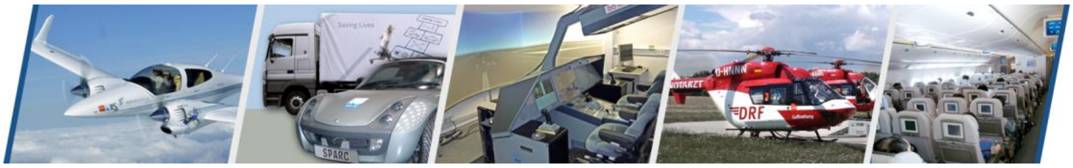

Institut für
Technische Physik

Bachelorarbeit

Analysis of Certification Requirements for Laser Doppler Anemometry in Large Aircraft

Bo Held

Zeitraum: 05.05.2025 – 05.09.2025
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Aufgabenstellung

ABSCHLUSSARBEIT

Analysis of Certification Requirements for Laser Doppler Anemometry in Large Aircraft

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Kontext

Das Institut für Technische Physik des DLR hat ein Laser-Doppler-Anemometer (LDA) entwickelt, das auf dem Dopplereffekt basiert und in der Lage ist, den Flugwindvektor eines Luftfahrzeugs präzise zu bestimmen. Flugversuche haben die Leistungsfähigkeit und Zuverlässigkeit dieses Systems eindrucksvoll bestätigt. Im Vergleich zu herkömmlichen Pitot-Statik-Systemen und Anstellwinkelsensoren bietet das LDA den Vorteil, dass es den Flugwindvektor ohne physische Interaktion mit der das Luftfahrzeug umgebenden Strömung oder Umwelt erfassen kann.

In der Vergangenheit haben klassische Sensoren wie Pitot-Statik-Systeme und Anstellwinkelsensoren mehrfach zu schwerwiegenden Zwischenfällen geführt, da ihre Leistungsfähigkeit unter widrigen Umweltbedingungen beeinträchtigt wurde. Diese Probleme konnten zwar durch verbesserte Verfahren und Systemaktualisierungen teilweise behoben werden, dennoch bleibt das Risiko bestehen. Das LDA bietet eine vielversprechende Alternative, da es unempfindlich gegenüber den Umweltbedingungen ist, die klassische Sensoren stören, und somit einen wichtigen Beitrag zur Flugsicherheit leisten kann.

Aufgabe

Im Rahmen dieser Arbeit soll analysiert werden, für welche grundlegenden Flugzeugtypen die LDA-Technologie geeignet ist. Dabei werden insbesondere die relevanten Regularien im Zusammenhang mit der Erfassung von Indicated Air Speed (IAS) und Angle of Attack (AOA) betrachtet. Es gilt zu prüfen, welche Regularien in Form von Vorschriften, Acceptable Means of Compliance (AMC) oder Guidance Material (GM) verfügbar und aktuell gültig sind. Zusätzlich sollen potenzielle weitere Vorteile der Technologie abgeschätzt werden, beispielsweise hinsichtlich Sicherheit, Zuverlässigkeit oder Wartungsaufwand.

Zu Beginn der Arbeit soll eine systematische Übersicht der infrage kommenden Flugzeugkategorien sowie der einschlägigen Regularien erstellt werden. Anschließend werden daraus konkrete Anforderungen und Anwendungsfälle abgeleitet. Darüber hinaus könnte untersucht werden, wie die Integration der LDA-Technologie in bestehende Systeme gestaltet werden kann und welche wirtschaftlichen oder betrieblichen Auswirkungen sich daraus ergeben.

Die Arbeitsschritte im Einzelnen:

- **Einarbeitung in die Grundlagen der Zulassung**
  - Überblick über die europäischen Zulassungsvorschriften CS-25.
  - Analyse der Acceptable Means of Compliance (z.B. ARP4754, RTCA DO-160g).
  - Vertiefung in das Messprinzip des Laser-Doppler-Anemometers (LDA).
- **Erstellung einer Übersicht über infrage kommende Flugzeugtypen**
  - Kategorisierung der Typen nach Zulassungsvorschriften und Anwendungsbereichen.
  - Bewertung der Anforderungen an Air Data-Systeme für CS-25 Flugzeuge im Commercial-Air-Transport.
- **Untersuchung aktueller Messmethoden**
  - Analyse der Funktionsweise und Leistungsfähigkeit von Pitot-Static-Systemen und Angle-of-Attack-Sensoren.
  - Untersuchung der Datenformate in Avioniksystemen für Air Data.
  - Bewertung der erforderlichen Datenraten und Genauigkeiten aktueller Messmethoden.
  - Vergleich der Leistungsfähigkeit und Einsatzgrenzen der bestehenden Systeme.
- **Vergleich von LDA und aktuellen Air-Data-Systemen im Kontext der CS**
  - Auswahl und Evaluierung relevanter Eigenschaften für die Eignung der LDA-Technologie.
  - Abschätzung der Risiken und potenziellen Herausforderungen beim Einsatz von LDA.
  - Identifikation von potenziellen Vorteilen der LDA-Technologie im Hinblick auf Sicherheit, Zuverlässigkeit und Betriebsaufwand.
- **Dokumentation der Ergebnisse**
  - Zusammenfassung der Untersuchungsergebnisse und Vergleichsdaten.
  - Formulierung von Empfehlungen für die Integration der LDA-Technologie.
  - Darstellung potenzieller regulatorischer Anpassungen zur Unterstützung der neuen Technologie.

Die Ergebnisse Der Arbeit sind in einem Vortrag zu präsentieren.

Beginn:

Abgabe:

Betreuer:	M.Sc. Hugo Uittenbosch
	Dr. rer. nat. Oliver Kliebisch
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Stuttgart, den 05.09.2025

Bo Held

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[1] Nachzulesen in den DFG-Empfehlungen zur "‘Sicherung guter wissenschaftlicher Praxis"’ bzw. in der Satzung der Universität Stuttgart zur "‘Sicherung der Integrität wissenschaftlicher Praxis und zum Umgang mit Fehlerverhalten in der Wissenschaft"’

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Analysis of Certification Requirements for Laser Doppler Anemometry in Large Aircraft

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Der Universität Stuttgart übertrage ich das Eigentum an diesen zusätzlichen Fassungen und räume dem Institut für Luftfahrtsysteme an dieser Arbeit und an den im Rahmen dieser Arbeit von mir erzeugten Arbeitsergebnissen ein kostenloses, zeitlich und örtlich unbeschränktes, einfaches Nutzungsrecht für Zwecke der Forschung und der Lehre ein. Falls in Zusammenhang mit der Arbeit Nutzungsrechtsvereinbarungen des Instituts mit Dritten bestehen, gelten diese Vereinbarungen auch für die im Rahmen dieser Arbeit entstandenen Arbeitsergebnisse.

Stuttgart, den 05.09.2025

Bo Held

Abstract of Bachelor Thesis

Analysis of Certification Requirements for Laser Doppler Anemometry in Large Aircraft

The Institute of Technical Physics at the Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Centre) (DLR) is developing a Laser Doppler Anemometer (LDA) capable of precisely measuring the airflow vector around an aircraft, which represents an alternative to Pitot-static systems and flow angle measurement vanes. These conventional systems are susceptible e.g. to icing and can provide unreliable air data while the LDA performs real-time uncertainty calculations on its measurements of True Air Speed (TAS), Angle of Attack (AoA), and Angle of Sideslip (AoS), supplying near-instantaneous information on the reliability of its data. Furthermore, the technology interacts only optically with the air.

Flight tests confirmed the system's feasibility and showed strong correlation between LDA measurements and reference data. Ongoing development efforts aim to further refine the technology, focusing on improving integration and performance while addressing lessons learned from the earlier campaigns.

This thesis analysed the applicability of certification requirements for integrating LDA technology into large commercial aircraft regulated under CS-25. This was done by comparing conventional systems to the LDA technology, focusing on performance characteristics, novel risks and challenges as well as potential scenarios for integration. Certification Specification (CS) as well as industry standards (e.g. AS8002B, ARINC 738-3) applicable to state-of-the-art instruments were reviewed, and the gathered performance data was checked for its consistency. The comparison of the systems identified key advantages of the LDA including improved data integrity, aerodynamic benefits and simplified maintenance. As challenges for the introduction, asynchronous data rates and the need for adapted calibration procedures were identified. The study then proposed solutions to align the LDA with regulatory demands, such as statistical data rate compliance methods, revised accuracy requirements for TAS measurements and integration strategies for hybrid systems.

Based on these analyses, the applicability of the CSs on the LDA was assessed. Additionally, potential adaptations to CS-25 were suggested to accommodate the novel measurement principles of the technology without compromising safety.

The findings demonstrated that while LDA technology shows promise for enhancing aviation safety and efficiency, its adoption is complicated by regulation, prescribing conventional technology. While certification may be possible under a *Special Condition (SC)*, more fundamental changes to the certification framework are suggested.

Kurzzusammenfassung der Bachelorarbeit

Analyse von Zulassungsvoraussetzungen für die Laser-Doppler Anemometrie (LDA) für Großflugzeuge

Das Institut für Technische Physik des DLR entwickelt ein Laser Doppler Anemometer (LDA), das in der Lage ist, den Anströmvektor der Luft an einem Flugzeug präzise zu bestimmen. Die Technologie stellt eine Alternative zu Pitot-Statik Systemen und Windfahnen zur Messung des Anstellwinkels dar. Diese herkömmlichen Systeme sind fehleranfällig für die Bereitstellung von unzuverlässigen Daten. Im Gegensatz dazu, führt das LDA eine Berechnung der Unsicherheit der True Air Speed (TAS), des Anstellwinkels und des Schiebewinkels durch, was Informationen über die Zuverlässigkeit der Daten liefert. Flugtests bewiesen die Realisierbarkeit des Systems sowie eine starke Korrelation zwischen den Messungen des LDA und den Referenzdaten. Das Projekt zielt nun darauf ab, die Technologie weiterzuentwickeln, wobei der Schwerpunkt auf der Verbesserung der Integration sowie der Leistungssteigerung liegt. Hierzu werden Erkenntnisse aus den Testkampagnen berücksichtigt.

Im Rahmen dieser Arbeit wurde die Anwendbarkeit der Zertifizierungsanforderungen für die Integration der LDA-Technologie in große Verkehrsflugzeuge (nach CS-25) untersucht. Dazu wurden herkömmliche Systeme mit der LDA-Technologie verglichen, wobei der Schwerpunkt auf den Leistungsmerkmalen, neuartigen Risiken und Herausforderungen sowie potenziellen Szenarien für die Integration lag. Zertifizierungsspezifikationen sowie Industriestandards (z. B. AS8002B, ARINC 738-3) wurden untersucht und die gesammelten Leistungsdaten auf ihre Stimmigkeit überprüft. Der Vergleich der Systeme ergab wesentliche Vorteile des LDA, unter anderem die erhöhte Integrität der Daten, aerodynamische Vorteile sowie die vereinfachte Instandhaltung. Als Herausforderungen für die Einführung wurden asynchrone Datenraten und die Notwendigkeit angepasster Kalibrierungsverfahren identifiziert. Die Arbeit schlägt Lösungen vor, um die Zulassbarkeit des LDA zu ermöglichen, wie z. B. Methoden zur Einhaltung der Datenrate, überarbeitete Genauigkeitsanforderungen für TAS-Messungen und Integrationsstrategien.
Auf Grundlage der Analysen wurde die Anwendbarkeit der Zertifizierungsspezifikationen auf das LDA bewertet. Darüber hinaus wurden potenzielle Anpassungen für CS-25 vorgeschlagen, um die neuartigen Messprinzipien der Technologie zu berücksichtigen, ohne die Sicherheit zu beeinträchtigen.

Die Ergebnisse zeigen, dass die LDA-Technologie zwar vielversprechend für Sicherheit und Effizienz in der Luftfahrt ist, ihre Einführung jedoch durch Vorschriften erschwert wird, die konventionelle Technologien vorschreiben. Während eine Zertifizierung unter einer sogenannten *Special Condition (SC)* bereits möglich ist, werden fundamentalere Änderungen des Zertifizierungsrahmens vorgeschlagen.

Acknowledgements

I would like to thank **Oliver Kliebisch** and **Bastian Lüttig** for their guidance and the opportunity to undertake this work.

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Lastly, I want to express my heartfelt appreciation to my entire learning group, whose collaboration and shared enthusiasm made my studies both productive and enjoyable.

Contents

List of Figures

List of Tables

Glossary

ARINC 429	Two wire avionic data bus used on a lot of commercial and transport aircraft, suceeded by ARINC 664/AFDX bus
ARINC 664	Avionics Full Duplex Switched Ethernet; modern avionics bus based on ethernet technology
ARINC 738-3	Industry standard for Air Data and Inertial Reference Unit (ADIRU)
ARP4754B	Standard detailing processes used to develop civil aircraft and systems
ARP4761A	Guidelines for Conducting the Safety Assessment Process on Civil Aircraft, Systems and Equipment
AS8002B	Minimum Performance Standard (MPS) for Air Data Computers
CS-23	Certification Specifications (CSs) for Normal Category Aeroplanes
CS-25	CSs and Acceptable Means of Compliance for Large Aeroplanes
CS-Definitions	Definitions and abbreviations used in CSs for products, parts and appliances
CS-ETSO	CSs for European Technical Orders
Deviation	Type of Certification Review item; Used to amend the certification basis
DLR	German Aerospace Centre; German federal government space and aeronautical research agency
DO160G	Standard describing environmental conditions and test procedures for airborne equipment
ED-140A	Minimum Operational Performance Standard (MOPS) for Air Data Modules
Line of Sight velocity	Speed of an aerosol particle parallel to the lightbeam
Pitot-static system	Airspeed measurement probes currently used on commercial air transport aircraft
Rayleigh-Pitot Formula	Formula to calculate mach number from the relation of total pressure to static pressure in supersonic flow with one bow shockwave
SAE International	US-based standards organization, also publishing standards in the aerospace field; formally known as Society of Automotive Engineers (SAE)
Special Condition	Type of Certification Review item; amends certification basis with new requirements

List of Acronyms

ADC	Analogue to Digital Converter
ADIRS	Air Data and Inertial Reference System
ADIRU	Air Data Inertial Reference Unit
ADM	Air Data Module
ADR	Air Data Reference
AFDX	Avionics Full Duplex Switched Ethernet
AMC	Acceptable Means of Compliance
AoA	Angle of Attack
AoS	Angle of Sideslip
ARINC	Aeronautical Radio, Incorporated
ARP	Aerospace Recommended Practice
ASI	Airspeed Indicator
CAS	Calibrated Airspeed
CCA	Common Cause Analysis
CFD	Computational Fluid Dynamics
CRI	Certification Review Item
CS	Certification Specification
CS-ETSO	Certification Specifications for European Technical Standard Orders
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Centre)
EASA	European Union Aviation Safety Agency
ESF	Equivalent Safety Finding
EU	European Union
EUROCAE	European Organization for Civil Aviation Equipment
FAA	Federal Aviation Administration
FAME	Future Air Data System Module Evaluation
FCS	Flight Control System
FMEA	Failure Mode and Effects Analysis
FOD	Foreign Object Debris
FS	Full Scale
FuLDA	Future Laser Doppler Anemometer
GTE	Ground Test Equipment
IAS	Indicated Airspeed
ICAO	International Civil Aviation Organization
ILS	Institute for Aircraft Systems
IRS	Inertial Reference System
ISA	International Standard Atmosphere
LDA	Laser Doppler Anemometer
LOS	Line of Sight
LTAS	Local True Airspeed

MALE	Medium Altitude Long Endurance
MOC	Means of Compliance
MOPS	Minimum Operational Performance Standard
MPS	Minimum Performance Standard
MTBF	Mean Time Between Failure
MTOW	Maximum Take-off Weight
NASA	National Aeronautics and Space Administration
NESLIE	New Standby Lidar Instrument
OEM	Original Equipment Manufacturer
PRA	Particular Risks Analysis
RBC	Reliable Broadcast
RPAS	Remotely Piloted Aircraft System
RTCA	Radio Technical Commission for Aeronautics
SC	Special Condition
SSEC	Static Source Correction Error
TAS	True Air Speed
TAT	Total Air Temperature
TC	Type Certificate
UAV	Unmanned Aerial Vehicle
USA	United States of America
VIP	Very Important Person
ZSA	Zonal Safety Analysis

List of Symbols

Symbol	Description	Unit
A	Speed of Sound	$\mathrm{m\,s^{-1}}$
α	Angle of Attack	°
β	Angle of Sideslip	°
δ	Ratio of air pressure $\frac{p_s}{p_{a,SL}}$	-
f	Data Rate	Hz
f_D	Doppler shift frequency	Hz
f_p	Pressure Frequency	$\mathrm{s^{-1}}$
H_P	Pressure Altitude	m
k	Number of measurements	-
λ	Adiabatic index of air	K
M	Mach Number	-
Φ	Phase Lag	°
$P(k)$	Probability of k event	-
λ	Mean number of events in a given interval	-
p_d	Dynamic Pressure	Pa
$p_{s,ind}$	Indicated Static Pressure	Pa
$p_{a,SL}$	Pressure; standard atmosphere at sea-level	Pa
p_s	Static Pressure	Pa
p_t	Total Pressure	Pa
$p_{t,ind}$	Indicated Total Pressure	Pa
Q_C	Impact Pressure	Pa
R	Mass-specific gas constant of air	$\mathrm{J\,kg^{-1}\,K}$
r	Average rate of measurements	Hz
r	Recovery Ratio	-
ρ	Air Density	$\mathrm{kg\,m^{-3}}$
$\rho_{a,SL}$	Air density; standard atmosphere at sea-level	$\mathrm{kg\,m^{-3}}$
σ	Uncertainty	-
$\vec{v}_{ind}$	Local airflow vector	$\mathrm{m\,s^{-1}}$
T	Interval	s
θ	Ratio of temperature $\frac{T_S}{T_{a,SL}}$	-
T_S	Static Air Temperature	K
$T_{a,SL}$	Temperature; standard atmosphere at sea-level	K
T_T	Total Air Temperature	K
t	Lag Time	s
V	Airspeed	$\mathrm{m\,s^{-1}}$
V_1	Decision Speed	kt
V_2	Takeoff Safety Speed	kt
V_C	Calibrated Airspeed (CAS)	$\mathrm{m\,s^{-1}}$
V_{DF}	Demonstrated Flight Diving Speed	kt
V_{FE}	Maximum Flap Extended Speed	kt
V_{MO}	Maximum Operating Limit Airspeed	kt
V_{SR}	Reference Stall Speed	kt
V_T	True Airspeed (TAS)	$\mathrm{m\,s^{-1}}$
$\vec{v}$	Airflow vector	$\mathrm{m\,s^{-1}}$

1 Motivation and Objective

> "In aviation, even the most innovative idea or product is useless, unless the rules allow its installation or use. [. . .] Rules need to foster innovation without compromising existing levels of safety" [1]

This quote from a recent publication of the European Union Aviation Safety Agency (EASA), documenting its stance on new technologies and business models in aviation sums up a core conflict of interests in aviation regulation. On the one hand the aviation industry is focused on safety and is therefore conservative towards the introduction of emerging technologies. The tragic accidents of the de Havilland Comet in the 1950s illustrate how innovation can outpace regulation which in turn affects safety. As the first commercial jetliner with a pressurized cabin, it suffered two catastrophic structural failures linked to fatigue around its square windows [2, p.36]. In response, regulators introduced stricter design and testing requirements, such as fail-safe design principles, which continue to shape today's certification framework [3]. The accidents stand as examples of innovation outpacing regulation and influenced the reluctance of today's certification landscape. This approach has contributed to today's high levels of aviation safety.

However, because the certification framework has been growing mostly reactionary to accidents and safety incidents such as this one, it tends to lag behind innovations, often mandating explicitly or implicitly the use of established technologies. For example, certain requirements in versions of the Certification Specifications (CSs) for Normal Category Aeroplanes (CS-23) restricted an aeroplane in this category to either have a reciprocating engine or a turbine, thus inherently ruling out electric aircraft from certification without special provisions [4, p.11], [5, p.1359], [6]. By complicating the certification process these restrictions majorly disincentivized the development of electric aircraft [4, p.14].

This problem is known by the regulators and limited steps are taken to react to it. For example in 2017 the CSs mentioned above were entirely rewritten in order to describe safety-objective based goals rather than specific technological solutions [1]. However, other pieces of legislation may still feature the same issues.

Similar challenges as for the introduction of electric engines may now be faced in the field of air data acquisition for large aircraft. Existing aeroplanes use Pitot-static systems and measurement vanes to measure the airspeed and the flow angles. These instruments have been the standard since the beginning of fixed-wing aviation [7]. Therefore, standards and requirements may be very narrowly focused on this type of system and the introduction of new technology may be complicated.

One such development that may replace the conventional instruments is the Laser Doppler Anemometer (LDA). It measures True Air Speed (TAS), Angle of Attack (AoA) and Angle of Sideslip (AoS) and determines the uncertainty of this data without disturbing the airflow. The testing of LDA technology onboard aircraft has been ongoing since 1971 when such a system was first flown on a NASA Convair 990 research aircraft [8].

Since then, a lot of projects have tried, developed and evaluated LDA systems for use on aircraft. For example, research into this field was conducted in the Netherlands with the New Standby Lidar Instrument (NESLIE) project in 2009. The team developed an instrument and tested it in flight. The project showed that such a system could be developed and calibrated for use on aircraft [9].

In the European Union (EU) AIM2 project in 2016, a French team evaluated the use of a LDA for flight test certification. The tests identified a very good agreement of the measured parameters with the data from a reference instrument [10].

Since 2019, a LDA is being developed at the Institute of Technical Physics at the Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Centre) (DLR) in a broader effort to advance optical air data technology. In spring and autumn of 2022, two test flight campaigns were conducted, proving the general applicability of the design as an airspeed and flow angle measurement instrument. The recorded data was analysed and measures to improve the design were identified which are used to design the next iteration [11, p.241].
A preceding master thesis by M. Lichtl focused on the preliminary safety analysis of the LDA. While also listing certification requirements, no deeper analysis on their intentions and applicability was performed [12].

Structure and Objective of this work

This work will build on the afore mentioned thesis. It should analyse the certification requirements applying to a LDA like the one developed at the DLR. This should highlight problems and challenges for certification either due to the design of the system or because of prescriptive regulation and regulatory lag as described above. Analysing this will give insight into how regulation may be changed to accommodate the new technology without sacrificing safety and lower the uncertainties for further development and eventual introduction of the technology into service on large aircraft.
To achieve this, regulatory documents and industry standards are reviewed to extract and compare relevant requirements against the LDAs capabilities and operational characteristics. The analysis evaluates both the benefits and the risks associated with adopting the LDA in aviation. Based on these findings, proposals are developed to adapt the regulatory framework, thereby supporting the introduction of this novel technology into civil aviation.

Chapter 2 begins by establishing the fundamentals, describing the certification process for large aircraft as well as the standards governing airspeed and flow angle sensors. It introduces the functional principles of conventional sensors alongside an explanation of LDA technology and details its current development status. Chapter 3 focuses on CS-25 requirements, particularly CS 25.1323 (airspeed indicating systems), and their Acceptable Means of Compliance (AMC). In Chapter 4 the performance demands on these systems are characterized by analysing industry standards and the physical limitations of conventional sensors. The performance metrics of the LDA are directly compared to those of traditional systems in Chapter 5 and advantages as well as risks and challenges for the introduction of LDA technology are identified. Chapter 6 proposes risk mitigation strategies and explores integration scenarios, illustrating how the LDA could be incrementally adopted to maximize its benefits while addressing regulatory hurdles. Chapter 7 discusses these strategies in depth and formulates specific proposals to adapt certification requirements for the LDA. Finally, Chapter 8 concludes with a summary of findings and an outlook on next steps, including further research and regulatory collaboration.

2 Fundamentals

This chapter outlines the fundamentals relevant to subsequent analyses. It begins by describing the standard development process for aircraft, including the stakeholders involved, relevant documents and standards. The validity, structure, and applicability of these elements are also discussed. Additionally, the chapter provides a brief overview of the aircraft development process and explores methods for amending the certification basis. Following this, a section is dedicated to the airspeed and flow-angle measurement devices and methods currently used in aircraft. Finally, the working principle and current state of development of Laser Doppler Anemometer (LDA) technology are explained.

2.1 Fundamentals of Aircraft Development and Certification

The development of large aircraft is highly cost- and time-intensive. Consequently, these machines are developed by Original Equipment Manufacturers (OEMs), which are large multinational companies with decades of expertise and substantial capital. OEMs are responsible for developing and certifying the aircraft, but they often delegate the development of specific components, such as the airspeed indicating system, to trusted suppliers. This approach leverages the supplier's specialized expertise and helps distribute risk. However, the introduction and certification of new technologies remain under the purview of the OEMs, in close coordination with the European Union Aviation Safety Agency (EASA). EASA is the authority responsible for aviation safety in the European Union (EU) and several surrounding states. It implements rules concerning certification and continuing airworthiness. Its counterpart in the United States of America (USA) is the Federal Aviation Administration (FAA). Both agencies coordinate on most regulations. The phases of the certification process, as well as the relevant documents, will be further specified below.

2.1.1 Certification Process

The certification process is based on regulation set by the European Parliament and the Council of Europe [13]. It is designed as a "two pillar approach", the two pillars being the aircraft manufacturer (OEM) which must be a Part 21 certified design organization and EASA. Both parties are in constant dialogue during the whole process.

The goal of each aircraft development is to produce documentation on construction, manufacturing, operation, maintenance, and repair of the aircraft. The documentation and its creation are reviewed by the manufacturer and EASA. If it (and therefore the corresponding aircraft) is in compliance with all certifications and national standards, EASA issues a *Type Certificate (TC)* [14, pp.25-28] thereby certifying the serial production of the model. Each individual aeroplane has to be certified once more to assure that it complies with the type certificate. This document is known as the airworthiness certificate.

The type certification process itself is segmented into three stages [15]:

First, the technical familiarization and certification basis are defined. This includes Certification Specifications (CSs) (see Section 2.1.2) and in case features are not covered, Certification Review Items (CRIs) (see Section 2.1.3). They both define requirements for the design. The certification basis is not updated to its newest version for five years to allow steady regulation for the certification process.

Then, Means of Compliance (MOC) are determined. They describe how each fulfilment of a requirement will be demonstrated.

The MOC are then demonstrated, for example in flight and ground tests or by analysis/engineering review. Finally, EASA completes its assessment and issues a TC [15].

2.1.2 Documents and Standards

The following paragraph details documents and standards either set by EASA in coordination with the OEM and its suppliers or independently developed by the industry.

Certification Specifications

Since this thesis is limited to large aircraft, the CSs and Acceptable Means of Compliance for Large Aeroplanes (CS-25) apply. Its newest version at the time of writing is Amendment 28. They are applicable on turbine powered large aeroplanes with a Maximum Take-off Weight (MTOW) of more than 5700 kg [16, CS 25.1], [17].
CS-25 is structured into subparts which focus on different aspects of the aeroplane (e.g. flight, structure, powerplant). Requirements are identified with Airworthiness Codes and sometimes amended by Acceptable Means of Compliance (AMC) [14, pp.22-25]. This work focuses heavily on Section F "Equipment" and in particular on CS 25.1323 "Airspeed Indicating System".

The Certification Specifications for European Technical Standard Orders (CS-ETSO) set requirements for the certification of individual components outside a specific aircraft type. Therefore, the certification is not self-reliant. Certified components must still be approved under CS-25 when they are installed in the aircraft, but some compliance can be attributed and the certification process can be shortened. This makes this certification method ideal for equipment to be installed in multiple aircraft types. CS-ETSO is divided into two subparts. Subpart A sets applicability and requirements on environmental conditions and subpart B lists equipment types such as the Air Data Computer under ETSO-C106a [14, pp.24-25]. For this thesis amendment 17 was used as it was the newest at the time of writing [18].

Amendment 2 of the Definitions and abbreviations used in CSs for products, parts and appliances (CS-Definitions) clarifies abbreviations and special terms used in the other CSs [17].
The AMC often rely on standards issued by non-government bodies such as SAE International, European Organization for Civil Aviation Equipment (EUROCAE) or Radio Technical Commission for Aeronautics (RTCA) which will be presented in the following paragraph.

Industry Standards

Aerospace Recommended Practice (ARP) 4754B "Guidelines for Development of Civil Aircraft Systems" is a standard issued by SAE International. It defines processes to ensure the safety of the overall aircraft design by specifying methods on how to show compliance with regulations and how a company can develop its own standards [19].
DO-160G "Environmental Conditions and Tests Procedures for Airborne Equipment" specifies the environmental conditions hardware designed for use on aircraft has to endure as well as the associated tests to show compliance. What tests equipment has to perform is defined in the Minimum Performance Standard (MPS) and Minimum Operational Performance Standard (MOPS) [20].
One of these is AS8002B titled "Air Data Computer Minimum Performance Standard". It is the applicable standard for certification of Air Data Computer under ETSO-C160a. The document defines tests, output labels, accuracy, and other performance figures for subsonic aircraft [21].
ED-140A describes the same for Air Data Modules [22].
Aeronautical Radio, Incorporated (ARINC) 738-3 is an industry standard detailing characteristics

of integrated digital Air Data and Inertial Reference System (ADIRS). In the context of this work only the air data reference side is important for which the standard details minimum performance figures of inputs and outputs [23].

2.1.3 Certification Review Item (CRI)

As already mentioned in Section 2.1.1, if the existing certification basis (consisting of CSs and linked standards) is not sufficient it can be amended by a CRI. This might be because of a new design not covered by requirements or means of compliance or because of newly identified safety concerns not addressed by regulation. The initiative to amend the certification base can come both from the design organization or the regulator (EASA). There are four types:

The *Special Condition (SC)* is the most comprehensive type. It is used in case of:

- novel and unusual design features
- unconventional use of a design
- newly identified hazards (either from a new design or from similar products with similar design features in service)

These conditions lead to new requirements that can be defined in a Special Condition[24], [25].

If literal compliance with an applicable specification cannot be achieved an *Equivalent Safety Finding (ESF)* is used. It details how the safety aim of a requirement can be met by adding alternative requirements to the CSs or dedicated characteristics of design and procedures. The goal of this record is to ensure an equivalent level of safety to the existing requirement. [25].

The *Deviation* is used if a design does neither literally nor with its intent complies with a CS or a Special Condition. In this case mitigating factors have to be set up such as inspections, limits to flight hours or operational/airworthiness limits to ensure the design meets the same level of safety as normally guaranteed by the CS or SCs. Since this is the most elaborate of all amendments and linked with the most risks it should only be proposed in as an exception [25].

Means of Compliance (MOC) are most commonly used. As mentioned in Section 2.1.1 they specify how compliance with the CSs, SCs, ESFs, or Deviations can be demonstrated. If AMC are already present to amend the CS, there is usually no need for additional MOC [25].

2.2 State-of-the-Art Air Data Measurement

In the following paragraph methods and instruments currently used on aircraft to measure airspeed and flow angles will be described. Then, integration of the airspeed indicating system into current aircraft will be explained.

2.2.1 Operational Principle of Pitot-Static Systems

Pitot-static systems are currently used to measure airspeed on commercial transport aircraft while vanes are used for flow angle measurement. The Pitot-static system uses pressure measurements to calculate the speed of the aircraft. It consists of probes and the corresponding sensors. The operational principle on how to measure airspeed from pressure is explained first, followed by a description of probes and sensors. Finally, flow angle measurements are explained.

Measuring Speed from Pressure

Airspeed can't be measured directly using pressure based techniques [26]. Therefore, total pressure p_t and static pressure p_s are measured to calculate dynamic pressure p_d. Their relation is the following:

$$p_t = p_s + p_d \tag{2.1}$$

p_d can also be called impact pressure Q_C. Using Bernoulli's principle and assuming constant air density ρ (incompressible flow) the airspeed V can be calculated as:

$$Q_C = p_t - p_s = \frac{\rho}{2} V^2 \tag{2.2}$$

The earlier assumption that air density remains constant is only valid to an airspeed of around $V < 250\,\mathrm{kt}$ or a Mach number of $M < 0.3$. At this point compressibility effects of the air becomes too high to neglect - a correction for compressibility is needed [27, pp.19-21], [28, pp.655-656].

In subsonic flow this is done under the assumption of isentropic flow with the total pressure relation:

$$\frac{p_t}{p_s} = (1 + 0.2M^2)^{3,5} \tag{2.3}$$

The Mach number M defined as:

$$M = \frac{V}{A} \tag{2.4}$$

The speed of sound A can be calculated with the static air temperature T_S as:

$$A = \sqrt{\lambda R T_S} \tag{2.5}$$

This results in the following equation for calculating airspeed V from impact pressure Q_C in compressible, subsonic flow [29, p.247]:

$$Q_C = p_s \cdot [(1 + 0.2\frac{V^2}{A^2})^{3.5} - 1] \tag{2.6}$$

In supersonic environments the flow passes through a shockwave before it enters the pressure orifices resulting in a loss of total pressure. This is accounted for by the Rayleigh-Pitot Formula [29, p.247]:

$$Q_C = p_s \left[\frac{166.92 \left(\frac{V}{A}\right)^7}{\left[7\left(\frac{V}{A}\right)^2 - 1\right]^{2.5}} - 1 \right]. \tag{2.7}$$

Pressure Probes

The Pitot tube itself was invented in 1732 by Henri Pitot in Paris to measure the flow velocity of the river Seine [31, p.363] and was improved to its current state by Henry Darcy in 1858 [32]. The tube is oriented parallel to the airflow and measures the total pressure p_t. Its internals can be seen in Fig. 2.1. In addition to the pressure orifices and tubes the Pitot tube features a heating element to prevent icing and rain and a drain hole to allow rain and/or moisture to leave the system.

The static pressure orifice is situated perpendicular to the incoming airflow.

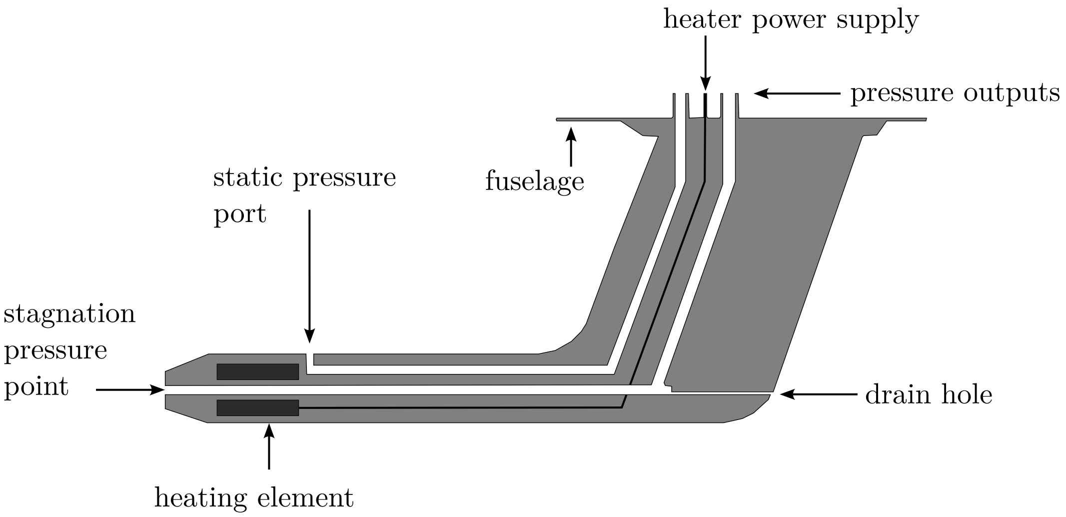

Figure 2.1: Internals of a Pitot-static tube/Prandtl tube; schematic derived from [30, Fig. 4]

There are several configurations of Pitot-static systems. There is the Pitot-static tube, also known as Prandtl-Tube which measures both static pressure and total pressure at the probe [28, pp.650-651].
Static pressure orifice and Pitot probe can also be separated. Some aeroplanes have their static pressure orifices located on the fuselage and both pressures are transduced independently into analogue or digital readings by pressure sensors [26, p.3].
Then there is the integrated air data transducer which is used on the Airbus A380. In this case, the Pitot tube is combined with the Angle of Attack (AoA) flow vane (as explained in Section 2.2.2) [29, p.119]. The entire Pitot tube may also be rotating with the incoming airflow to allow airspeed measurements at high AoA (see Section 4.1.2).

Figure 2.2: Integrated air data transducer on the copilot side of an Airbus A380 [33]

Pressure Sensors

Pressure sensors are connected to the Pitot tube via air hoses. They are subject to high environmental requirements. Two types of sensors are mainly used in aviation [29, pp.250-251].
Vibrating pressure sensors use the change of resonant frequency of an oscillating mechanical system. This frequency can be easily measured and turned into a digital signal. Since the sensor does not have any moving parts it is very reliable.

The other sensor technology are solid state capsule pressure sensors. They are made up of a capsule with a thin diaphragm made out of silicon, quartz or special ceramics. The diaphragm deflects linearly under the input pressure. Internal strain gauges allow the pressure to be measured by sensing their resistance. For these sensors, analogue to digital conversion is more complicated. They are also sensitive to acceleration, as the diaphragm can deflect as a result. The elasticity change must also be compensated by continuously measuring the internal temperature [29, pp.250-251].

2.2.2 Operational Principle of Angle of Attack/Sideslip Measurement Systems

There are several types of sensors to measure the flow angles, but mechanical vanes are most commonly used in commercial aviation. They are comprised of a small, pivoted vane installed with low fiction bearings that can rotate in the direction of the incoming airflow. Potentiometers or synchro resolvers are used as angle transducers [26, p.6]. As already mentioned in Section 2.2.1 they can also be combined with the Pitot probe [28, pp.651-652], [29, pp.256-257]. Most aircraft only have a sensor for the AoA and the Angle of Sideslip (AoS) is indirectly measured. Only some aircraft like the Airbus A380 or some fighter jets have a dedicated sensor for AoS measurement [28, p.651].

2.2.3 Integration

The following section should give an overview over how the sensors and probes described above are integrated in the aircraft. This covers both the physical integration of the sensors and how the provided data is processed. Since the systems differ over different aeroplane manufacturers and models the Air Data Reference (ADR) system of the Airbus A320-Family will be used as an example.

Air Data Architecture

A system overview can be seen in Fig. 2.3. There are three Pitot probes, six static ports, three AoA sensors and two total air temperature probes.
The Pitot tubes are installed on the side of the fuselage and connected via tubing to an Air Data Module (ADM) which encases the pressure sensors. The data is sent via ARINC 429 bus to the Air Data Inertial Reference Unit (ADIRU). This computer combines air reference data with inertial reference data and processes and outputs it to various other subsystems. The air data system is set up in three redundant subsystems. Two systems supply data respectively to the pilot and copilot while the third one acts as a backup system. Its tubing is also directly connected to the backup Airspeed Indicator (ASI). All systems can supply their data to three Air Data Inertial Reference Units (ADIRUs). The data is not voted, only the flight crew can switch which data is displayed on their monitors. [34].

Processing of Air Data

As already established in Section 2.2.1, historically speed was not corrected for compressibility effects. Additionally, errors were not accounted for by the instrument. This was caused by the use of simple, mechanical instruments. The associated, measured speed is known as Indicated Airspeed (IAS). In modern large transport aircraft it is only displayed by the backup instrument.

With the advent of air data computers the correction of compressibility effects and error compensation became possible. Furthermore, airspeed was normalized to standard atmosphere

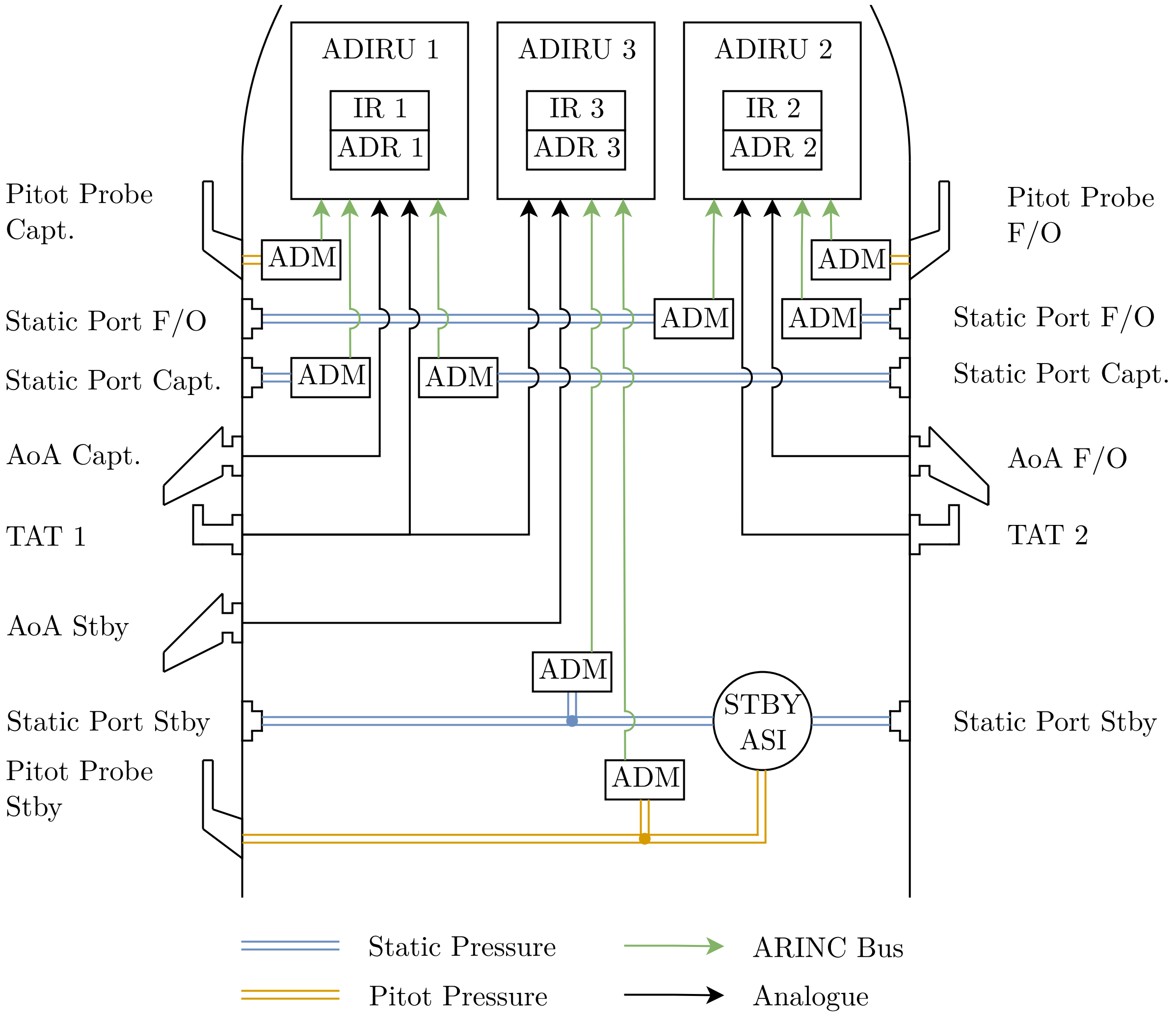

Figure 2.3: Schematics of air data systems structure in an Airbus A320; derived from [34]

at sea level. This airspeed definition is called the Calibrated Airspeed (CAS) V_C. Compared to the True Air Speed (TAS) calculated with Eq. (2.6), CAS is always referenced to the same air density $\rho_{a,SL}$. Since lift and drag are proportional to the density, pilots do not have to recalculate airspeed for every atmospheric condition and height. For example landing speeds can be defined as a constant. The downside of this speed definition is that it does not reveal the actual airspeed of the aircraft. This is why TAS is calculated and mainly used for navigational purposes [29, pp.237-240].

The process of airspeed calculation in modern aircraft is displayed in Fig. 2.4. In an Airbus A320 all these calculations are done by the ADIRU.
It begins with the measurement of the indicated static pressure $p_{s,ind}$, the indicated total pressure $p_{t,ind}$, Total Air Temperature (TAT) T_T and the AoA α. The measurements are compensated for errors using calibration data stored in look-up tables dependent on altitude and Mach number. Then, CAS is calculated by first determining impact pressure Q_C with Eq. (2.2). CAS can be computed by solving the following equation for V_C.

$$Q_C = p_{a,SL}\left\{\left[1 + 0.2\left(\frac{V_C}{A_0}\right)^2\right]^{3.5} - 1\right\} \tag{2.8}$$

To get the TAS, the Mach number is calculated via Eq. (2.4) using static air temperature T_S

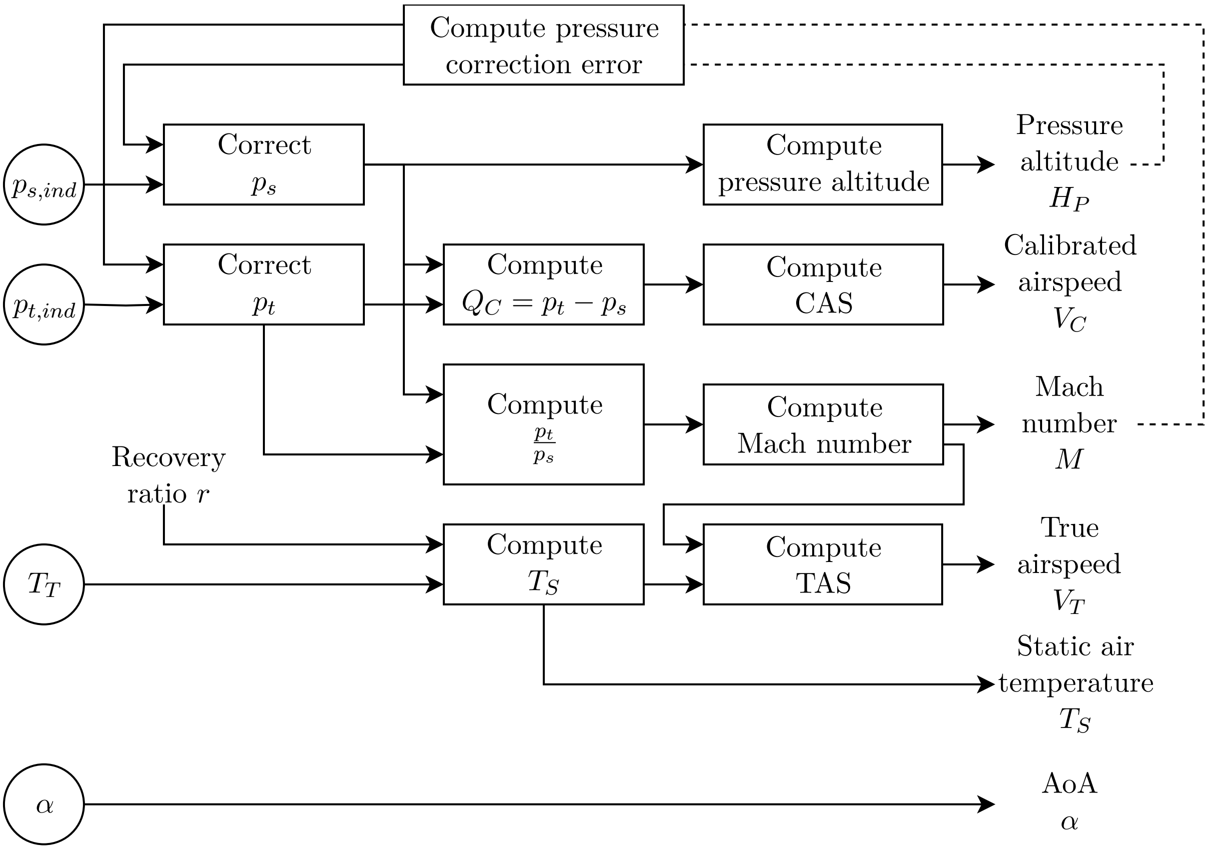

Figure 2.4: Calculation process for air data; derived from [29, Fig. 7.15]

[29, p.248]. TAS V_T is computed by applying:

$$V_T = M \cdot \sqrt{\kappa R T_S} \tag{2.9}$$

2.3 Laser Doppler Anemometer

The LDA is an optical instrument used to measure the airflow vector, in effect the airspeed and direction. To better understand the characteristics of the LDA technology its functional principle and the current state of development will be explained in the following passage. Several implementations of the LDA technique exist. This work limits its scope to a specific implementation which is referred to as homo- or heterodyne LDA.

2.3.1 Operational Principle

The instrument is typically separated into a section where the laser source, an interferometer, and the electronics for signal processing are located. The other part, also called *transceiver*, is an optical element which is installed at a viewport on the fuselage. Its purpose is to image the laser light into the surrounding flow.

The working principle of a LDA with one channel is displayed in Fig. 2.5. A fibre laser source produces laser light with a wavelength of $\lambda = 1550\,\text{nm}$. It is then split into a local oscillator and a main beam. The latter is relayed via fibre optic cables to the optical part, which focuses it into the airflow surrounding the aircraft. There, the light is scattered by aerosol particles which are following the streamlines of the airflow. Because of the relative motion between the aircraft and the particles, the Doppler effect causes a frequency shift f_D. The scattered

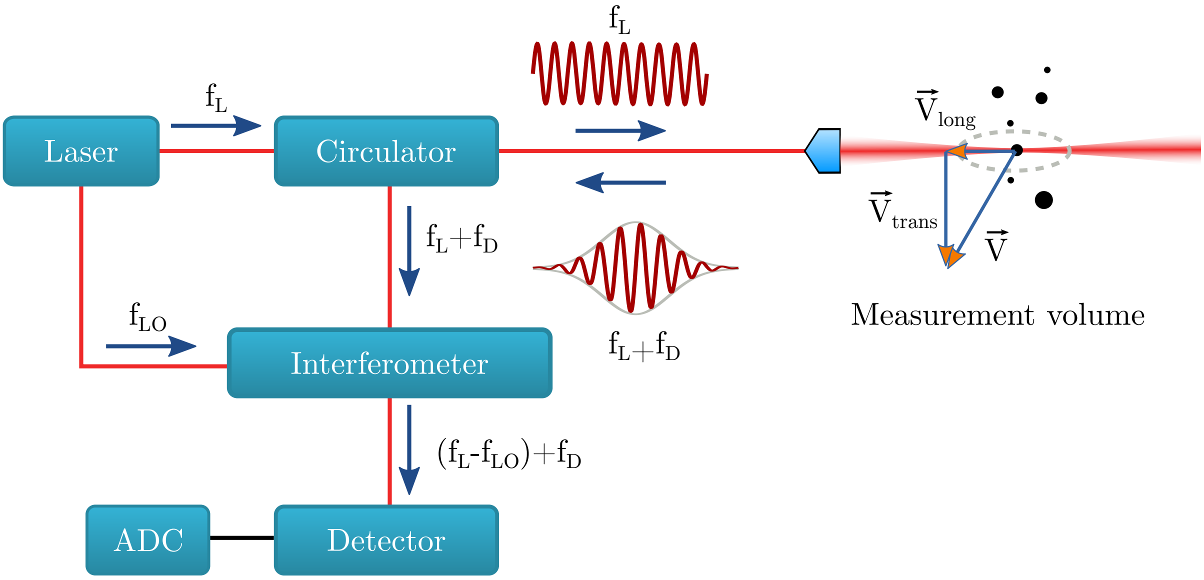

Figure 2.5: Functional principle of a single channel reference-beam LDA [11, Fig. 1]

light with the frequency $f_L + f_D$ is collected by the lens and continues via fibre optic cables to an interferometer, which allows direct measurement of the frequency shift f_D using the local oscillator signal. The interferometer can operate with homodyne and heterodyne measurements. For more information on these modes consult [35], [36]. The extracted frequency f_D is detected and digitized to be further processed [11].

The Line of Sight (LOS) velocity characterizes the projected speed of aerosol particles parallel to the light beam [35, p.8]. With one laser channel as explained above and the interferometer in homodyne mode, only the magnitude of the Line of Sight velocity can be calculated as:

$$v_{LOS} = \left| \frac{\lambda}{2 \cdot f_D} \right| \tag{2.10}$$

If the interferometer measures in heterodyne mode the sign of the velocity can be measured which results in:

$$v_{LOS} = -\frac{\lambda}{2 \cdot f_D} \tag{2.11}$$

To get a full airflow vector $\vec{v}$, the concept is expanded to four channels with the same structure as above but with every light beam angled into a different direction. Three LOS channels allow the construction a determined set of equations that allows for the reconstruction of the flow vector. Four channels allow the use of a Moore-Penrose Inversion which leads to the airflow vector $\vec{v}$ but also the uncertainty σ of each measurement [36].

Further processing finally results in the following parameters output by the LDA:

- True Air Speed (TAS) V_T
- Angle of Attack (AoA) α
- Angle of Sideslip (AoS) β
- uncertainty σ.

2.3.2 State of Technology

Since 2019, the Institute for Technical Physics at Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Centre) (DLR) has been developing its own LDA in a broader effort to advance optical air data measurement. The Future Air Data System Module Evaluation (FAME) project focused on establishing a proof of concept with weight, size, and performance as a lesser concern. The project used one laser source for all four channels as well as four individual optics. These can be seen in Fig. 2.7 as well as the heating elements situated between them. Flight testing on the DLR Dassault Falcon 20E research aircraft began in April 2022 with a campaign over southern Germany and continued in October 2022 in the skies over northern Germany. During flight, airspeed, AoA and AoS were recorded in different altitudes, climates and at different speeds and manoeuvres. Fig. 2.6 shows the instrument installed on the aircraft ready for the tests. After the campaign, this data could be compared to reference values measured at the nose boom of the aircraft via a five hole probe. The campaigns showed "strong correlation between the LDA values and a nose boom sensor [installed on the aircraft]" [11, p.241].

A successor is currently being developed under the name *Future Laser Doppler Anemometer (FuLDA)*. Each channel will have its own laser source and all channels will be combined in one optic. The main goal is the development of a system with a higher performance and integration by applying lessons learned from the prior campaigns. A lower size and weight are secondary objectives. At the time of writing the project is in the process of system integration.

Figure 2.6: LDA Optics installed in the DLR Dassault Falcon 20E research aircraft [37]

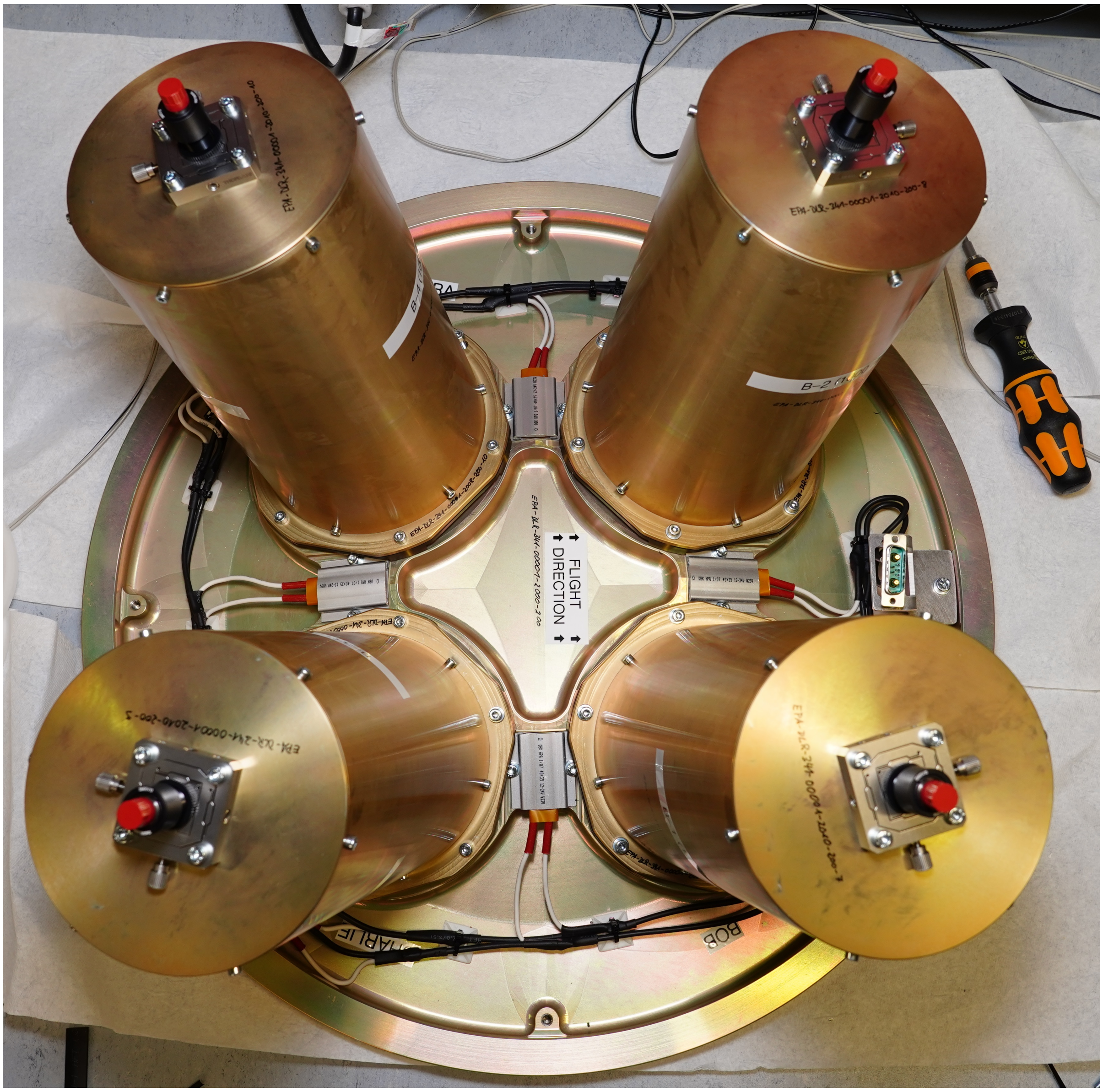

Figure 2.7: Optical element of the LDA; the optics for all for channels as well as the heaters between them can be seen [37]

3 Assessment of CS-25

As established in Section 2.1.2, CS-25 sets requirements for the certification of large aircraft. This chapter describes relevant requirements to the proposed functions of the LDA. First, the range of this document regarding aircraft categories is explored. Next, regulatory requirements in the CSs for equipment with the functions of the LDA (airspeed and flow angle measurement) are described. No requirements covering the measurement of the flow angles were found, only requirements describing its use (for example for control systems [16, CS 25.672]). Therefore, except for CS 25.1309 (see Section 3.2), only sections that explicitly deal with the airspeed indicating system will be presented. This excludes requirements that transcend the technical differences between conventional systems and LDA technology such as demands on power supply.

3.1 Overview of Applicable Aircraft Categories

CS-25 deals with large turbine powered aeroplanes with a MTOW above 5700 kg [16, CS 25.1], [17]. The applicable aircraft are separated from smaller models by the commuter aircraft category covered by CS-23. Aeroplanes with less than 19 seats and less than 8618 kg MTOW fall in this category and can be certified under these generally less strict specifications [38, CS 23.2005], [17].
A general overview over applicable aircraft categories together with attributes describing the primary concern for airspeed and flow angle indicating systems in each category can be seen in Fig. 3.1.
Civilian aircraft can be separated into commercial transport aircraft, business jets and aircraft with special roles. In civilian aircraft design, safety remains the paramount concern, with cost representing the next most significant consideration. Commercial transport aircraft, whether for cargo or passenger transport, are separated by their range. Examples for aircraft covered by this category are the Airbus A220, the Airbus A320-Family or the Airbus A350. Only the biggest business jets are covered by CS-25. Types include the Gulfstream G550 or the Dassault 8X. Special roles mean the use of civilian aircraft for example for research, firefighting or Very Important Person (VIP) transport. In these roles special requirements may arise for example firefighting aircraft fly highly dynamic flight manoeuvres normally outside the flight envelope of civilian aircraft. Government aircraft may include features to further increase the safety of personnel.

CS-25 is originally only intended for civil aviation. However, military aircraft developments often use the civil certification basis since they mostly share their airspace with civil aviation and the same basic design requirements. For example the Airbus A400M got a Type Certificate (TC) by EASA and therefore was certified in accordance with CS-25 [39]. Furthermore, Eurodrone, a European Medium Altitude Long Endurance (MALE) Remotely Piloted Aircraft System (RPAS) currently in development will be compliant with CS-25 [40]. Military aircraft can be sorted in transport, fighter, bomber, and surveillance aircraft according to their roles. Strategic transport aircraft assure logistics over long distances and primarily have the same flight profiles as commercial transport aircraft. Tactical transport aircraft focus on directly supplying the military theatre like landing at bases, dropping cargo or performing air-to-air refuelling. Therefore, they have a much more demanding flight envelope with high and quickly changing airspeed and AoA. The category includes the afore mentioned Airbus A400M or the Lockheed C-130. Fighters generally have the most demanding flight profiles with extreme speeds and flight states, especially air superiority fighters. Together with Unmanned Aerial Vehicle (UAV) and bomber aircraft they often rely on stealth properties to conceal themselves from enemy radar.

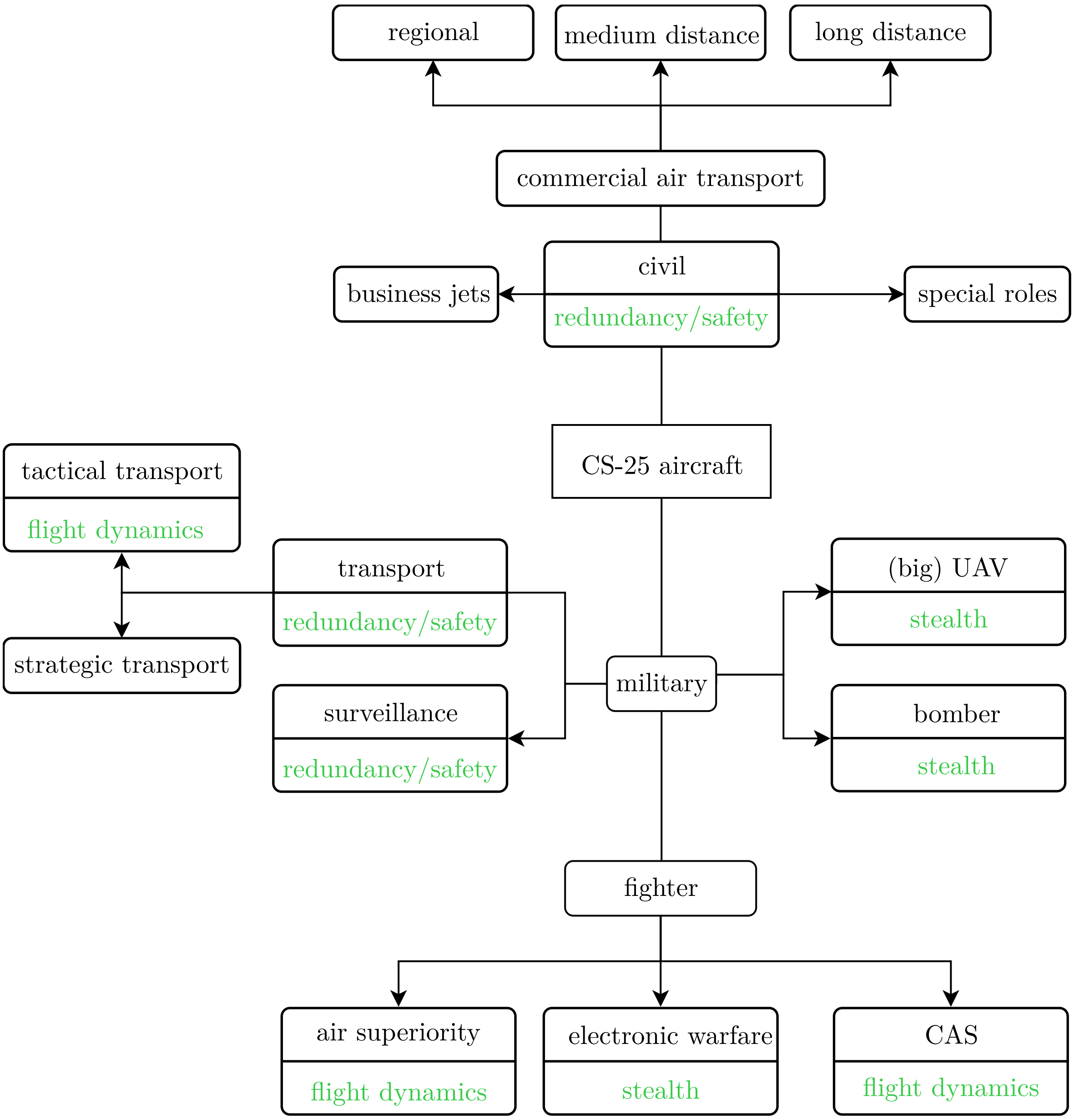

Figure 3.1: Overview of aircraft categories either directly or implicitly covered by CS-25; Key attributes and requirements for airspeed indication instruments in each category are marked in green

3.2 General Requirements on System Design and Analysis (CS 25.1309)

This requirement describes basic safety guidelines for all equipment installed in the aeroplane focusing on failure conditions of equipment.
Systems must be designed to endure environmental and aeroplane operating conditions. The connected AMC reference DO160G and thus environmental tests specified by this standard and the MPS/MOPS.
Furthermore, when equipment is designed the safety impacts of its operation and failure must be analysed for severity and the corresponding probabilities respected. Severity is classified according to Table 3.1.

Table 3.1: Classification of failure conditions and corresponding severity

Classification of Failure Conditions	Severity
No Safety Effect	No effect on aeroplane No effect on operational capabilities or safety Inconvenience
Minor	Slight reduction in functional capabilities or safety margins Slight increase in workload Physical discomfort
Major	Significant reduction in functional capabilities or safety margins Physical distress Possibly including injuries Significant increase in workload
Hazardous	Large reduction in functional capabilities or safety margins Serious or fatal injury to a few passengers or cabin crew Physical distress/excessive workload impairs ability to perform tasks
Catastrophic	Normally with hull loss Multiple fatalities

The probabilities of failure conditions are categorized in:

• Extremely improbable	$10 \times 10^{-9}\,\mathrm{h}^{-1}$
• Extremely Remote	$10 \times 10^{-7}\,\mathrm{h}^{-1}$
• Remote	$10 \times 10^{-5}\,\mathrm{h}^{-1}$
• Probable	$10 \times 10^{-3}\,\mathrm{h}^{-1}$
• Frequent	$10 \times 10^{-3}\,\mathrm{h}^{-1}$.

The severity and probability are linked according to Fig. 3.2. This means, the failure rate and severity must be in the “acceptable” region. There are some exceptions and special provisions to this. For more information on these, the original requirement in CS-25 should be consulted [16, CS 25.1309].
The corresponding AMC also link to methods on how to analyse systems and equipment on failure conditions, their severity as well as the probability. They are detailed in ARP4754B and ARP4761A. This includes processes such as Failure Mode and Effects Analysis (FMEA), Particular Risks Analysis (PRA), Common Cause Analysis (CCA) and Zonal Safety Analysis (ZSA). An analysis like this was already done for the LDA in an early state of development in

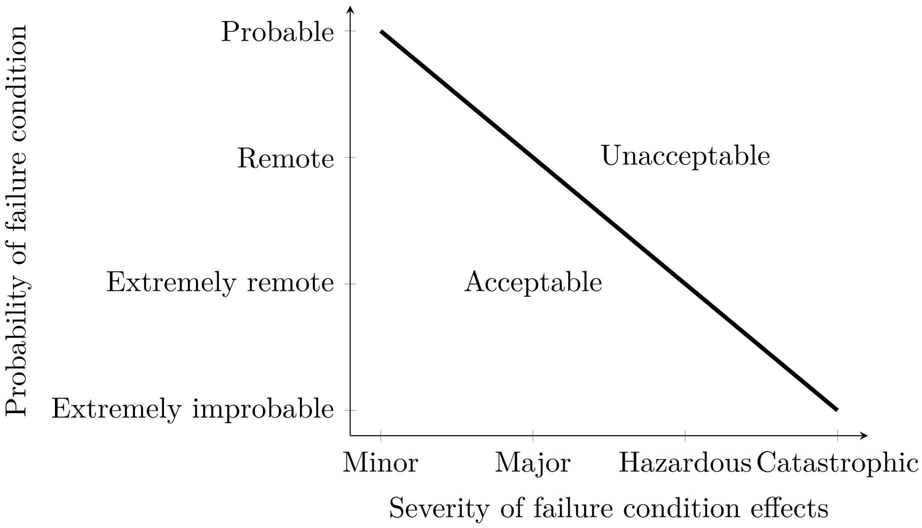

Figure 3.2: Relationship between probability and severity of failure condition effects [16, AMC 25.1309]

the master's thesis proceeding this work [12]. Additionally, three more requirements should be mentioned:

- Indications of unsafe system operating conditions must be provided to the flight crew
- All electrical wiring must be handled according to the requirements detailed in subpart H
- Maintenance procedures for the equipment have to be documented.

3.3 Assessment of Relevant Requirements for Airspeed Indicating Systems

CS 25.1323 is titled "Airspeed Indicating System" and lists requirements for such systems. It is applicable to the whole system including the (displaying) instrument as well as probes, sensors, and computers. CS 25.1324 and CS 25.1326 concern the prevention of icing on the probes [16]. All requirements are summarized in Table 3.2.

The first requirement states that the airspeed indicating instrument must be calibrated to show TAS at sea level and standard atmosphere conditions when total and static pressure are applied. This requirement is only applicable on the (displaying) instrument itself, not on the entire system [16, CS 25.1323(a)].

Furthermore, the system must be calibrated to determine the so-called system error. CS-25 defines it as the relation between IAS and CAS. The requirement is applicable in flight and during the accelerated takeoff ground run. On the ground the calibration must be performed at an airspeed from 0.8 times the decision speed V_1 to the maximum takeoff safety speed V_2 under approved ranges of altitude and weight. The required accuracy must be also reached during a critical engine failure at the minimum value of V_1 with specific configurations for wing flaps and power settings as per CS 25.111 [16, CS 25.1323(b)].

The *ground truth* airspeed error (excluding the instrument error) i.e. the error derived by comparison to a calibrated reference sensor should not be greater than 3 % of the airspeed or

5 kt, whichever is greater [16, CS 25.1323(c)]. This definition is valid in a speed range from

- V_{MO} to 1.23 V_{SR} with wing flaps retracted
- 1.23 V_{SR} to V_{FE} with wing flaps in landing position.

IAS must change perceptibly with CAS in the same sense from

- 1.23 V_{SR} to the speed at which stall warning begins
- V_{MO} to $V_{MO} + \frac{2}{3}\left(V_{DF} - V_{MO}\right)$

Below the stall warning speed V_{MO} and at higher speeds up to the demonstrated flight diving speed V_{DF}, IAS must not change in the wrong sense. The corresponding AMC define an acceptable rate of change of IAS to CAS [16, CS 25.1323(d) & (e)].

There must be no conflicting and misleading indications during takeoff from initiation of rotation to achieving a steady climb and the airspeed indicating lag must not lead to significant errors in the calculation of takeoff and stopping distances [16, CS 25.1323(f) & (g)].

The system must be arranged to prevent malfunction and entry of moisture, dirt or other substances. The applicable AMC concretise that the possibility of a moisture blockage must be kept at an acceptable minimum. The system's design and installation should ensure positive drainage of moisture and avoid chafing of tubing [16, CS 25.1323(h)].

The Pitot tubes must be far enough apart to avoid damage to both tubes for example in case of a bird strike [16, CS 25.1323(j)].

Pitot tubes must be heated. The AMC contain specific notes on icing conditions and tests [16, CS 25.1324]. The last requirement adds the need for an alert in case of heating failure [16, CS 25.1326].

Table 3.2: Requirements on Airspeed Indicating Systems in CS 25.1323 [16]

Airworthiness Code	Description
CS 25.1323(a)	Instrument Calibration
CS 25.1323(b)	System Calibration
CS 25.1323(c)	Accuracy Requirements
CS 25.1323(d)&(e)	Reduced Accuracy Requirements near V_S and V_{MO}
CS 25.1323(f)&(g)	Misleading readings at takeoff
CS 25.1323(h)	Guidelines for system arrangement and design
CS 25.1323(j)	Requirement regarding birdstrikes and damage
CS 25.1324	Ice preventing and heating
CS 25.1326	Alert in case of heating failure

4 Analysis of Limitations and Performance demands

The requirements outlined in Chapter 3 were developed based on Pitot-static systems and AoA measurement vanes, thus addressing risks specific to these conventional technologies. To extend these requirements to the LDA, this chapter examines the limitations and performance demands of existing systems, to be able to identify differences and commonalities to the LDA later on. Given the confidentiality constraints imposed by manufacturers, performance data for current airspeed and flow-angle indication systems remain inaccessible. Meanwhile, the performance of sensors can be separated into a physically possible performance and an output performance. The first one is defined by physical phenomena while the latter just describes what the instrument is sending onto the avionics bus. The output performance is often not bound by the physically possible one. Consequently, this discussion first establishes general bounds on robustness, integrity, and accuracy-limiting errors. These findings are then supplemented by minimum performance specifications for air data computers and modules, providing a baseline for estimating system capabilities.

4.1 Comparison of Limitations and Errors

In order to fully capture all relevant limitations and errors a brainstorming session [41] was conducted. This was prepared by assessing PRA and FMEA presented in [12] as well as literature on air data systems. Furthermore, MPS/MOPS were evaluated for environmental conditions and requirements. The list of derived limitations and errors was then presented to a number of experts on avionics systems at the Institute for Aircraft Systems (ILS) where it was discussed and amended. The relevant results are presented below.

4.1.1 Limits on Robustness and Integrity

Robustness characterizes a sensor's durability in environmental conditions, for example what temperatures and pressures it can be exposed to without being damaged after.
Integrity describes the sensor's ability to detect erroneous measurements. This is especially important for airspeed indication since wrong airspeed readings that are followed blindly can lead to stalls or overspeed events.

Blockage, Icing, and Moisture

A Pitot tube may become blocked due to several causes, including insect ingress during ground operations [42], forgotten Pitot tube covers [43], or icing and moisture accumulation. The primary concern in such cases is not the absence of measurements but the potential for erroneous data to be supplied to aircraft systems and the flight crew. Detecting this unreliability is exceptionally challenging, as demonstrated by Jäckel et al. [30]. If undetected, such failures can lead to unrecoverable flight conditions.

Icing may present as either rime or clear ice, potentially obstructing both the Pitot tube and the AoA measurement vane. While probes are equipped with heating systems to mitigate this risk, failures persist, as evidenced by eight accidents attributed to Pitot tube icing since 1973 [30, p.3].

Heavy rainfall and moisture ingress represent additional blockage risks. Although Pitot probes incorporate drainage openings and baffle plates as well as substantial heating power, extreme precipitation or internal condensation can still compromise functionality [44][45, pp.9-15].

External Damage

Probes and vanes are protruding from the fuselage and are especially prone to bird strikes at take-off and in-flight, Foreign Object Debris (FOD) during take-off and damage by ground vehicles [29, p.128].

4.1.2 Limits on Accuracy

Accuracy in this case describes the difference between the sensor measurements and data supplied by a more precise reference instrument. For example during the flight tests of the FAME project a very precise and calibrated multi-hole probe mounted on a nose boom was used to gather reference data to later determine the accuracy of the instrument [11].

Leakage

The tubing connecting the Pitot probe with the sensor can leak due to the pressure difference inside the hull. This leakage leads to pressure loss and therefore errors. Leakage errors impact both static and total pressure [23, p.18].

Installation Tolerance

The corrected airspeed measurement characterized by CAS depends among other factors on the installation angle and position of the sensor. Installation tolerances cause errors in measurement. This error is often combined with the position error described in the next section.

Position Error

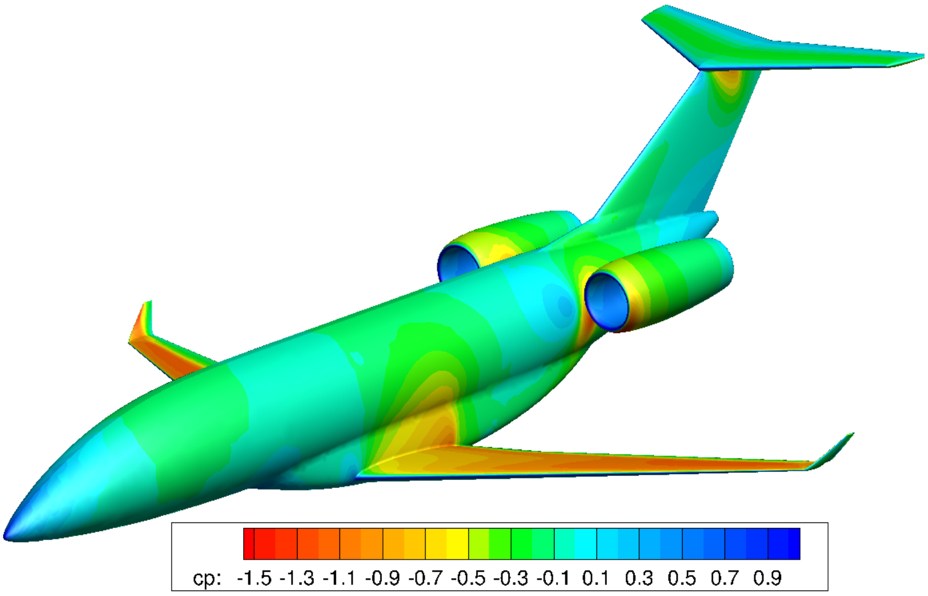

Figure 4.1: Pressure coefficient on a business jet in flight [46, Fig. 31]

Position error is the error due to aerodynamic disturbances in the airflow near the aeroplane.

This results in different pressures at the location of the pressure orifices compared to the free stream pressures in undisturbed flow. This can be seen in Fig. 4.1 where the pressure coefficient, the dimensionless difference to the free stream pressure, along the aircraft has been simulated using Computational Fluid Dynamics (CFD) for a single point in the flight envelope [46]. The airflow is further disturbed by the Pitot tube itself sticking into the airflow [27, p.36].

At subsonic speeds flow perturbations are nearly isentropic. As long as the Pitot tube is not installed in a region of localized supersonic flow, behind a propeller or in the wing wake the impact of the position error on total pressure p_t is negligible [27, p.37].

Static pressure p_s is much more sensitive to the position error. Thus, the static orifices should be located in an area where it is close to zero. However, the flow and therefore the error changes with aircraft speed and AoA. The instrument is typically calibrated to account for this (see Section 4.2) [26, pp.3-4]

The position error also impacts AoA and AoS measurement since the local AoA is altered by the disturbed flow as well. Depending on the axis, this phenomenon is called *upwash* or *sidewash*. Generally, the error increases with decreasing distance to surfaces creating lift [26, pp.5-6].

In trans- and supersonic airflow, shockwaves appear in front of and along the aircraft fuselage. They cause a total pressure loss and therefore errors in airspeed measurement. This can be quantified via the Rayleigh-Pitot Formula, but the probe may have to be mounted on a noseboom in order to only allow one bow shockwave in front of it [26, p.2].

Error due to AoA and AoS

Most Pitot tubes are fixed. If the AoA or the AoS changes, the component of the airflow velocity entering parallel to the Pitot tube's middle axis changes. This results in an error in airspeed measurements. Different shapes of tube openings change its characteristics as can be seen in Fig. 4.2 [28, p.650].

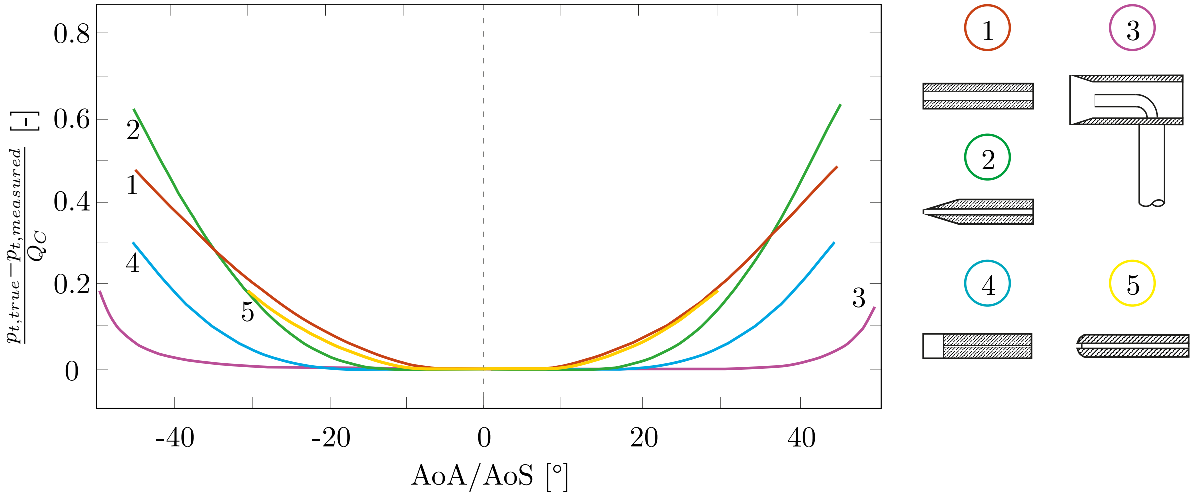

Figure 4.2: Characteristics of different Pitot tubes at varying flow angles; derived from [28, p.650]

Lag & Attenuation

Changes of pressure propagate with the speed of sound and are bound by the properties of sound waves. This results in limitations on the instrument.

In a stationary view, the concern is the lag of measurements, lag being the time delay between the physical event at the location of interest and its acquisition by the sensing device. The longer the tubing between probe and pressure sensor, the longer it takes for a pressure change to travel this distance [27, p.35]. The lag can be approximated by a first order model [26, p.13]. In order to qualitatively describe the lag time it can be approximated as follows. Ambient pressure $p_{a,SL}$, temperature $T_{a,SL}$ and air density $\rho_{a,SL}$ can be obtained from the International Civil Aviation Organization (ICAO) International Standard Atmosphere (ISA) [47]. The gas constant R as well as the isentropic exponent λ are provided by [48]. The length of tubing is assumed to be 20 cm.
The speed of sound A is determined as $A = 340.35\,\mathrm{m\,s^{-1}}$ using Eq. (2.5). Therefore, the lag time t can be calculated as:

$$t = \frac{l}{c} = 5.876 \times 10^{-4}\,\mathrm{s} \tag{4.1}$$

This error is in the magnitude of less than one millisecond and therefore quite small. The lag time can be reduced even more by shortening the tube and positioning the air data module close to the pressure orifices.

From a dynamic point of view, phenomena like resonance and attenuation need to be considered. The pressure wave is dampened by frictional attenuation inside the Pitot tube which causes a total pressure loss and phase lag. Reflections cause hard to estimate positive and negative interference [26]. These effects can also be reduced by shortening the pressure lines [49, p.28] and can be approximated by a second order model [50].

Flow angle measurement vanes have a high lag because of the inertia of the rotating vane assembly [49].

Vibration and Bending Error

In-flight aeroelastic effects of the structure like bending or vibration impact the accuracy of AoA measurement, and to a smaller extent, the airspeed measurement. All aeroplane structures have an eigenfrequency and are therefore subject to vibration. Especially less rigid structures like the noseboom can not be designed rigid enough to make bending and vibration negligible. This results in further complication of resonance and attenuation for Pitot-static systems as well as artificial signals in flow angle measurement [49, p.26].
Furthermore, angular rate and acceleration of the aeroplane impact the measurement vane [26, p.6].

Pressure Sensor Errors

The sensors itself have measurement errors depending on their functional principle. In Section 2.2.1 some of them were already mentioned, for example solid state sensors are sensitive to acceleration and temperature changes [29, p.254].

4.2 Calibration

Some of the aforementioned errors can be mitigated through sensor calibration. Table 4.1 summarizes all errors discussed in Section 4.1.1, specifying whether they are compensable via calibration and, if applicable, the corresponding methods.

Calibration is split in two parts: First, the individual parts of the airspeed indicating system are calibrated on the ground according to the MPS/MOPS referenced by CS-ETSO. Then, the whole system is calibrated when it is installed in the aeroplane on the ground and during flight. Data tares like an air data test set are used to simulate pressures and measure leakage (see Section 4.1.2) [26, p.11]. In this case the requirements set by the CSs are important, especially CS 25.1323 (c) (see Section 3.3).

The system is also calibrated in flight, mostly to mitigate the position error (see Section 4.1.2) by flying special manoeuvres or comparing the instrument readings to data gathered by a reference instrument for example a very precise instrument on a noseboom. This is done to characterize the Static Source Correction Error (SSEC), a function dependent on Mach number M and altitude which can be used by the air data computer to quickly correct the measurements in flight [26], [29, p.249].

Calibration of the flow angles to compensate the position error is done via a trajectory reconstruction with data from flight tests [26, pp.6-7].

Table 4.1: Overview of errors affecting conventional Pitot tubes and flow angle measurement vanes and their calibration

Error	Affected Value	Can be calibrated/corrected?	Calibration method
Leakage	Airspeed	Yes	Data tare
Position Error	Airspeed AoA & AoS	Yes	SSEC Trajectory reconstruction
Error Due to AoA & AoS	Airspeed	Yes	SSEC
Lag error	Airspeed AoA & AoS	No	
Attenuation Error	Airspeed	No	
Vibration & Bending Error	Airspeed AoA & AoS	No	
Pressure Sensor Error	Airspeed	Partially	Data tare

4.3 Performance of State-of-the-Art Systems

To further evaluate the requirements on state-of-the-art systems, absolute values are needed. For this work minimum requirements on range, accuracy, data rate, frequency response and long term stability set by AS8002B, ED-140A and ARINC 738-3 were analysed. These documents only provide minimum requirements for the output of the ADIRU or the Air Data Module (ADM). Most performance figures are discussed for their applicability and validity by comparison with other standards, other requirements or the physical limitations described above.

Range

AS8002B allows the required range of the sensor to be defined by the aircraft manufacturer [21, p.7].

Other standards define minimum ranges for airspeed and measurement altitude. The range

is set as a pressure envelope. For static pressure this minimal range goes from 100 mbar to 1100 mbar which translates to around −2290 ft to 53 080 ft. Airspeed is required to be measured at least from a total pressure of 100 mbar to 1400 mbar [22, Tab. 3.1]. The CAS output has to have at least a range from 30 kt to 100 kt and the TAS out from 100 kt to 590 kt [23, Tab. 7-2]. This range seems to be acceptable for subsonic aircraft but since it is a minimum it can and should be expanded on. The range depends on the flight envelope of the aircraft set by the OEM. Therefore, the requirement set by AS8002B seems to be the most useful one.
The flow angle output should range from −60° to 60° according to ARINC 738-3 [23, Tab. 7-2] which seems to be enough for all civilian aircraft. Aircraft commonly do not reach an AoA that high outside of emergencies.

Accuracy

Accuracy includes attenuation, threshold sensitivities of the sensor, repeatability, and manufacturer equipment errors and depends on the sensor's integration into the aircraft [21, p.7]. Pressure data output must have a minimum accuracy of ±0.25 mbar [22, Tab. 3.2].
Airspeed accuracy is defined variable depending on altitude. For the CAS, this can be seen in Table A.1 and Table A.2, with the minimum tolerance set between 5 kt and 1 kt by ARINC 738-3 [23, Tab. 7-2] and between 5 kt and 2 kt by AS8002B [21, Tab. 3]. These tolerances are meant for the output of the air data computer alone. They are plotted in Fig. 4.3 together with the tolerance for the whole airspeed indicating system described in Section 3.3. The only tolerance for TAS is given by ARINC 738-3 as ±4 kt throughout the entire speed range [23, Tab. 7-2].

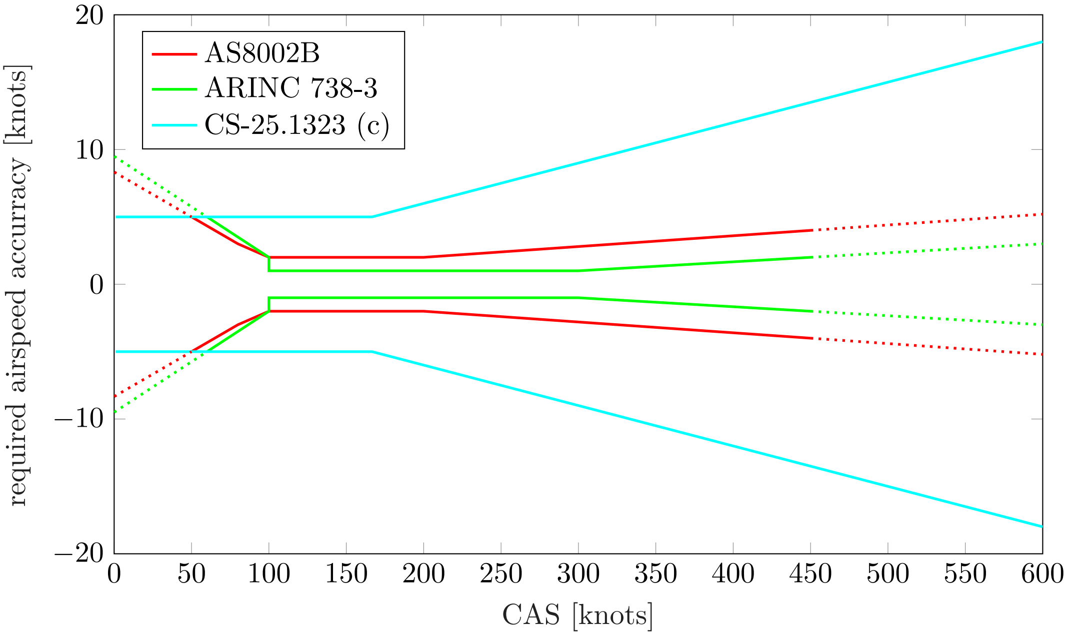

Figure 4.3: CAS tolerance of different standards; Interpolated values (in accordance with the standard) are shown as dotted lines

As can be seen in Fig. 4.3 the standards disagree. AS8002B is stricter in the lower speed range while being more forgiving than ARINC 738-3 above 100 kt. The tolerance given by CS-25 is much higher as it applies not only on the air data computer output but on the full airspeed indicating system.
While the accuracy for CAS is changing with rising airspeed, the tolerance for TAS is set as a constant. This is not conclusive.

The tolerance for AoA and AoS output is required to be ±0.25° for all point of the flight envelope [23, Tab. 7-2].

Data Rate

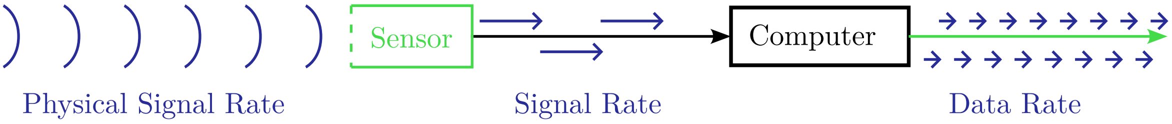

Figure 4.4: Illustration to clarify the difference between (physical) signal rate and data rate

In order to fully describe the following analysis, two terms must be defined: *Data Rate* refers to the frequency of the output data transmitted via an avionics bus. However, since this data is already heavily processed, the data rate may not reflect the actual update frequency of the value. In contrast, the *(physical) signal rate*, denotes the actual frequency at which the values can change, determined by physical constraints or the sensor's sampling frequency.

Table 4.2: Transmit intervals and resulting data rate requirements according to different standards

Source	Description	Transmit Interval		Data Rate	
		Min	Max	Min	Max
ED-140A	Pressure output ADM	31 ms	29 ms	32.26 Hz	34.48 Hz
ARINC 738-3	Pressure output ADIRU	125 ms	62.5 ms	8 Hz	16 Hz
ARINC 738-3	CAS output ADIRU	125 ms	62.5 ms	8 Hz	16 Hz
ARINC 738-3	AoS & AoA output ADIRU	125 ms	62.5 ms	8 Hz	16 Hz

Table 4.2 presents the required transmit intervals and the calculated data rates of the air data computer output. The largely unprocessed pressure data output by the ADM has the highest requirements, whereas the more processed data, such as CAS, exhibits a lower output frequency [22, Tab. 3.2], [23, Tab. 7-2].
As mentioned previously, this reflects the processed data transmitted by the computer via the avionics bus and may not represent the system's actual performance. Consequently, to establish physically based signal rate requirements, the frequency response function was analysed. It characterizes the system's reaction to oscillatory inputs. This is critical due to associated phenomena, such as lag and attenuation, as discussed in Section 4.1.2. The requirement defines how the instrument must respond to pressure oscillations, thereby providing context for the analysed data rate constraints. The function frequency response for ADM is described in ED-140A. The Bode plot in Fig. 4.5 is taken from this standard. It shows the lower band limit of the magnitude of pressure measurement over the pressure frequency. According to the document, the upper band limit is platform dependent. For the ADIRU the maximum magnitude is set to 2 dB by ARINC 738-3 [23, p.23].
Fig. 4.5 shows the magnitude plunging to an infinitely low value at 3 Hz pressure frequency. Consequently, pressure frequencies of more than 3 Hz can be infinitely attenuated and the highest signal rate possible would lie at 3 Hz. Since the plot describes the lower limit this value can be interpreted as the minimal required data rate [22, p.7].

The high difference between the output data rate of the unprocessed pressure data of 33 Hz compared to the low physical signal rate of 3 Hz analysed here is striking. However, the latter one relies on physical requirements while the output interval does not have this foundation.

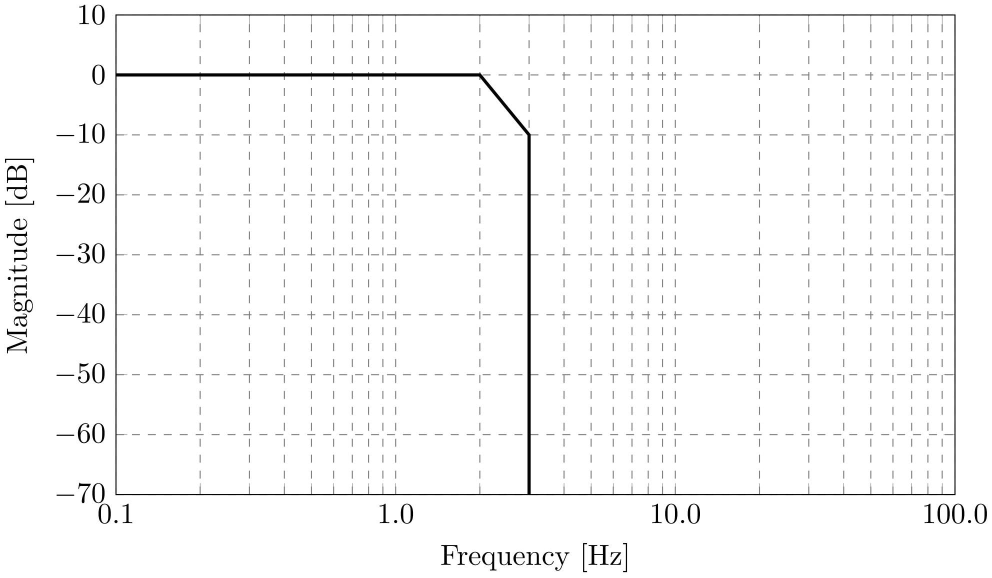

Figure 4.5: Function frequency response of an ADM according to ED-140A [22, Fig. 3.1]

Therefore, the lower signal rate is assumed to better characterize the update frequency of the airspeed data, since the output data is not explicitly forbidden to make use of additional filtering, regularization and interpolation algorithms.

Lag

ARINC 738-3 covers the frequency response of an air data computer with a set of very specific requirements. They state that an aircraft should fly at a constant altitude of 6000 ft and vary its airspeed sinusoidally around a centre value at a specific amplitude displayed in Table 4.3. The electrical output of the air data computer needs to lag the pressure variation Φ less than 15° at a pressure variation f_p of 0.05 Hz and less than 90° at a pressure variation of 1.5 Hz. The requirement includes transport lag from the pressure orifice to the sensor [23, p.23].

Table 4.3: Requirement for frequency response of an air data computer according to [23, p.23]

Altitude	CAS	
	Centre Value	Sinusoidal Variation
6000 feet	200 knots	± 1.354 mb
6000 feet	350 knots	± 1.354 mb

Lag times can be calculated as follows:

$$\tau = \frac{\Phi \cdot \frac{\pi}{180}}{f_p \cdot 2\pi} \tag{4.2}$$

This results in lag times of respectively 0.0833 s and 0.1667 s. The lag times here are much higher than just the lag because of the speed of sound calculated in Section 4.1.2. This is due to the fact that it factors in transport and processing time and a worst case scenario is assumed. Therefore, the lag times are determined to be an acceptable requirement.

Long Term Stability Performance

Long term stability describes the change of accuracy over the lifetime of the system. The measurement drift of air data computers need to be monitored. This is typically done by accelerated testing of a batch of equipment. Their performance is analysed and possible recalibration cycles assessed. This results in maintenance items and their timing [22, p.7].

Performance of Products

As an example the data sheet of a pressure sensor and a combined ADIRU/ADM will be examined and compared to the minimum values above.

The "Keller Serie 33X piezo-resistive pressure sensor" is chosen as an example for a pressure sensor. It is often used in laboratories and while it has a different working principle than the ones presented in Section 2.2.1, it can be still used as a comparison for accuracy. According to Table A.3 from its data sheet it has an accuracy of less than ±0.05 % of Full Scale (FS) at temperatures between 20 °C and 25 °C [51]. The accuracy for this limited temperature range is comparable since sensors used in aviation are compensated for temperature. In a hypothetical measurement range of 0 mbar to 2600 mbar (corresponds to airspeeds up to 426 m/s) [29, p.251] the absolute accuracy would be ±1.3 mbar. This shows the extreme accuracy of aerospace grade sensors which are required to measure with an accuracy of ±0.25 mbar.

The requirements can also be compared to the data-sheet of the "ADI-32000 Product Series" manufactured by Air Data Incorporated. It is an air data computer designed to comply with ETSO-C106a for use in transport aircraft, military trainers, helicopters and UAV.
CAS range is set from 0 kt to 800 kt with an accuracy of ±3 kt at 50 kt. All outputs including CAS, TAS, AoA and AoS are computed at a frequency of 60 Hz [52].
Range and tolerance seem to be in line with the minimum requirements analysed above. The computation rate which is assumed to equal the output data rate is much higher. However, as explained above this may not be reflective of the signal rate.

5 Comparison of LDA Technology to Conventional Systems

This chapter compares the aspects of state-of-the-art systems, analysed in Chapter 4, with those of the LDA. Additionally, it presents novel risks and advantages of the LDA in comparison to Pitot-static system and flow angle measurement vanes.
The applicability of risks and limitations gathered in Chapter 4 was analysed for LDA technology. A matrix was created to evaluate whether the LDA is more, less, or equally susceptible to each aspect, supported by relevant arguments. The results were presented and discussed with experts from the DLR and the ILS. The resulting assessment of all risks and limitations is presented in Section 5.1, while the resulting advantages are described in Section 5.3.
New risks and challenges were identified using the safety analysis conducted by M. Lichtl in his master's thesis and by comparing the working principles, integration, and performance of state-of-the-art systems with the LDA. They were discussed and amended in the setting described above and are presented in Section 5.2.

5.1 Assessment of Risks and Limitations for the Laser Doppler Anemometer

The LDA is susceptible to disruption of the measurement and acquisition path, comparable to conventional systems discussed in Section 4.1.1. This can be primarily due to obstructions such as a protective cover, FOD, or dirt on the optical window. Additionally, ice or rain may impede laser transmission. However, unlike Pitot tubes, the LDA's window is not oriented into the airflow, which substantially reduces ice accretion. Furthermore, strategic installation can minimize rain exposure. A key distinction from Pitot-static systems is the LDA's ability to detect the blockages and obstructions with high reliability. This feature is elaborated in Section 5.3. Moisture ingress is mitigated through hermetic sealing, while the optical cavity can be purged with a noble gas to prevent internal condensation.

External damage is still a concern for the LDA as the windows can be damaged by FOD during take-off and by birdstrikes in flight. However, the risk is also reduced since the instrument sits flush with the fuselage.

Compared to conventional methods, the LDA is unaffected by leakage or attenuation, as its measurement principle does not depend on pressure-based methods and thus eliminates the need for tubing. By employing laser light which propagates at nearly a thousand times the speed of pressure waves the system minimizes measurement lag (excluding processing delays).

Additionally, from a vector projection perspective, airspeed measurements remain independent of AoA and AoS, and the sensor is highly resilient to vibrational disturbances.
Bending of the aircraft structure has effects on the accuracy of flow angle measurement. In order to calculate the parameters, the airflow vector must be transformed from a local coordinate system, originating in the transceiver, to an aeroplane-fixed one. If the structure bends, the relative position of the origins of both coordinate systems changes and the flow angle measurements are erroneous. Fig. 5.1 illustrates the positions of both coordinate systems for the potential position of LDA modules at the front of the aeroplane.

The same problem occurs due to the installation tolerance of the transceiver. The deviation

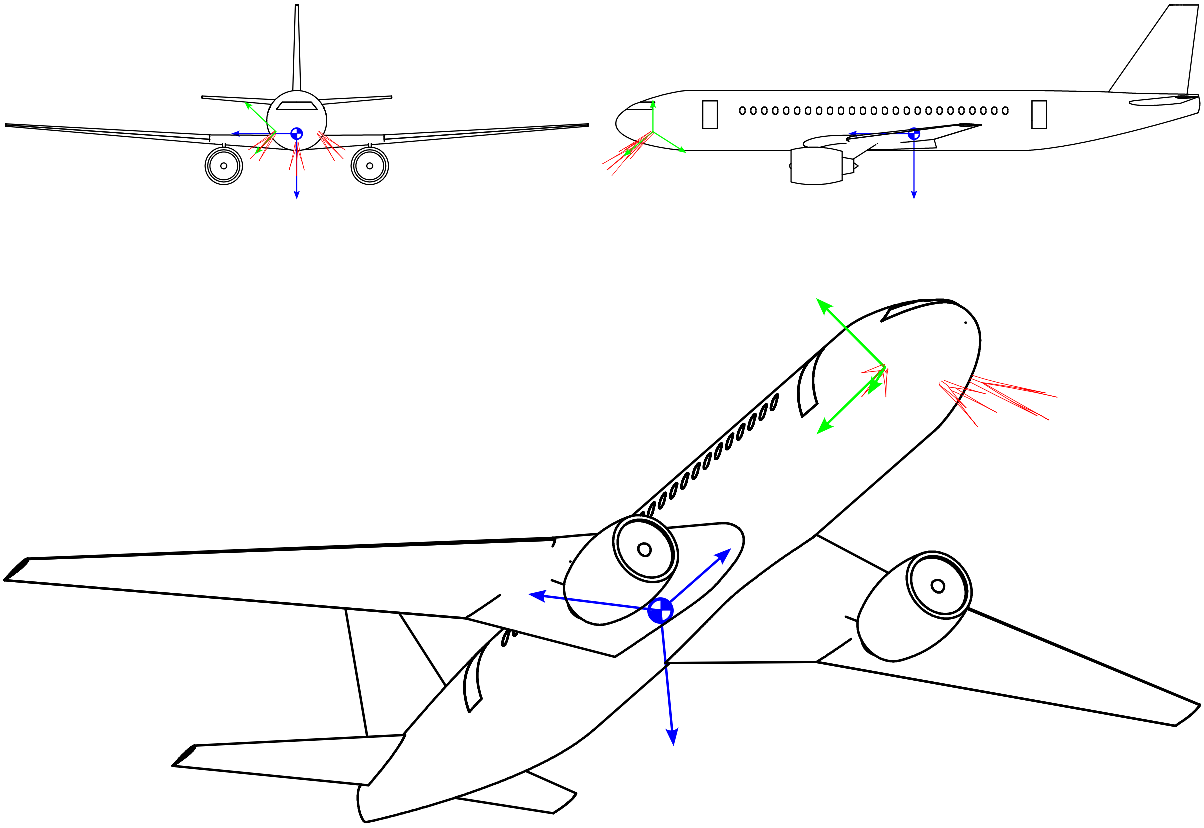

Figure 5.1: Potential positioning of three LDA modules on the fuselage including the coordinate system of the LDA (green) and the aeroplane-fixed one (blue)

both in position and angle from the installation target introduces errors in the flow angle measurements. This tolerance may cause errors if it is not mitigated correctly by calibration. The insufficient assessment and calibration of the installation tolerance proved to be a major cause for inaccuracies during previous flight tests of the LDA [11, p.239].

The position error described in Section 4.1.2 remains applicable to LDA technology. However, unlike Pitot tubes, the LDA offers the distinct advantage of measuring at greater distances from the fuselage, enabling data acquisition outside the boundary layer without disrupting the airflow. This capability is discussed in further detail in Section 5.3.
Furthermore, it can be hypothesized that the LDA laser beam may be capable of traversing shockwaves with negligible impact on measurement accuracy. If validated, this could enable measurements upstream of shockwaves, presenting an additional operational benefit. The technology's built-in self-diagnostic capabilities mitigates drift, a feature discussed in greater detail in Section 5.3.

All the errors and limitation including their applicability and impact on LDA technology are summarized in Table 5.1.

Table 5.1: Summary of assessed risks and limitations

Risks or Limitations	
Risk	Applicability/Impact
Blockage	Lower
Moisture	Lower
Error due to AoA/AoS	Not Applicable
Leakage	Not Applicable
Attenuation	Not Applicable
Lag	Lower
Installation Error	No change
Vibration Error	Not applicable
Bending Error	No change
Position Error	Lower

5.2 Novel Risks and Challenges

The adoption of LDA technology introduces a fundamental shift in measurement principles, posing a key challenge to its integration. Unlike the long-established process for airspeed data acquisition (see Section 2.2.3), the LDA directly measures TAS. Consequently, downstream systems such as the ADIRU or avionics bus architectures will require modification to fully accommodate this technology.

An additional challenge for integration of the LDA is eye safety. The LDA uses laser beams with a power of 1 W per channel [36, p.6747]. Although not visible to the human eye, this makes it hazardous to personnel standing near the focal point. During flight, the immediate surrounding of the laser is deemed to be inaccessible and therefore the safety of people is guaranteed. However, during maintenance and even during taxiing this may not be the case and measures to ensure the protection of people are needed.

Another risk associated with the system stems from manufacturing tolerances. For accurate measurements, the laser beams of the individual channels must be precisely aligned relative to each other. Deviations in the optical axis (illustrated in Fig. 5.2) arising from tolerances can introduce errors in both airspeed and flow angle measurements. However, since the magnitude of such errors is directly correlated with manufacturing precision, they can be minimized through controlled fabrication processes. Moreover, as a systematic error, this effect can be mitigated via calibration.

The testing and calibration of the system itself is another challenge. The systematic errors such as manufacturing, installation and position error must be analysed and the overall accuracy of the system must be tested. Conventional methods for in flight calibration can be applied for the LDA to achieve this. However, a reliable calibration and testing method on ground must be developed analogue to the Air Data Test Set. This is critical to keep maintenance effort and time on par with conventional instruments.

The laser beams of the LDA are restricted in their angle towards the incoming airflow. Because of performance limitations of the Analogue to Digital Converter (ADC), the upper limit of the measurable Doppler shift of each channel is restricted. Therefore, the beams can not be installed facing directly in the direction of the airflow. Instead, the projected LOS velocity is reduced by increasing the angle between the optical axis and the airflow. However, the projection of the TAS onto the individual laser beam optical axes must yield sufficiently large values in order to

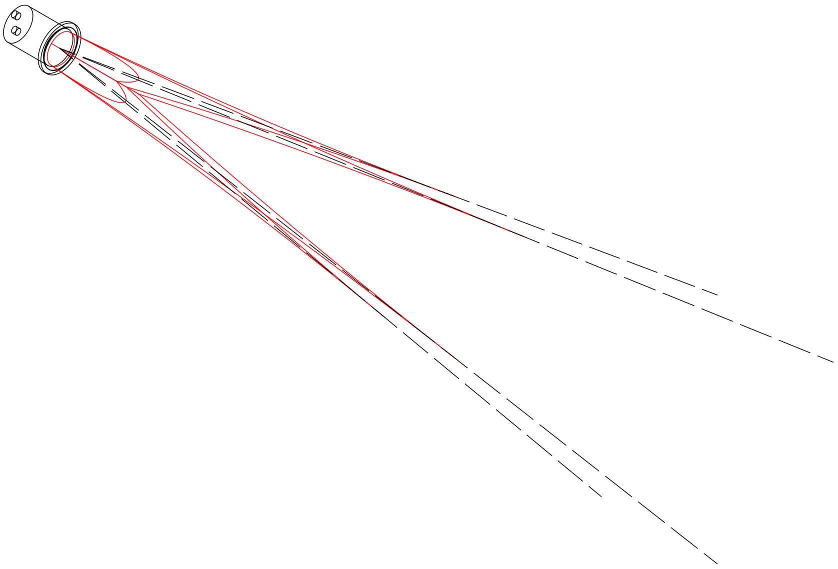

Figure 5.2: Optical axis of the LDA instrument

avoid ambiguity errors. In practice the LDA orientation must be optimized with available CFD data. This results in requirements on installation as well as the range of measurable airspeed and flow angles.

One of the major causes for the output of an incorrect airflow vector analysed by M. Lichtl were large particles. These could be rain droplets or ice crystals that cause scattering but are too heavy to follow the airflow and may result in a lower airspeed and different flow angles than smaller particles [12, p.50]. According to experts the size of particles is easily identifiable by analysing magnitude and signal characteristics of the scattered light. This in-situ characterization is one of the main goals of the upcoming flight campaigns for the FuLDA instrument.

However, the biggest challenge for the technology was identified as the asynchronous data rate. The LDA can not provide a consistent data rate like Pitot-static system systems since its measurement intervals depend on the presence of aerosol particles. Aerosol distribution is complex to describe as it depends on multiple factors including but not limited to altitude, weather and climatic region. Therefore, it is easier to describe the distribution of measurement events as a statistical distribution of independent events, in particular a Poisson distribution. The probability of accomplishing a specific number of measurements k per interval $P(k)$ is described as

$$P(k) = e^{-\lambda} \cdot \frac{\lambda^k}{k!} \tag{5.1}$$

where λ is the mean number of measurements in a given interval T. The equation can be expanded to substitute λ with the average measurement rate r by defining it as

$$\lambda = r \cdot T \tag{5.2}$$

This leads to the following equation:

$$P(k) = e^{-r \cdot T} \cdot \frac{(r \cdot T)^k}{k!}. \tag{5.3}$$

This distribution model is further used in Section 6.1.3 to formulate suggestions on data rate requirements for the LDA.

5.3 Advantages of LDA Technology

Potential advantages of the LDA technology developed from the assessment above were grouped into five categories.

Uncertainty Calculation/Integrity

One of the biggest advantages of the usage of an overdetermined LDA with four or more channels is the capability of calculating uncertainty for every measurement. Unreliable airspeed and flow angle measurements can be detected instantly which increases the integrity of the data compared to Pitot-static system systems. The probability of the system supplying an incorrect airflow vector was preliminarily concluded to be $3.85 \times 10^{-6}\,\mathrm{h}^{-1}$ and all failure modes leading to this were due to internal faults or potential design errors [12, p.49]. An estimated Mean Time Between Failure (MTBF) of 14.492 h for the failure of the pitot probe can be used as a comparison [53, Tab. 4]. It is equal to a failure probability of $7.692 \times 10^{-5}\,\mathrm{h}^{-1}$. However, according to [12, p.50] the more fitting comparable failure mode of the LDA is a total failure which was assessed at a probability of $5.77 \times 10^{-5}\,\mathrm{h}^{-1}$. While this makes the LDA comparable to the pitot tube in its probability of total failure, a quantitative description on the rise of integrity can not be made. However, with the multiple causes for the supply of an unreliable airspeed vector by conventional systems (see Section 4.1.1), a sharp rise in integrity can be safely assumed. The only external cause for an incorrect airflow vector measurement by the LDA are big particles which can potentially be excluded during data acquisition as described in Section 5.2.

Aerodynamic Advantages

Position error is minimized for the LDA because it sits flush with the fuselage and therefore does not interact with the medium during data acquisition. Furthermore, measurements can be conducted far away from the fuselage where the air is less disturbed. For example, the laser used in the FAME programme was focused between 500 mm to 1000 mm away from the fuselage [11, p.234]. As assessed above, even the measurement in front of shockwaves may be possible. Furthermore, the aerodynamic drag caused by the measurement vane and pitot-tube is minimized due to its flush mounting. This could lead to a higher fuel efficiency of the overall aeroplane, reducing the operating cost.

Dissimilar Technology

Due to its completely different operation and design the technology may increase the overall safety of an air data system when used in conjunction with state-of-the-art systems by reducing Common Cause Failures. The remaining failure modes were analysed by M. Lichtl and identified either to be caused by integration into the aircraft e.g. the power supply or by external causes like birdstrikes, icing or maintenance errors [12, p.46].

Manufacturing and Maintenance

One LDA system functionally replaces up to three individual sensors: one Pitot tube, one AoA measurement vane and one AoS measurement vane. For all these individual sensors holes in the fuselage have to be created which requires more material and special construction to counteract the concentrated stress [54]. Especially modern carbon fibre constructions like the fuselage of the Boeing 787 benefit highly from fewer breakthroughs as they are manufactured as monolithic segments which are wound in one go. Each saved breakthrough avoids a manufacturing step in cutting it [55]. The decreased weight contributes to a higher fuel efficiency. Additionally, maintenance is simplified because of the functional grouping.

Adding to the simplified maintenance, no flushing and leak checks of tubing [56] have to be performed after each time the system was worked on. Those procedures are time and resource intensive since they have to be done over long intervals to be able to test for the high required pressure accuracies of the system (see Section 4.3). The LDA will need to be tested as well, but troubleshooting may be easier due to the high self-diagnosing ability of the system. Most causes of failures and system degradation can be identified by the system itself and may even allow a greater use of predictive maintenance.

Performance

Compared to state-of-the-art systems the LDA features several performance improvements.
As outlined in Section 5.1, the measurement lag is inherently reduced, since the instrument's primary measurement operates at the speed of light. However, as discussed in Section 4.3, the dominant contribution to lag arises from signal processing. Preliminary analyses suggest that the total processing time remains well within the latency requirements of state-of-the-art systems.
As mentioned above, the new technology is not susceptible to vibration and bending and the measurement of airspeed is possible at high AoA and AoS.
The self-diagnosing functions allow high long term stability. The drift of the wavelength as well as decreasing laser power can be monitored, compensated and insufficient performance detected.

6 Suggestions on Requirements and Integration of LDA Technology

The following chapter describes potential solutions to the risks and challenges for the LDA that were assessed in Chapter 5. They were developed in discussion with experts from the DLR and the ILS in order to restore compatibility with conventional technologies. Additionally, different aspects of integration into an aircraft are analysed, and several options explored. They can be used to assess the impact of the LDA on downstream systems and resulting conflicts with requirements.

6.1 Selection of Possible Characteristics for Suitability of LDA Technology

From the analysis done in Chapter 5 the following key areas requiring solutions to restore comparability and compliance to state-of-the-art instruments were identified: Calibration, Accuracy and Data Rate. Suggestions on their handling for the LDA are made below.

6.1.1 Suggestions for Calibration

To correct systematic errors such as installation and manufacturing errors a specialized calibration instrument, analogous to an air data test set, is required. The Laser Doppler Anemometer (LDA) is currently calibrated in a controlled laboratory environment using a rotating laser-engraved disc to simulate the motion of aerosol particles. This method enables precise characterisation of the instrument's response under controlled conditions.

For accurate calibration, the LDA must be positioned at a fixed angular orientation relative to the test setup. This can be achieved by integrating fixture points on the fuselage, which serve as stable reference markers for mounting the calibration instrument. By using these fixtures as a baseline, the installation error can be systematically quantified following the instrument's integration into the aircraft.

The development of Ground Test Equipment (GTE) based on this technology is feasible. Such a system would allow for repeatable, high-precision calibration by ensuring consistent alignment between the LDA and the reference flow field generated by the rotating disc.

6.1.2 Proposals for Accuracy Requirements

As described in Section 5.2, a key challenge in introducing the LDA arises from its direct measurement of TAS. To ensure proper characterisation of the instrument's performance and thus its compliance with accuracy requirements the existing requirements must be adapted specifically for the LDA.

For this the accuracy requirements described in Section 4.3 in CAS need to be converted to TAS. This was done in Fig. 6.1 using the equation

$$V_T = 1479.1\sqrt{\theta\left[\left(\frac{1}{\delta}\left\{\left[1+0.2\left(\frac{V_C}{661.4786}\right)^2\right]^{3.5}-1\right\}+1\right)^{\frac{1}{3.5}}-1\right]} \tag{6.1}$$

used to convert CAS V_C in knots to TAS V_T in knots. The equation is dependent on the ratio of air pressure δ and the ratio of temperature θ [57, p.70].

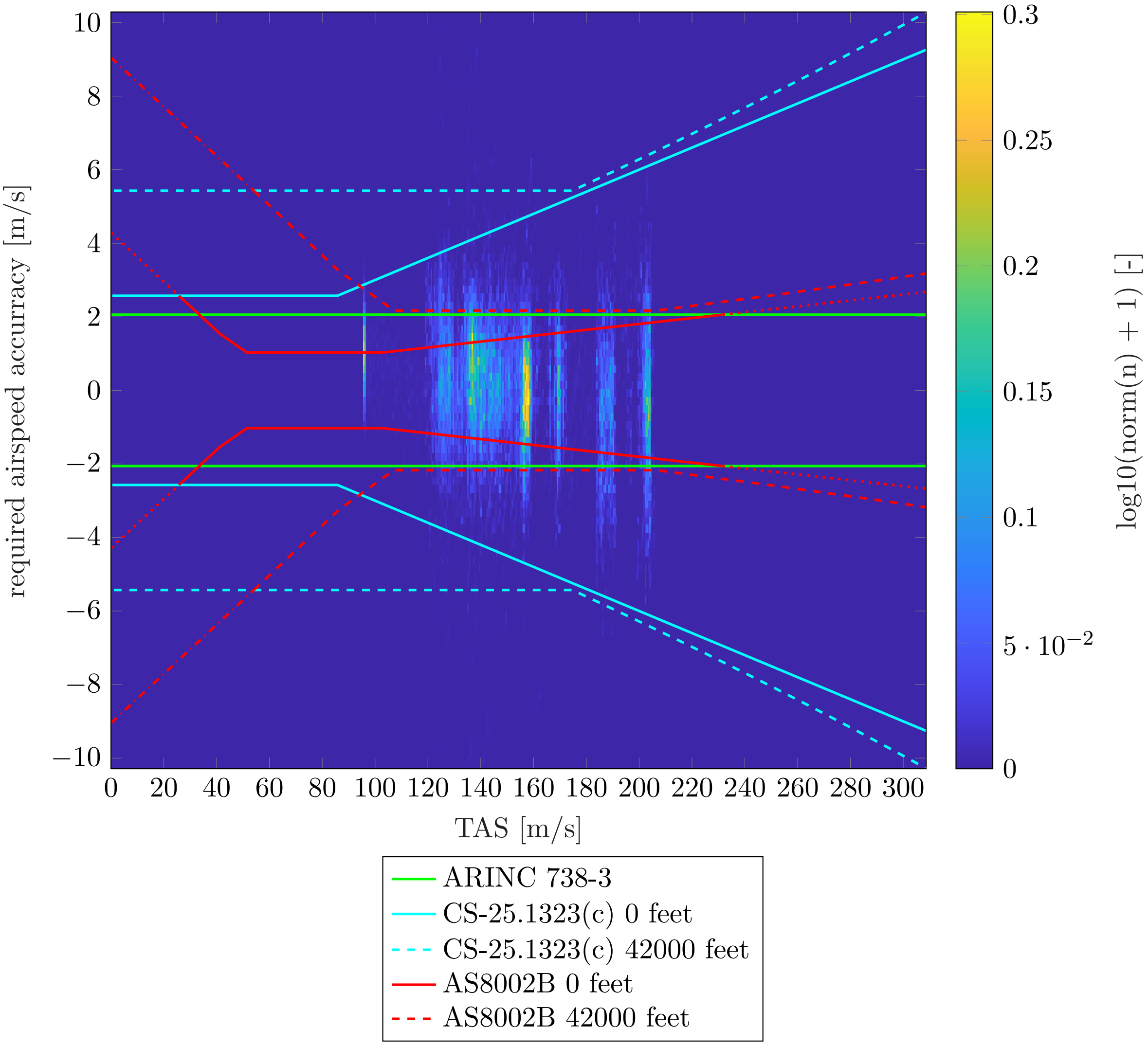

Figure 6.1: Heatmap of weighed residuals of LDA airspeed data from the FAME campaign, relative to the reference instruments and plots of the required airspeed tolerance of different standards converted to TAS at different altitudes; Interpolated values (in accordance with the standards) are shown as dotted and dotted/dashed lines; Derived from [12, Fig. 3.1]

At sea level and standard atmosphere CAS and TAS are equal. In order to define edge cases, the accuracies were converted with the conditions of the standard atmosphere at 42 000 ft. This is the highest altitude the LDA was ever tested on. The conversion was done for the accuracies defined by CS-25 and AS8002B. Additionally, the accuracy for TAS output set by ARINC 738-3 is plotted in green.

The heatmap in the background of Fig. 6.1 shows the distribution of airspeed residuals of LDA measurements during the last test campaign. The data is normed and weighed to exaggerate the appearance of outliers for the purpose of comparisons against the standard.

6.1.3 Suggestions for Data Rate Compliance

As outlined in Section 5.2, the asynchronous measurement rate of the LDA represents one of its most significant challenges when compared to conventional systems. To nevertheless satisfy the analysed requirements, two potential solutions are proposed:

The first proposal builds on the statistical distribution of measurement intervals analysed in Section 5.2. It aims to specify a minimum average measurement rate for the LDA, ensuring that—with a defined probability—the resulting data rate meets or exceeds the required minimum. This can be done by calculating an average rate r for recording no measurement events k ($k = 0$) in an interval T with a probability $P(k)$ using Eq. (5.3).
With $k = 0$ the equation simplifies to

$$P(k) = e^{-r \cdot T}. \tag{6.2}$$

The probability for having no measurement events in one interval is assumed at $P_{MBTF} = 7.692 \times 10^{-5}\,\mathrm{h}^{-1}$ using the MTBF for Pitot tubes [53, Tab. 4]. To allow some budget for other failure conditions of the LDA the probability was reduced to $P(k = 0) = 5.0 \times 10^{-5}\,\mathrm{h}^{-1}$.
The interval in which at least one measurement event must be recorded was set using the analysed data rate in Section 4.3. The minimum output data rate given by ARINC 738-3 (8 Hz) as well as the minimum data rate assumed by analysing the frequency response (3 Hz) were used. Two cases were assessed. One, were at least one event has to be measured each interval (1) and one, where a measurement event only needs to be recorded every two intervals (2). Both cases are illustrated in Fig. 6.2.
The assumed values and their corresponding calculated minimum average rates can be seen in Table 6.1.

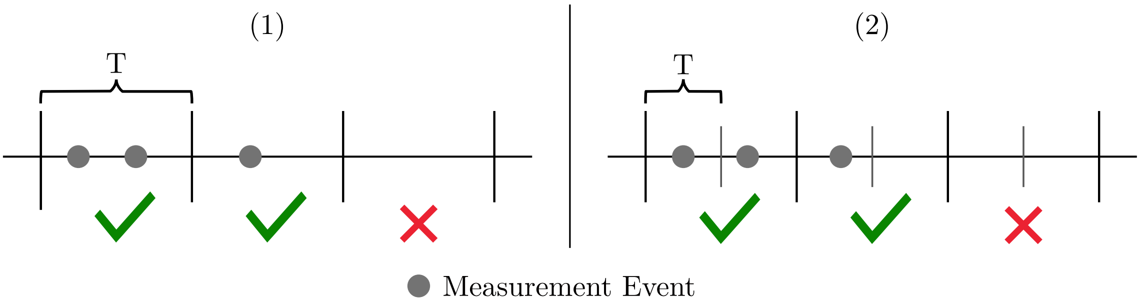

Figure 6.2: Distribution of measurement events on a rigid interval to showcase the limits chosen for compliance with a required data rate

Table 6.1: Minimum required data rates for the LDA

Data Rate f	Case	Transmit Interval T	Average Data Rate r	Variance λ
3 Hz	(1)	0.3333 s	29.71 Hz	9.903
	(2)	2 · 0.3333 s	14.86 Hz	1.855
8 Hz	(1)	0.125 s	79.23 Hz	52.81
	(2)	2 · 0.125 s	39.61 Hz	9.903

Another suggestion to achieve a constant data rate could be to use Kalman filters. A Kalman filter is an algorithm designed to estimate unknown variables based on a series of previous measurements [58]. Implementation as well as performance of such a system was analysed in a master's thesis by C. Mayer at the Institute of Technical Physics at DLR. Three filter types were assessed, a synchronous filter, an asynchronous filter and a filter relying on sensor fusion with the Inertial Reference System (IRS).
The synchronous filters synchronized the irregular measurement events in all four LDA channels to a constant data rate of 10 Hz. In most cases measurement outliers could be separated from actual jumps. Using the filters the estimation of TAS and AoA was enhanced, proven by a

reduction of the standard deviation by 16 %. However, the filter still showed insufficiencies when fast and short-paced manoeuvres in the span of seconds were performed.
Asynchronous filters processed measurements in the frequency of the measurement events. They showed potential but could not be proven suitable in the thesis because they reacted to hard on jumps.
The usage of sensor fusion with the IRS was also not successful but presented opportunities for further development because the higher data rate of the sensor could be used to bridge measurement event gaps. Potential solutions to alleviate the found deficiencies were proposed [59].

6.2 Integration of LDA Technology

This section describes different aspects, ideas, and possibilities for integration of the LDA on the basis of analysed advantages and risks. First, the positioning of the transceiver on the fuselage is assessed. Then, suggestions for the problem of the new measurement principle of the LDA are made. A new calculation process is introduced and different allocation of tasks presented. Finally, suggestions on the integration of LDA sensors into the air data architecture presented in Section 6.2.3 are made.

6.2.1 Position

The installation position of state-of-the-art systems is primarily decided by the quest to minimize the position error. This is also applicable for the LDA transceiver. Furthermore, as assessed in Chapter 5 the instrument has the advantage of being flush with the fuselage and being able to measure in a distance from the fuselage without disturbing airflow, inherently reducing the position error. Since the LDA measures three parameters at once, special care should be taken to compare the position error of all values at one location. In a conventional system for example the AoA measurement vane is generally located on the side of the fuselage while the AoS measurement vane is located on the bottom. This is because the aerodynamic disturbance of the fuselage is much lower at these positions. An LDA positioned on the side of the fuselage therefore might not be able to reliably measure AoS. Therefore, either the combination with state-of-the-art systems or multiple LDA systems at different positions may be needed.
Generally, it should be suggested to use methods like CFD or wind tunnel tests to determine an area where the position error is minimal.

Another requirement that could influence the position of the LDA is the angle limitations of the laser beams described in Section 5.2. Furthermore, the positioning of the instrument could be guided by laser safety requirements. For example, if the instrument is installed on the top side of the fuselage eye safety requirements can be fulfilled more easily. The simplest approach is a retrofit solution, wherein the LDA transceiver is installed in one of the existing viewports currently occupied by systems such as the Pitot tube or a measurement vane. This location offers several advantages:

- Reuse of existing fuselage designs, eliminating the need for structural modifications.
- Availability of pre-defined spaces for the transceiver and fibre-optic cable routing.
- The curvature of the fuselage allows all laser beams to be angled slightly forward into the airflow, fulfilling the requirement on installation angle while also achieving a flush fit.
- Pre-characterised position error, which has been demonstrated to be minimal for conven-

tional systems.

However, since the LDA measures at a greater distance from the fuselage, the position error may differ from that of traditional sensors and require reassessment. The installation of three LDA instruments at locations similar to the ones occupied by conventional instruments is illustrated in Fig. 5.1.

6.2.2 Integration of Data Streams

As outlined in Section 5.2, the computational process for the LDA must be revised. Unlike conventional systems where TAS represents the final output of airspeed calculations (see Section 2.2.3), the LDA directly measures TAS, effectively inverting the computational workflow. However, since TAS alone is insufficient for pilot operations as CAS provides a more intuitive and safer reference for airspeed monitoring (see Section 2.2.3) it must still be provided.

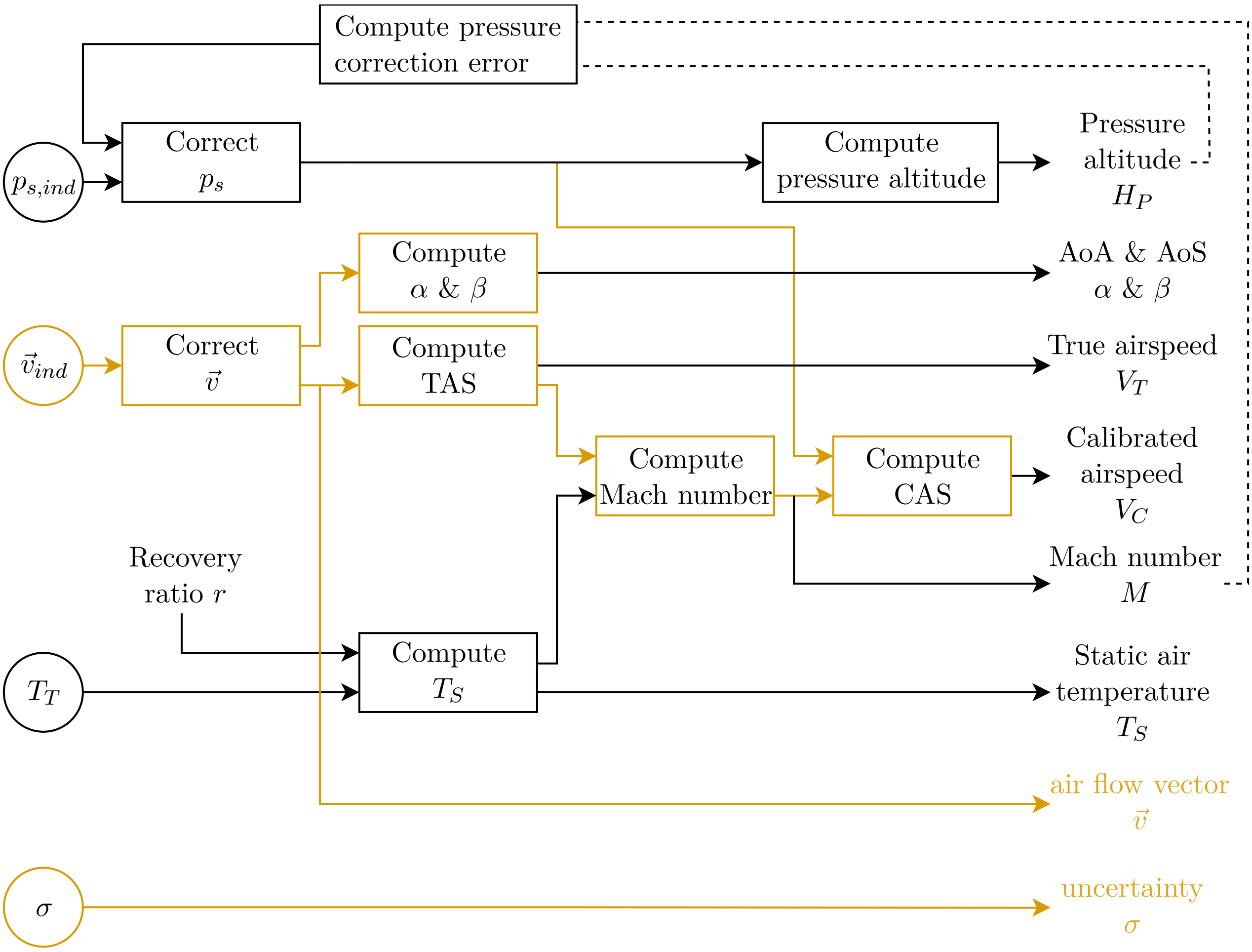

Figure 6.3: Schematic of a possible calculation process for integration of the LDA; Changes to the conventional process (see Fig. 2.4) including newly measured and output parameters as well as new calculation steps are coloured orange

The processing pipeline begins with error correction of the indicated airflow vector $\vec{v}_{ind}$, accounting for position, installation, and manufacturing errors. Subsequently, the corrected measurements are used to compute the TAS V_T as well as the AoA α and the AoS β. To derive the Mach number M, Eq. (2.9) is rearranged and solved for M. The CAS V_C is then obtained by solving the system of Eqs. (2.2) and (2.3) for the impact pressure (Q_C), which is substituted into Eq. (2.8) to yield:

$$\left[(1+0.2M)^2 \cdot p_s\right] - p_s = p_{a,SL}\left\{\left[1+0.2\left(\frac{V_C}{A_0}\right)^2\right]^{3.5} - 1\right\}. \tag{6.3}$$

Solving for V_C provides the CAS. Finally, the airflow vector $\vec{v}$ and its associated uncertainty σ can be directly output as additional results.

The allocation of computational tasks between the LDA and existing avionics systems has significant implications for the avionics bus layout, data labels, and overall system architecture. Three distinct integration scenarios emerge, each presenting unique trade-offs in terms of complexity, efficiency, and compatibility with current designs.
To retain most of the state-of-the-art architecture the LDA could do all the calculations described above internally. The system could even emulate the behaviour of a conventional ADM by transmitting total pressure to the ADIRU, thereby requiring no change to it. This makes this variant the *retrofit solution*.
However, the LDA would require not only static pressure and static air temperature inputs, necessitating modifications to the avionics bus layout, but also external calibration data, such as the installation position. Furthermore, consolidating multiple functions into the LDA significantly increases its complexity, undermining the intended simplicity of a retrofit. Additionally, the inefficient data flow is another problem of this approach. Computing total pressure from airspeed, transmitting the data to the ADIRU and then reconverting it back to airspeed introduces unnecessary processing latency and additional sources for errors and failures. Thus, while this scenario initially appears to preserve existing architecture, its hidden requirements and inefficiencies compromises its primary advantage.

An alternative solution shifts the computational processes almost entirely to the ADIRU. In this scenario, the LDA would solely function as an airspeed sensor, transmitting the local airflow vector $\vec{v}_{ind}$. The ADIRU then performs all subsequent calculations including error correction, coordinate system transformation, TAS derivation and CAS computation. The air data is distributed as vectors to the instruments/displays, the Flight Control System (FCS) and other downstream systems. This method eliminates unnecessary processing delays as the airflow vector can be relayed directly without prior processing. Additionally, it allows the LDA to be functionally divided from the air data processing systems and focused on its core role as a precise vector measurement device.
However, this approach requires the definition of new data labels for vector transmission over the avionics bus and demands substantial modifications to the ADIRU.

A third, hybrid scenario, offers a compromise by dividing the computational tasks between the LDA and ADIRU:
The LDA calculates TAS and flow angles (AoA, AoS) while the ADIRU handles the remaining calculations, such as CAS and Mach number. This separation allows the avionics bus layout to remain unchanged, as the LDA does not require additional inputs. Required modifications to the ADIRU are limited, while the LDA transmits only TAS and flow angles, reducing its computational load.

Integration of Uncertainty

The uncertainty is the novel parameter introduced by the LDA, as the airflow vector can be derived from TAS and flow angles, parameters which are already used by air data systems. The

purpose of these values is to characterise the integrity of the supplied data. There are several scenarios on how to integrate this parameter.
One approach is to set a threshold for the uncertainty in the LDA. If this threshold is reached, the LDA stops sending computed data over the avionics bus and instead indicates invalid data. For example, a possible implementation using an Avionics Full Duplex Switched Ethernet (AFDX) bus can utilise the Functional Status (FS) by setting it to the *ND (No Data)* or *NCD (No Computed Data)* position [60].
Another idea is to repurpose the maintenance word which most devices connected to the avionics bus transmit. It could not only cover monitoring data but also transmit the uncertainty to the ADIRU. As a third option, a dedicated label only for the uncertainty data could be created. In both cases, the ADIRU could compare the uncertainty across all systems and perform a voting-based validation of the supplied data.

6.2.3 Possible Integration Architectures

This section explores how LDA instruments can be integrated into the established air data architecture. Three different variants all derived from the air data architecture of an Airbus A320 (shown in Fig. 2.3) were considered.

LDA as a Full Backup Instrument

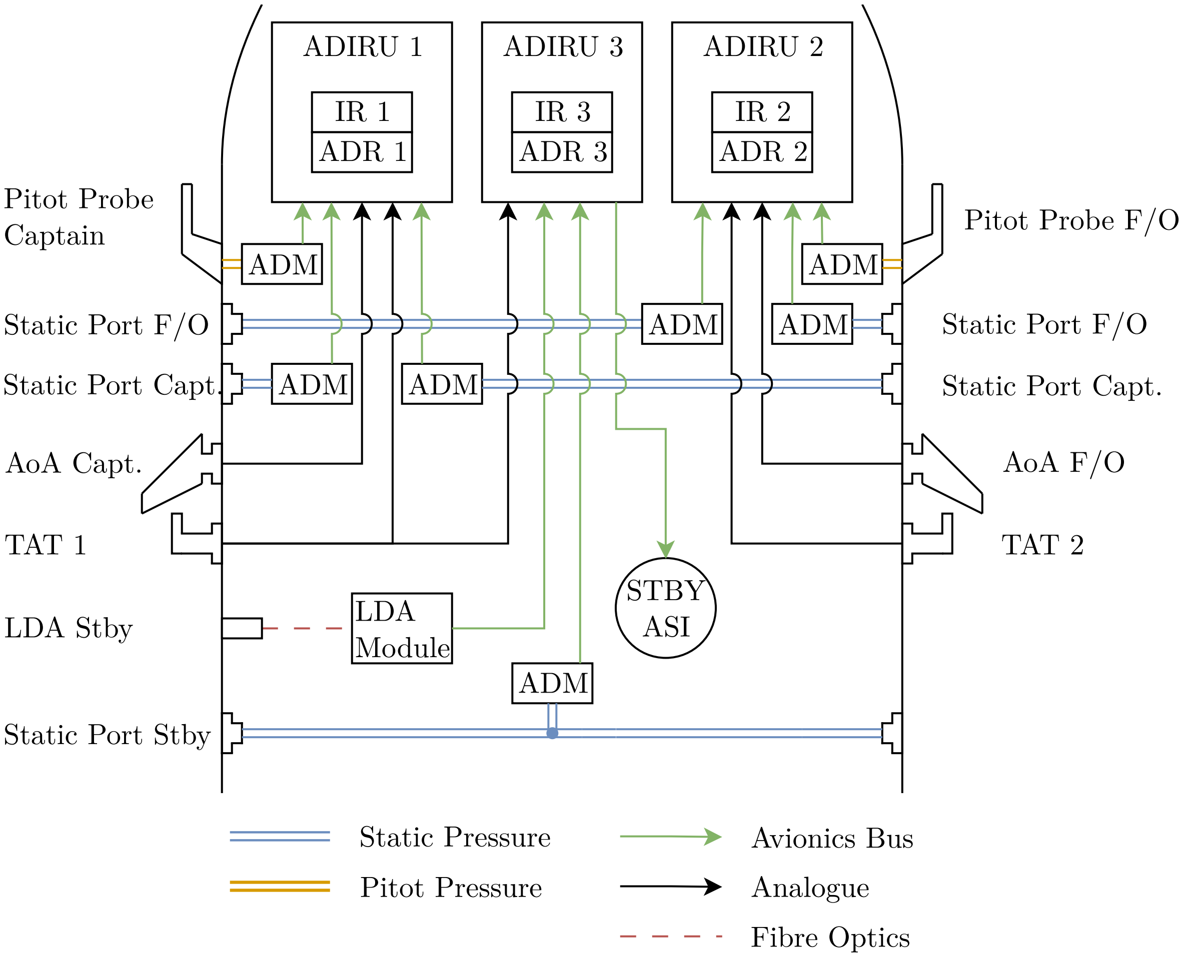

Figure 6.4: Schematic for integration of one LDA module as a standby instrument

The first suggested architecture, based on M. Lichtl's thesis, uses the LDA as a backup instrument. A schematic similar to this configuration is illustrated in Fig. 6.4. This means that the technology operates parallel to state-of-the art systems, replacing the Pitot tube and the AoA measurement vane while supplying airspeed, AoA and potentially AoA to the third ADIRU [12, Fig. 5.3]. The instrument itself is separated into the transceiver and the LDA Module. The transceiver is mounted flush with the fuselage and the LDA module can be installed in the electronics bay of the aircraft. The parts are linked via fibre optic cable which can be installed alongside electric cables. The LDA Module sends its data via avionics bus to the ADIRU number 3.
In a cockpit similar to most Airbus types, data supplied by the LDA would not be visible to the pilots in standard configuration on their displays. The data is only displayed on the backup instrument or if the pilots actively choose to display the standby data on their screens [34].
The standby airspeed instrument looses the direct total pressure input and therefore has to derive its airspeed from the ADIRU via an electronic connection.

LDA as a Partial Backup Instrument

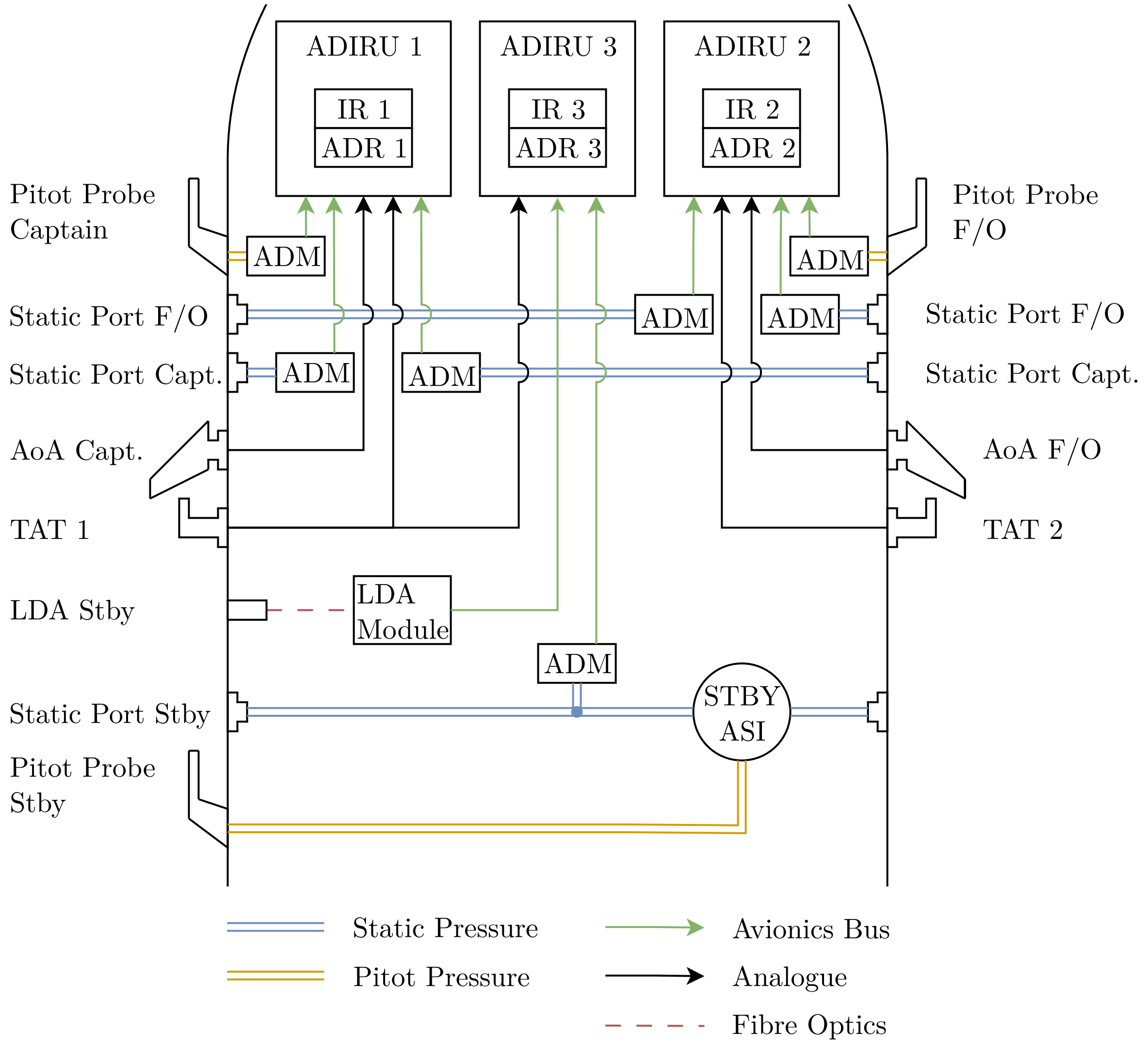

Figure 6.5: Schematic for the alternative integration of one LDA module as a standby instrument; Compared to Fig. 6.4 the Standby Instrument is supplied with total pressure by a Pitot Tube

However, this architecture introduces a significant safety concern: the standby instrument's reliance on the third ADIRU, the LDA, and the avionics bus for operation. Such dependency may compromise compliance with CS 25.1309 safety requirements. To mitigate this, an alternative schematic (Fig. 2.4) reinstates the Pitot tube for the standby airspeed instrument. In an air data system similar to the one of most Airbus aeroplanes, the information supplied by the LDA would be displayed on the primary flight displays and the standby instrument would display the data directly calculated from pressures. In the subsequent schematics the first proposal for the standby instrument is used.

Full Utilization of the LDA

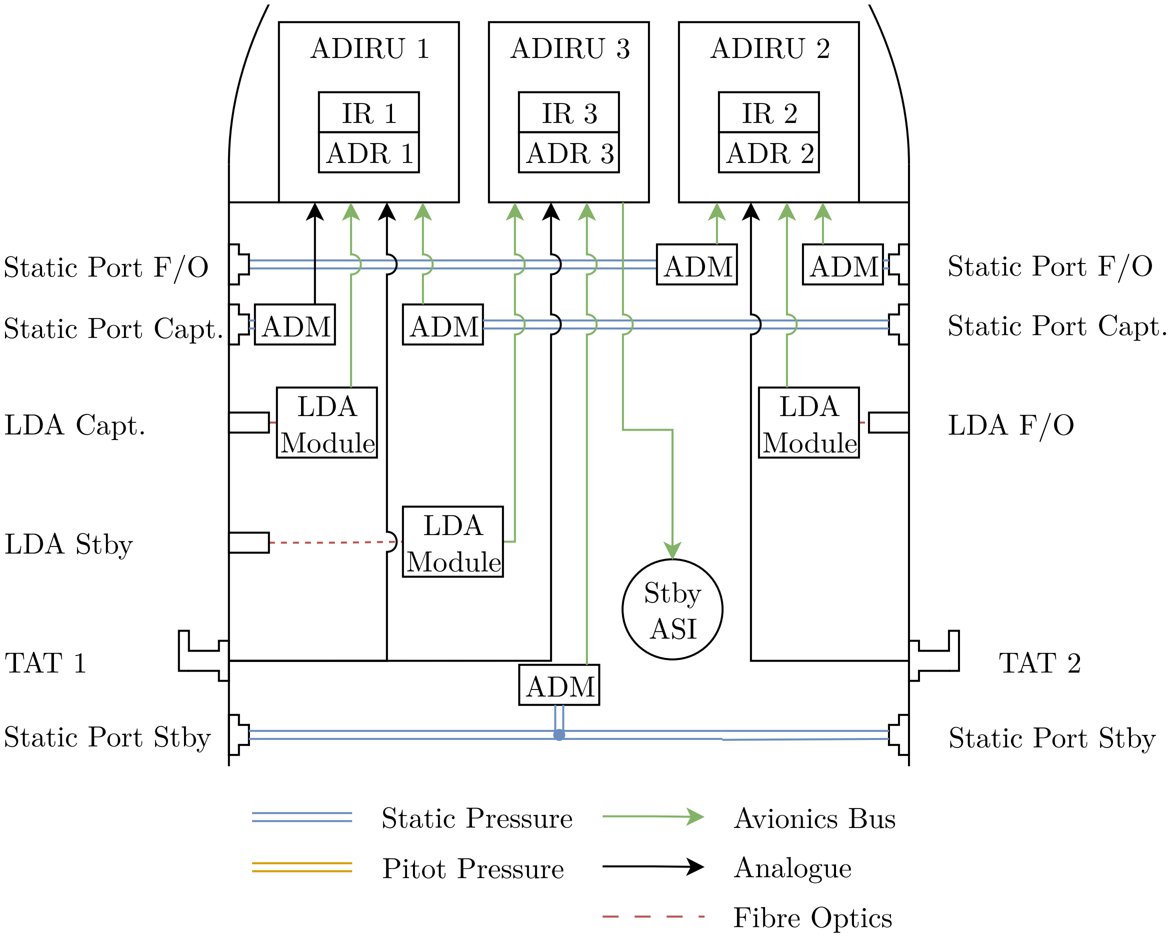

Figure 6.6: Schematic for integration of three LDA modules

Another possibility would replace all legacy airspeed and flow angle measurement systems with LDA technology. Just like the state-of-the-art systems, each LDA Module sends its data only to one ADIRU. The proposal is illustrated in Fig. 6.6.

Voting

Finally, the assembly can be configured in a way that allows *consensus* to be reached between the systems. A possible triplex configuration where each ADIRU is assumed to be one computer lane is shown in Fig. 6.7. An echo node is added to achieve *Byzantine fault tolerance*. More information on this can be found in [61], [62]. If the ADIRU is assumed to be duplex redundant, the echo node is not necessary.

The ADIRUs (and the echo node) are connected via a cross-communication data link (XLane). This way, the Reliable Broadcast (RBC) attributes can be achieved for the data exchange between all three air data systems. The voting can be performed either through a conventional voting mechanism like VoA3 or on the basis of the uncertainty supplied by the LDA (see Section 6.2.2). Combinations are also possible, for example the LDA can have an uncertainty threshold and the data is still voted on by the ADIRU.

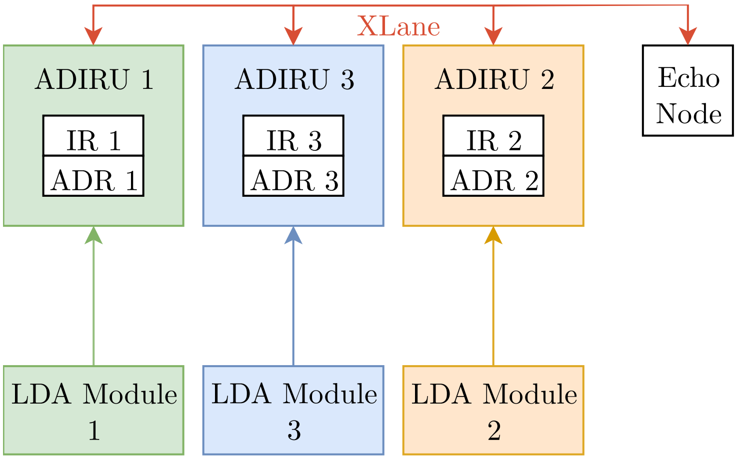

Figure 6.7: Schematic for integration of three LDA modules with voting by the ADIRU

7 Discussion and Suggestions

This chapter evaluates the validity of the assessments and recommendations proposed for the LDA in preceding chapters, including the underlying assumptions. Furthermore, the chapter presents proposals to align the CSs analysed in Chapter 3 with the distinctive characteristics of the LDA. Each specification is discussed in terms of its applicability and necessary changes to it. Additionally, possible new requirements are suggested.

7.1 Proposed Performance Requirements for LDA Systems

Most recommended performance requirements for the LDA were developed on the basis of minimum performance requirements of the output data of state-of-the-art systems. Therefore, they also only constitute minimum performance requirements. The validity of the suggestions in Section 6.1 is discussed in the following section.

7.1.1 Airspeed Data Rate

The suggested average rate for LDA measurements relied on several assumptions for the probability of no measurements $P(k)$, the required measurement interval T and if one or two intervals are allowed to have no recorded measurements (scenario (1) or (2)). The probability $P(k)$ can be deemed to be acceptable. Nearly all failures of a state-of-the-art system result in no or wrong measurements since there are no integrity checks. The LDA may have other failure modes outside not delivering an airflow vector in one interval. Therefore, allowing a budget for these other failures was necessary, and the chosen probability appears to be a good preliminary and conservative fit.

The required data rates are also acceptable since they are picked based on the minimum performance standard and analysed physical limits. A data rate of 3 Hz seems to be a more realistic minimum requirement since it relies on physical limitations rather than output specifications. However, to factor in the case of higher performance demands it was adequate to include the higher data rate of 8 Hz

As for the scenarios, (2) can be assumed to be more realistic. No measurement in 0.6667 s in the worst case may not be noticeable by a Pilot. Commercial Air Transport aircraft are not involved in highly dynamic flight manoeuvres so this scenario should also be no problem for the FCS. Additionally, the low data rates more often occur at high altitudes where air density is low and therefore less aerosol particles are in the air. At these heights, large aircraft are in cruise which is not a very dynamic phase of flight and not a high data rate is needed. The more dynamic manoeuvres of takeoff, approach, and landing are at lower altitudes where the aerosol density is generally higher, and therefore the data rate is less of a concern.

Consequently, the minimum average rate for LDA of around 15 Hz can be seen as a preliminary baseline for the requirements for applicability of the LDA.

According to experts, average data rates of 14 Hz up to 80 Hz seem possible for near future iterations on LDA technology, so the requirements calculated in this work look promising for future implementation and allow potential performance improvements. Overall, the method is very advantageous since it allow the description of average requirements independently of the aerosol distribution.

Kalman filters were assessed as a method to ameliorate the data rate of the LDA. However as discussed by C. Mayer, the filters need to be further developed and analysed. Especially, the certification of Kalman filters needs to be assessed.

7.1.2 Airspeed Accuracy

The method of converting accuracies from CAS to TAS produces a baseline for accuracy requirements. CAS and TAS are equal to each other at sea-level and standard atmosphere. The airspeed tolerance increases with the aircraft's altitude. Therefore, the accuracies set by the standards can still be used as a conservative baseline for instrument accuracy, even with the airspeed as TAS.
As a comparison of the indicated residuals of the LDA to the required accuracies (shown in Fig. 6.1) only CS-25 is applicable. This is because the LDA was installed in the aircraft and therefore not only internal errors were at work but also integration errors such as installation tolerance or position error. Interestingly, the data provided by the LDA is already very accurate and mostly within the accuracy boundaries set by CS-25. This is especially remarkable since the design used in these flight tests was not focused on achieving a high accuracy but served merely as a proof-of-concept. This achievement gives an outlook on the possible improved performance of the system.
The other standards are much more strict concerning the required airspeed tolerance since they only focus on the instrument itself, outside the integration into an aeroplane. As already assessed in Section 4.3 the constant output accuracy requirement of ARINC 738-3 is not very sensible since errors increase with growing airspeed. Therefore, the definition based on the accuracy required by CAS seems to be more fitting as well.

7.1.3 Flow Angles

Very few requirements on the AoS and AoA were found. Since the LDA functionally groups the measurement of flow angles with the airspeed, the data rate and the accuracy are both dependent on the generally stricter airspeed requirements. The data rate of the AoA and AoS data will be the same as the one for airspeed. The 3 Hz defined above as the plausible minimum data rate for airspeed measurements does not match the 8 Hz set as a minimum output requirement (see Table 4.2). Whether the output transmit intervals set by the standard are actually based on physical constraints or not could not be finally assessed. However, the analysis of the airspeed requirements opens doubt on the foundation of the requirement.
The only accuracy demand for the flow angles was assessed at ±0.25°, no conflicts to this requirement could be estimated.

7.2 Applicability of Certification Requirements

The next section discusses the requirements assessed in Section 3.3 and whether they are applicable to the LDA. Most of the requirements are very precise in nature but may have a more general intention behind them. Different approaches will be discussed in order to decide whether the LDA can comply with a requirement. As assessed in the previous chapters the two technologies, conventional and LDA, have key differences in their working principle which is why some requirements in CS-25 are very specifically formulated for conventional systems. LDA technology may literally not be able to comply with them and the requirement is therefore not applicable. Other specifications may be technically applicable to the LDA, but their original intention is lost, requiring changes to it (see Section 7.4).

CS 25.1323(a) primarily demands the determination of the instrument error as well as its subsequent compensation by calibration. While the specification concentrates on the instrument and not on the measurement system it implicates that the sensors must be able to supply all the data necessary to calculate TAS at standard sea-level which equals the CAS. The LDA directly measures TAS and together with other sensors already installed on the aircraft is also able to supply CAS to a system. The specification is generally applicable. However, a passage of the requirement focuses on the instrument having to show minimal error with total and static pressure applied. Technically, this can be complied with by the LDA since the pressures are also applied on the transceiver, they are just not used for measurements. From another point of view, this could be interpreted as a requirement for every instrument measurement to be based on pressure measurements, which would make it a prescriptive requirement. In both cases CS 25.1323 (a) is not applicable to the LDA or at least requires changes.

The next requirements, CS 25.1323 (b), (c), (d) and (e) cover the accuracy of the system. CS 25.1323 (b) defines the system error as the relation between IAS and TAS and gives specific flight states at takeoff where this error must be determined. This could be because these situations resemble edge cases with very high performance demands on the system. Especially a takeoff with an engine failure on one side may lead to a high AoS and therefore a high error (see Section 4.1.2). Furthermore, all speeds are defined as CAS. With new calibration methods for the LDA (see Section 6.1.1), the requirement is applicable, but changes are still necessary.

CS 25.1323(c) concretises the system error by characterising the tolerance as displayed in Fig. 4.3. On the one hand sight this may be to set concrete error bounds especially in edge cases like the engine loss scenario demanded by the requirement before. On a more fundamental level, it could intend a limit to the tolerance of measurements between all systems installed in the aeroplane. All in all, the instrument just has to be as accurate as required by the standard. Since this seems to be within reach, as discussed in Section 7.1.2, the requirement is applicable to the LDA.

The next two demands, CS 25.1323(d)&(e) may soften the hard set limit from CS 25.1323(c) in the edges of the flight envelope. This could be due to an increased position error (see Section 4.1.2) near the stall speed and above the maximum operating speed. The LDA has not been fully tested in this regime, however theoretically there are only minor differences between conventional systems and the new technology in this regard. As introduced in Section 5.3, the LDA generally has a lower position error due to its flushness with the fuselage. The high AoA flown near stall speed also does not have the same effect on the LDA as on conventional systems. All in all, the requirement is applicable.

The next requirements (CS 25.1323(f)&(g)) forbid the occurrence of conflicting air data and overly high lag during takeoff. Crew workload during takeoff is especially high, so systems should be highly reliable in this phase. Since lag is much lower for the LDA compared to conventional systems this is not as much of a concern. The anticipated high accuracy of the LDA as well as the possibility to instantly analyse integrity of the instrument also makes these risks less critical. However, a low measurement rate of the LDA could appear indistinguishable to lag since it has the same effects. Therefore, the requirement is still necessary and applicable.

All the following requirements describe the robustness of the system. CS 25.1323(h) has clear requirements for arrangement and design of the sensor. Since moisture and blockage also concern the LDA the demands are applicable.

However, CS 25.1323(j) is specifically limited to pitot tubes. Therefore, it is not applicable although the underlying content, the arrangement of the sensors to protect them from birdstrikes, is still necessary.
Both CS 25.1324 and CS 25.1326 are entirely applicable to the LDA since icing and rain are still a concern for the instrument (see Section 5.1).

7.3 Integration of LDA Technology

Integration of Data Streams

The calculation process outlined in Section 6.2.2 ensures the provision of all parameters required by conventional airspeed indicating systems. Among the presented variants, the final approach where the full airflow vector is transmitted to the ADIRU, proves the most advantageous.
The first variant reveals that integrating the calculation process without modifying the ADIRU or avionic bus architecture is infeasible. By contrast, transmitting the local three-dimensional airflow vector streamlines LDA development by assigning distinct functional roles. The LDA no longer requires aircraft-specific installation data, thereby minimising design dependencies, while all calibration remains centralized in the ADIRU. Additionally, this method achieves the highest performance gains, as the corrected airflow vector is supplied directly to the FCS.

Integration Architectures

The integration scenarios introduced in Section 6.2 can be discussed with the main focus on possible advantages and disadvantages as well as possible problems for certification. The main priority for every integration variant should be its safety and therefore its compliance with CS 25.1309 (see Section 3.2). The design must be assessed using the specifications and methods provided by this section. Nevertheless, some qualitative statements can be made as strengths and weaknesses are discussed.

The LDA backup instrument solutions (see Section 6.2.3 and Section 6.2.3) have several key advantages. Most importantly, dissimilar redundancy minimises Common Cause Failures between redundant instruments [12, pp.46-47]. This is especially important since the LDA is a new technology and in the off chance of still undiscovered failures during flight air data is provided by proven instruments. As assessed, the data supplied by the LDA would not be used in normal operation by the flight crew in a state-of-the art setup without voting of air data. Therefore, this scenario could allow OEM to collect lots of performance data in the real world, while the technological risk stays low and flight crew are provided with a self-diagnosing airspeed system in case of an emergency.
The two variants for supply of the backup airspeed indicating instrument (seen in Section 6.2.3 and Section 6.2.3) give flexibility while considering possible safety concerns. The first, fully digital variant makes the standby ASI reliant on the correct function of one ADIRU, the LDA as well as the avionics bus including the power supply of all these parts. While the proposal is therefore likely less safe, it fully replaces the standby pitot-tube and circumvents possible certification hurdles.
These could be caused by the parallel use of different types of airspeed indication instruments. Due to the differences between conventional systems and the LDA, the backup instrument could disagree with the rest of the systems much more than usual. If the difference is causing difficulty for the pilot during takeoff (CS 25.1323 (e)) this integration scenario can not be certified.
However, it can be argued that if the system error guidelines set by CS 25.1323 (c) are complied with, at least from an accuracy standpoint no conflicting data can be supplied. As already discussed, the compliance of the LDA with this requirement is within reach (see Section 7.1.2), but lag in form of the asynchronous measurement rate may remain a problematic factor.

The use of only the LDA (see Section 6.2.3) allows full replacement of all AoA measurement vanes and (nearly) all pitot tubes (depending on the standby instrument integration). If all conventional systems are replaced the problem of possible differences between the systems is reduced and certification might be easier, however dissimilar redundancy is lost.

The possible challenges are also not applicable if the air data is voted (see Section 6.2.3). Modern aircraft systems commonly use this principle and the air data system could benefit a lot from its introduction in terms of safety and reduction of pilot workload.

7.4 Possible Regulatory Changes

As discussed in Section 7.2 changes to the specifications are needed. It must be stressed that these suggestions are not made in order to make the LDA comply inherently. They should rather restore applicability of the certification requirements and/or their original intention. Additionally, entirely new requirements may be needed to react to new hazards (identified in Section 5.2) or to be able to fully make use of the advantages identified in Section 5.3. The changes introduced may be recorded in a SC as described in Section 2.1.3 during a potential certification process of the system.
An alternative would be a full rewrite of CS-25. As with the change from Amendment 4 to 5 of CS-23, the whole CSs could be rethought to only include objective and design-independent requirements rather than ones that focus on precise technical solutions [63]. This is highly complex and involves lots of effort and coordination for both the EASA, the FAA and industry partners to not only rewrite the requirements but ensure compatibility with the old versions. In light of the complexity, a possible implementation as a SC was assumed for this work.

7.4.1 Adaptation of the CS-25 requirements

All airspeeds mentioned in requirements are defined as CAS. While the LDA directly outputs TAS which necessitates a conversion, the definition in CAS can still be recommended since it makes these values independent of air density.

CS 25.1323(a) must be generalised to be independent of pressure based airspeed measurement. Depending on the safety analysis of different integration architecture (see Section 6.2.3) the requirement could be restricted to require at least one pressure based (backup) instrument or could totally let go of the wording requiring the total and static pressure to be applied. However, this may want to be avoided since it is highly design-specific. Alternatively the intention of the requirement can be caught by requiring an instrument to "accurately characterise airspeed".

CS 25.1323 (b) requires some adjustments to retain the intention of the demands. Defining the system error as the relation of IAS and CAS was done to mandate the characterization of most systematic errors that can be calibrated (see Table 4.1) especially position error (see Section 4.1.2) and installation error (see Section 4.1.2). Due to the changed measurement principle of the LDA the error between IAS and CAS is non-existent. The systematic errors lie between the locally measured airflow vector or Local True Airspeed (LTAS) and the compensated airflow vector or TAS. The relationship between these parameters should be changed to define the system error.
The requirement may be amended by situations particularly demanding on the accuracy performance of the LDA, comparable to an engine failure being one of the most error-prone situation for a pitot-static system.

CS 25.1323(c) defines a quantitative tolerance for airspeed. For the usage of the LDA the definition can be kept as is, as discussed in Section 7.1.2.

As discussed in Section 7.2 CS 25.1323(d)&(e) are necessary for LDA technology. Like in CS 25.1323(b), the error has to be defined as the relation between LTAS and TAS, not IAS and CAS.

As already analysed in Section 7.2, the LDA is also susceptible to external damage and blockage of its windows. Therefore, CS 25.1323 (h) is applicable. The prevention of entry of moisture and blockage is more design specific to Pitot-static system but still necessary, and it is suggested to move these requirements to the corresponding MOC or AMC. These include the demand for tubing to be designed to avoid chafing and excessive bending. This can be amended to include fibre optic cables. The AMC could also include a provision on design and arrangement of the LDA to prevent overt exposure to rain.

CS 25.1323 (j) must be changed to not only apply to pitot tubes. A possible solution would be to draw inspiration from CS 25.1324 and define applicable instruments as "flight instrument external probes systems" with a limitation to the ones responsible for the measurement of airspeed.
Table 7.1 summarizes all requirements and corresponding suggestions.

Table 7.1: Requirements on airspeed indicating systems in CS 25.1323 [16]

Airworthiness Code	Description	Applicability	Suggestions for adaption for LDA
CS 25.1323(a)	Instrument calibration	Partially	instrument definition without requirement for pressures
CS 25.1323(b)	System calibration	Applicable	redefinition of system error
CS 25.1323(c)	Accuracy requirements	Applicable	no change necessary
CS 25.1323(d)&(e)	Reduced accuracy requirements near V_{SR} and V_{MO}	Partially	redefinition of system error; identification of performance demanding states
CS 25.1323(f)&(g)	Misleading readings at takeoff	Applicable	
CS 25.1323(h)	Guidelines for system arrangement and design	Partially	Amendment of MOC/AMC with changed risks
CS 25.1323(j)	Requirement regarding birdstrikes and damage	Applicable	wording "pitot tube" must be generalised
CS 25.1324	Ice prevention and heating	Applicable	
CS 25.1326	Alert in case of heating failure	Applicable	

7.4.2 Possible Further Requirements

Data Rate

Current airspeed indicating systems supply a continuous stream of data as pressure sensors can sample the pressure in fixed intervals. For the LDA this is not the case (see Section 5.2) and missing airspeed data has harsh safety implications. Therefore, the addition of a accurately defined physical data rate and bus data rate as a requirement seems to be recommendable.
In a SC, this could be done (see Section 2.1.3) with a requirement similar to CS 25.1323 (g) and (f). The results of an insufficient data rate are comparable to a high lag time. Therefore, a

requirement with similar wording could be set up but not only limited to takeoff and the takeoff distance but applicable to the whole flight.
The method for assuring a minimum data rate developed in Section 6.1.3 could be set up as MOC to demonstrate compliance with this requirement.

Flow Angles

No specifications explicitly requiring the measurement of AoA or AoS were found. However, in CS-25 the use or measurement of AoA is implicitly required or mentioned by many specifications. It seems recommendable to at least require the calibration of the AoA and AoS and define a system error like in CS 25.1323 (b).

Installation Practices for Fibre Optic Components

The LDA technology introduces optic components such as fibre optic cables to aviation. Some industry norms were found that give recommendations on the installation and design of optical components in aircraft. However, they were developed for the use of optical components for communications. The LDA technology introduces much higher power laser signals and e.g. polarization-maintaining (PM) fibres and requirements further regulating the design similar to paragraph H in CS-25 are needed. These may also factor in possible design guidelines to enhance work safety and ensure installation correctness during maintenance.

Supplementing MOPS/MPS and Industry Norms

Depending on integration the MOPS and MPS as well as industry norms regulating Air Data computers and avionic buses must be amended to include the new calculation processes and labels necessary for the implementation of LDA technology. Entirely new standards will be needed for the instrument itself which includes performance requirements and the definition of environmental conditions for the instrument in accordance with DO160G.

8 Conclusion and Outlook

This thesis evaluated the feasibility of certifying Laser Doppler Anemometry for airspeed and flow angle measurement in CS-25 large aircraft by comparing its performance against conventional Pitot-static systems and AoA vanes. The analysis reveals that while the LDA offers significant advantages in integrity, aerodynamics and maintenance, its adoption requires targeted adaptions to certification standards and integration strategies to address novel risks and operational differences.

Concerning regulatory compatibility, conflicts mostly due to prescriptive requirements (e.g. CS 25.1323) which assume pressure-based measurements were found. Critical deviations from conventional measurement methods included the direct measurement of TAS by the LDA which necessitates conversion standards and changed performance characteristics including the asynchronous data rate of the LDA.
Notable advantages over conventional systems include real-time uncertainty calculation and instrument self-diagnostics, which effectively rule out undetected failures, and thus unreliable airspeed measurements, inherent to Pitot-static system. Preliminary analysis estimates a much lower probability for the measurement of incorrect airspeed data compared to Pitot probes. The flush mounted design minimizes position error and drag, enabling measurements outside the boundary layer and possibly upstream of shockwaves. The technology could replace up to three conventional sensors with one unit simplifying fuselage design and maintenance.
Several risks and challenges of a LDA system were identified and possible mitigation strategies presented. This included erroneous measurements due to large particles which will be resolved by analysis of the scattered light. The impact of large particles and methods on how to account for their influence should continue to be monitored in the ongoing development of the LDA, especially with data from the upcoming flight tests of the FuLDA instrument. Another risk was identified in the installation and manufacturing tolerance of the instrument. This coincides with the need for appropriate calibration methods for the new technology mandated by certification requirements. A possible solution in form of a proposed Ground Test Equipment (GTE) based on a rotating engraved particle simulator disk was suggested.
The aerosol dependency and the resulting asynchronous data rate were identified as the primary challenge. It was proposed to address it by mandating statistical performance limits and implementing Kalman filters.
In order to define such constraints, the conventional performance values were assessed for their basis on physical fundamentals. Some required output parameters were found to not be compatible with requirements based on physical phenomena, therefore corrected output performance figures were recommended. The calculated statistical performance limits for a LDA system proved to be achievable by future iterations of the instrument, validating its further development. In this regard, further research on the effects of a low data rate on the avionics systems and crew can be recommended in order to further confirm the assumptions used to calculate the requirements. In terms of accuracy, the LDA TAS output was validated against regulatory requirements by converting CAS tolerances to TAS equivalents. Despite the early development status of the technology, it was found to already comply to the requirements of CS-25 in most tested flight states.
Several aspects of integration were covered including suggestions on the placement of the LDA transceiver and solutions for the different measurement principle and different integration architectures. Key areas identified to need changes were the avionics bus which needs to support new data labels and the ADIRU which has to handle TAS-CAS conversion. While an integration of the LDA as a standby instrument offers itself as a safe starting point for inclusion of such technology on aircraft, possible certification hurdles due to possible disagreement between

systems were identified. As a viable solution, an ADIRU voting logic was suggested. With further validation of the system a full replacement of conventional systems can be envisioned. A more in depth analysis of the integration scenarios and their technological implementation is recommended.
In the short term, certification via a Special Condition (SC) can be envisioned. For this, recommendations for changes of the certification requirements to reflect the analysed risks and differences compared to conventional instruments were made. Furthermore, among others, a new requirement to include demands for data rate was proposed since this is one of the key challenges for implementation of the LDA.

As anticipated in the introduction, the CSs as well as the industry standards proved to be highly specific to Pitot-static system systems. In the long run, a complete rewrite of CS-25 is necessary to remove requirements specific to technologies and instead define safety-based objectives. Since such a rewrite was already done for CS-23 in 2017, an analysis reusing the comparison done in this work and focusing on the applicability of the certification requirements in CS-23 to the LDA could be interesting. Partnerships with the industry, especially the OEMs, are necessary to stipulate the required momentum to not only tackle a giant task such as the rewrite but also to effect the change and development of industry standards. Meanwhile, a partnership with regulators through one of their programs for innovative technologies should be pursued as well. These steps will ensure a consistent harmonization of the regulatory environment for the next generation of air data systems.

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A Appendix

Table A.1: Minimum CAS accuracy according to AS8002B [21, Tab. 3]

Inch-Pound Units		SI Units	
Airspeed Knots	Tolerance ±Knots	Airspeed km/hour	Tolerance ±km/hour
50	5.0	90	9.30
80	3.0	150	5.60
100	2.0	180	3.70
120	2.0	220	3.70
150	2.0	280	3.70
200	2.0	370	3.70
250	2.4	460	4.40
300	2.8	560	5.20
350	3.2	650	5.90
400	3.6	740	6.70
450	4.0	830	7.40

Table A.2: Selected output parameters for the ADIRU/ADM according to ARINC 738-3; Derived from [23, Tab. 7-2]

Parameter	Octal Label	Data Type	Computer Operational Range		Accuracy	Transmit Interval (msec)	
			Min	Max		Min	Max
Indicated Impact Pressure (Qci)	215	BNR	0 mbar	372.5 mbar	±0.25 mbar	125	62.5
CAS	206	BNR	30 kt	450 kt	±5 kt at 60 kt ±2 kt at 100 kt ±1 kt at 300 kt ±1 kt at 450 kt	125	62.5
Allowable TAS	207	BNR	150 kt	450 kt	±0.25 mbar	125	62.5
TAS	210	BNR	100 kt	599 kt	±4 kt	125	62.5
TAS	230	BCD	100 kt	599 kt	±4 kt	500	125
Indicated AoA #1	221	BNR	-60 °	60 °	±0.25°	62.5	31.3
Indicated AoA #1 (left)	222	BNR	-60 °	60 °	±0.25°	62.5	31.3
Indicated AoA #1 (right)	223	BNR	-60 °	60 °	±0.25°	62.5	31.3
Indicated AoA #2 (left)	224	BNR	-60 °	60 °	±0.25°	62.5	31.3
Indicated AoA #2 (right)	225	BNR	-60 °	60 °	±0.25°	62.5	31.3
Computed AoA	241	BNR	-60 °	60 °	±0.25°	62.5	31.3
Indicated AoS	250	BNR	-60 °	60 °	±0.25°	62.5	31.3
Corrected AoS	253	BNR	-60 °	60 °	±0.25°	62.5	31.3
Maintenance word #6	155	DIS				500	250
Maintenance word #7	156	DIS				500	250

Table A.3: Performance data of a Keller Serie 33X piezoresistive pressure sensor [51]

Parameter	
Range	0-30bar relative pressure 0-1000bar absolute pressure
Resolution	0.0005% FS
Accuracy	$\leq \pm 0.05\% FS \quad (20°C - 25°C)$ $\leq \pm 0.1\% FS \quad (-10°C - 80°C)$