maneuvers. **Figure 8** shows the comparison between AoA signal coming from Nose Boom, ADS and the synthetic estimator during stabilized flight at different airspeed values. The AoA estimator provides accurate results over the entire airspeed range, with an excellent performance in the high-speed regime. On the other hand, **Figure 9** shows the comparison between the same AoA signals during dynamics maneuvers such as Wind Up Turn, Push Over and during acrobatic maneuvers. Also in this scenario, the AoA estimator behaves as expected and a good performance is achieved.

Therefore, considering the obtained results and that the analytical estimation is not provided to the pilot but it is used only to check the integrity of the AoA signal coming from the probe with a certain tolerance, the obtained errors levels are well within project requirements.

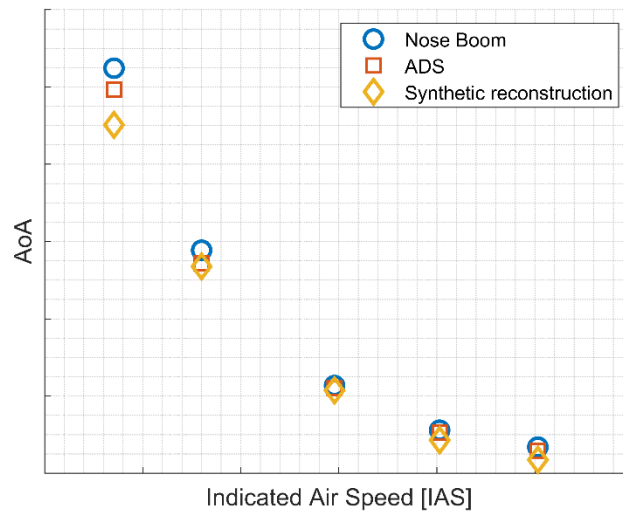


Figure 8 - Comparison between AoA signal coming from different sources during stabilized flight at different airspeed values

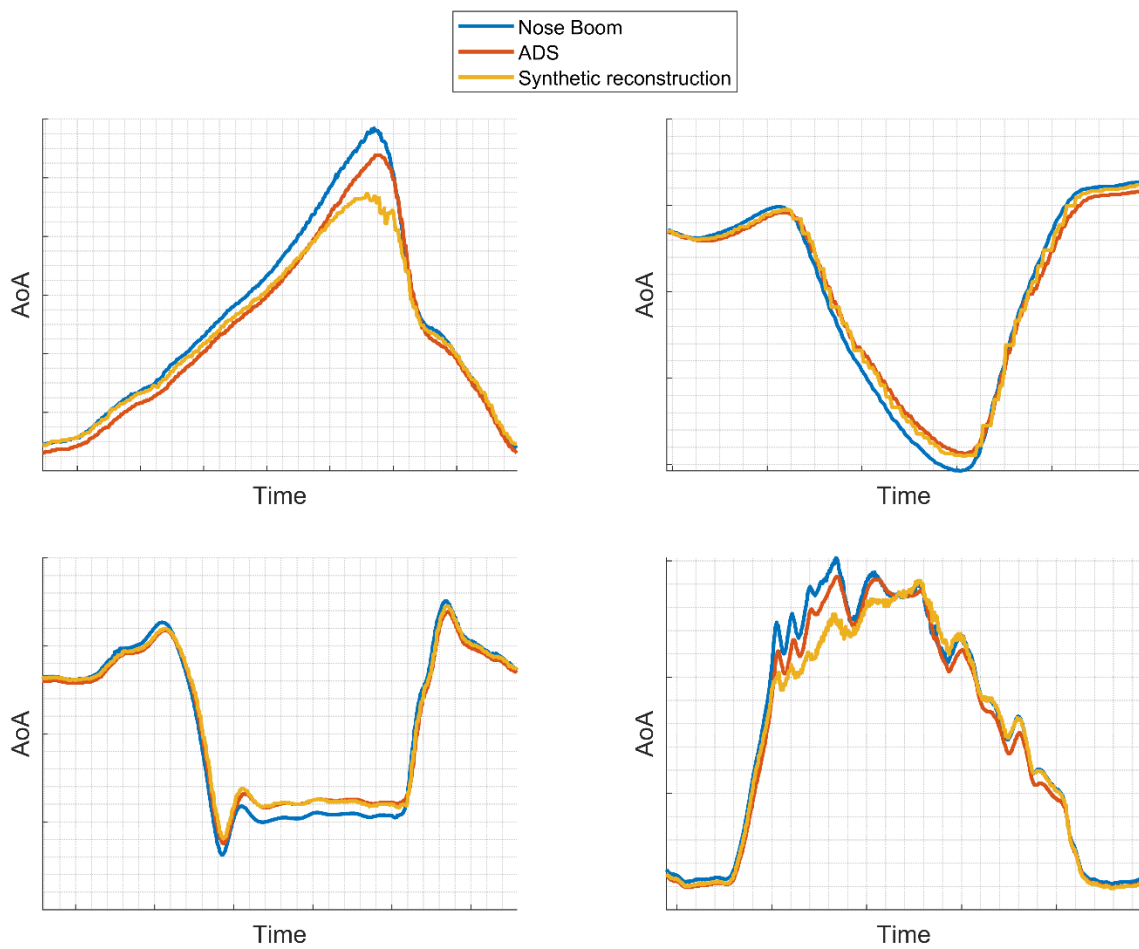


Figure 9 - Comparison between AoA signal coming from different sources during maneuvers

Once the capabilities of the AoA estimator are assessed, the new ADS performance should be analyzed in order to validate them. Two different types of analysis have been carried out in order to explore ADS behavior during dynamic maneuvers and to validate the satisfaction of A/C AWB requirements.

Regarding ADS performance, **Figure 10** and **Figure 11** show the comparison of altitude and CAS between ADS and the reference data coming from the Nose Boom. As an example, two highly dynamic maneuvers have been selected for the comparison since this was the scenario in which the previous ADS architecture failed. Therefore, the new ADS architecture is capable of correctly capture the airspeed and altitude of the aircraft also during this type of maneuvers, boosting the performance with respect to the previous architecture.

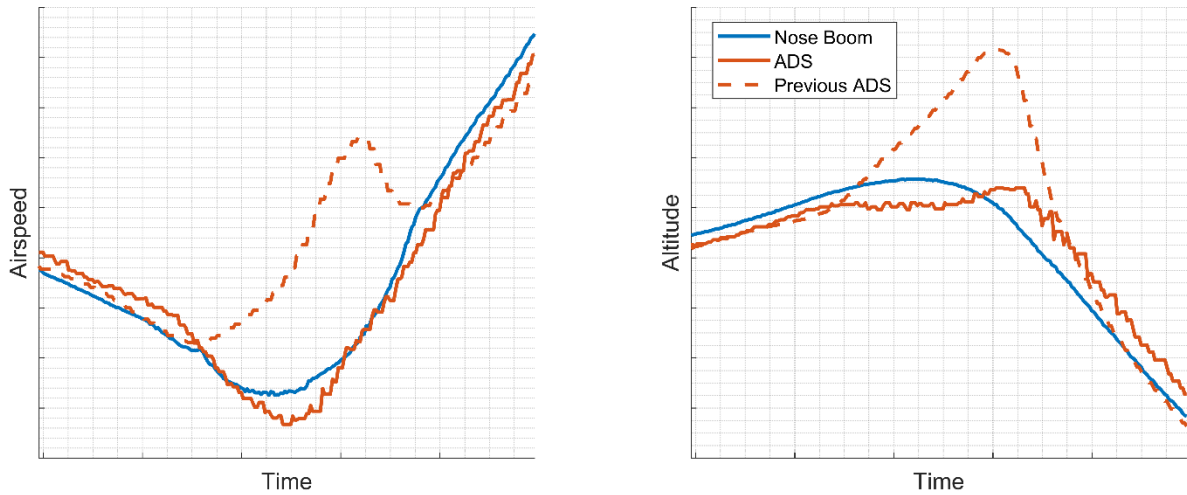


Figure 10 - Comparison between airspeed and altitude coming from Nose Boom and ADS, Maneuver 1

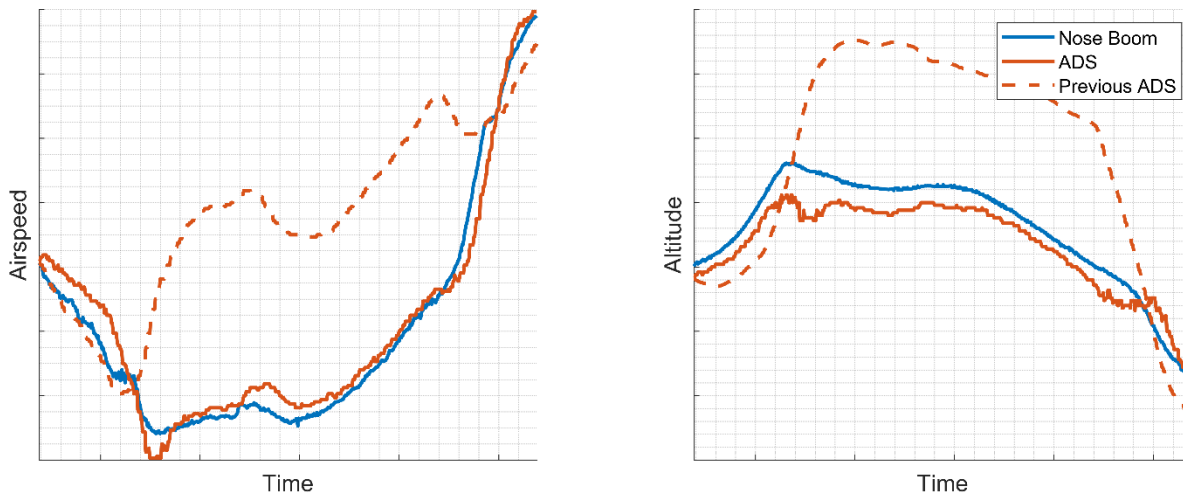


Figure 11 - Comparison between airspeed and altitude coming from Nose Boom and ADS, Maneuver 2

As mentioned above, the final validation of the HADS is provided by checking the satisfaction of A/C airworthiness requirements using the entire set of maneuvers available. In particular, the starting point is the outcome of the Tower Fly-By stabilized tests. Then, the entire set of maneuvers is exploited to evaluate ADS accuracy over the entire envelope. As reported in **Table 1**, the evaluation of altitude and airspeed errors (with respect to Nose Boom reference) over the entire operative envelope provides a positive result for both SSEC and SSEC3D.

Requirement	Preliminary compliance
SSEC3D altitude error (Flap Cruise)	✓
SSEC3D airspeed error (Flap Cruise)	✓
SSEC altitude error (Flap Cruise/Take-off, Landing)	✓
SSEC airspeed error (Flap Cruise/Take-off, Landing)	✓

Table 1 - Air data airworthiness requirements

4. Conclusion and Future Improvements

The performance of the ADS strongly depends on the pressure field around the aircraft, which is influenced by the flight condition of the aircraft itself. To improve the performance of the ADS in terms of uncertainty associated to the flight parameters of altitude and airspeed, a dedicated SW has been implemented onto the already defined avionic system. This paper showed a design process that resulted in a hybrid architecture with improved performance with respect to the starting baseline. This multidisciplinary approach covered several aspects from safety, SW design, to system and aerodynamic performance. The data shows good reduction of the errors resulting from considering the AoA for pressure calibration.

Future architectures may be developed in order to extend the set of independent variables on which the calibration matrix depends. Some of them may be:

- Directional terms such as sideslip angle. Indeed, the main limitation of the proposed architecture is the absence of such terms which results in a lower accuracy during lateral and directional maneuvers;
- Angular rates in order to further improve the accuracy of the ADS during highly dynamic maneuvers.

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References

- [1] Brandl A. *Techniques for effective virtual sensor development and implementation*, 2020.
- [2] Freeman D. B. *Angle of attack computation system*, 1973.
- [3] Zeis J. E. *Angle of attack estimation using an inertial reference platform*, 1988.
- [4] Colgren R. D., Fyre T. M. and Olson W. M. A proposed system architecture for estimation of angle of attack and sideslip angle, *Guidance, Navigation, and Control Conference and Exhibit*, 1999.
- [5] McGee L. A. and Schmidt S. F. *Discovery of the Kalman filter as a practical tool for aerospace and industry*, NASA Technical Memorandum, 1985.
- [6] Wise K. A. *Computational air data system of angle of attack and angle of sideslip*. Patent US 6,928,341 B2, 2005.
- [7] Adhika Pradipta Lie F. and Gebre-Egziabher D. Synthetic air data system, *Journal of Aircraft*, 2013.
- [8] Lu P., Van Eykeren L., Van Kampen E., De Visser C. C. and Chu Q. P. Adaptive three-step Kalman filter for air data sensor fault detection and diagnosis, *Journal of Guidance, Control, and Dynamics* 39.3 (Mar. 2016), pp. 590-604.
- [9] Schettini F., Di Rito G. and Denti E. Aircraft flow angles calibration via observed-based wind estimation, *Aircraft Engineering and Aerospace Technology* 91.7 (July 2019), pp. 1033-1038.
- [10] Rajkumar T. and Bardina J. Training data requirement for a neural network to predict aerodynamic coefficients, *SPIE Defense + Commercial Sensing* (2003), p. 92.
- [11] Samara P. A., Fouskitakis G. N., Sakellariou J. S. and Fassois S. Aircraft angle-of-attack virtual sensor design via a functional pooling narx methodology. *European Control Conference* (Sept. 2023), pp. 1816-1821.
- [12] Hardier G., Seren C., Ezerzere P., and Puyou G. Aerodynamic model inversion for virtual sensing of longitudinal flight parameters. *Conference on Control and Fault-Tolerant Systems* (Oct. 2023), pp. 140-145.
- [13] Cashman J.E., Kelly B.D., and Nield B. N. Operational use of angle of attack on modern commercial jet airplanes. *Tech. rep. 12* (2000), pp. 12–21.
- [14] RTCA Inc., DO-178C - *Software considerations in airborne systems and equipment certification*, December 13, 2011.
- [15] RTCA Inc., DO-331 - *Model-based development and verification supplement to DO-178C and DO-278A*, December 13, 2011.
- [16] Society of Flight Test Engineers, *SFTE reference handbook*, 2013.
- [17] MathWorks ©