Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

Executive summary

In-Flight Evaluation of an Optical Standby Air Data System

Problem area
Within the NESLIE (New Standby Lidar Instrument) project, an innovative optical air data system was developed, built and tested. The system applies the LiDAR technique to measure air speed. This principle differs from the customary pitot-static one, thereby reducing common failures in the total system and increasing flight safety. The performance of the system is evaluated in flight.

Description of work
The in-flight evaluation of the system was performed in the NLR Cessna Citation II research aircraft during spring 2009. The NESLIE system was successfully integrated in the research aircraft and a flight test campaign was flown. A large data set of measurements was gathered and evaluated. The performance of the system as a function of the atmospheric conditions was measured and the output of the system was compared with Citation air data.

Results and conclusions
This paper describes the standby air data system under test as developed in the NESLIE project, describes the integration of the system in the NLR Cessna Citation II research aircraft, gives an overview of the techniques applied during the flight test campaign and presents the results of the analysis of recorded data.

The evaluation results are very promising and show that the system can be calibrated for installation effects at the selected position. A large progress was made with respect to the state of the art in optical air data systems.

Applicability
Flight testing of the system in an already instrumented and relatively easy-to-modify research aircraft as presented proved to be effective and efficient. The aircraft will be made available for evaluations of the LiDAR based systems to be developed in the DANIELA en DELICAT projects.

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Contents

IN-FLIGHT EVALUATION OF AN OPTICAL STANDBY AIR DATA SYSTEM

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Abstract: Within the EC project NESLIE (New Standby Lidar Instrument), an innovative air data system was developed, built and tested. The system applies the LiDAR technique to measure air speed. This principle differs from the customary pitot-static one, thereby reducing common failures in the total system and increasing flight safety. The NESLIE system measures air speed in four different directions. The aircraft's TAS (True Air Speed), AOA (Angle Of Attack) and SSA (Side Slip Angle) are calculated from these speed measurements. The development resulted in a first test system. The in-flight evaluation of the system was performed in the NLR Cessna Citation II research aircraft during spring 2009. The performance of the system as a function of the atmospheric conditions was measured and the output of the system was compared with Citation air data. This paper describes the standby air data system under test as developed in the NESLIE project, describes the integration of the system in the NLR Cessna Citation II research aircraft, gives an overview of the techniques applied during the flight test campaign and presents the results of the analysis of recorded data. Flight testing of the system in an already instrumented and relatively easy-to-modify research aircraft as presented proved to be effective and efficient.

1 ABBREVIATIONS

AAB	Angle of Attack from Boom
ANSI	American National Standards Institute
AOA	Angle Of Attack
ARINC	Aircraft Radio Incorporated
CFD	Computational Fluid Dynamics
CMS	Citation Measurement System
EC	European Commission
FL	Flight Level
FTE	Flight Test Engineer
GPS	Global Positioning System
IEC	International Electrotechnical Commission
KIAS	Knots Indicated Air Speed
LiDAR	Light Detection And Ranging
MPE	Maximum Permissible Exposure
NATO	North Atlantic Treaty Organization
PCU	Process Control Unit
RTO	(NATO) Research and Technology Organization
SFTE	Society of Flight Test Engineers
SSA	Side Slip Angle
TAS	True Air Speed
TO	Take-Off
UTC	Universal Time Coordinated

2 INTRODUCTION

Optical technologies for air data gathering have been investigated and introduced in avionics and flight testing (see ref. 1 and 2). Measuring the air speed at a large distance from the aircraft can lead to systems that detect turbulence and wake vortice in front of the aircraft, thereby enhancing flight safety (see ref. 3 and ref. 4), or it can lead to systems that measure air data during the first flight of an aircraft type if calibrations of sensors are not available (see ref. 5). Flow measurements close to the aircraft require much less laser power than air speed measurements further away from the aircraft, but also require a calibration of the data to obtain aircraft air data, similar to calibrating a pitot-static system.

Such a short-range innovative lidar-based air data system was developed, built and tested in the NESLIE (New Standby Lidar Instrument) project that is supported by the European Commission. The system applies the LiDAR technique to measure air speed in four different directions. The aircraft’s TAS (True Air Speed), AOA (Angle Of Attack) and SSA (Side Slip Angle) are calculated from these speed measurements. The development resulted in a first test system of a future generation stand-by instrument for commercial aircraft.

This system has no probes protruding into the air contrary to traditional pitot-static air data systems. The laser-based instrument has drastically different failure modes compared with traditional systems, reducing the probability of common failures, which increases flight safety. Furthermore, the size, weight and cost of the system can be and need to be small and will be further reduced in future by applying emerging optical technologies.

The system was developed in the NESLIE consortium which consisted of following participants: THALES Avionics (coordinator, France), AIRBUS France, DASSAULT Aviation (France), EADS CRC (Germany), TEEM Photonics (France), IMEP (France), XenicS (Belgium), ITI-CERTH (Greece) and NLR (The Netherlands).

The in-flight evaluation was performed in the NLR Cessna Citation II research aircraft during spring 2009. The flight test set-up, the flight test operations and the evaluation results are presented in this paper.

3 OBJECTIVES

The flight test objective was to prepare and execute the NESLIE flight tests in such a way that the required data could be obtained safely, effectively and efficiently. The data analysis objective was to evaluate:

- the performance of the NESLIE system as a function of particle concentration, size, type and mixture, for which flight test altitudes, weather conditions, visibilities and locations (over water, rural and urban areas) were varied.
- the correlation between the NESLIE system output and aircraft reference data derived from standard aircraft systems and specific flight test instrumentation.

4 SET-UP

4.1 Aircraft

NLR's Cessna Citation II research aircraft (Figure 1) was selected for testing the new air speed measurement system. Selection was based on the aircraft's flight envelope. This envelope matches the envelope for which the new air speed measurement system had to be evaluated. The Citation II aircraft can fly up to an altitude of 43,000 feet with speeds up to 262 KIAS / Mach 0.705.

Figure 1 **NLR's Cessna Citation II research aircraft ready for a NESLIE test flight from Amsterdam Airport Schiphol with the modified emergency hatch and noseboom.**

4.2 Experimental Equipment

The new air speed measurement system under test is based on four LiDARs. The four laser beams, invisible to the human eye, are aligned and focussed on a very small volume just outside the aircraft fuselage (Figure 2). Looking further away in the free-stream is not possible, as the system would then become too big and heavy for a future generation stand-by instrument for commercial aircraft. Consequently, calibration of the system will be needed, as for a pitot-static system. Calibrations are presented in section 6.

The key characteristics of the light from the laser units are:

- Wavelength: 1.55 μm
- Beam waist at focal point: 0.100 mm
- Focal length of collimating optics: 350 mm

Part of the emitted laser energy is backscattered to the system's receiver by particles in the airflow, like aerosols, water and ice particles. The shifted frequency (Doppler shift) in these four returned signals is a measure for the air speeds along each of the four axes. With three out of the four axes, the aircraft's air speed vector (magnitude and direction) can be determined. A fourth axis is used to determine a consistency parameter.

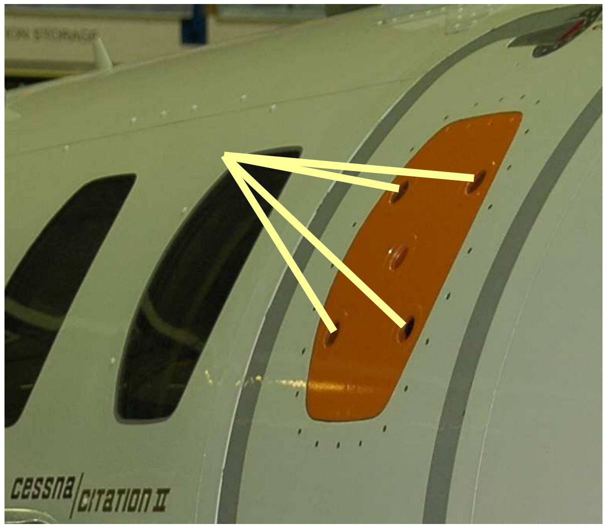

Figure 2 **Alignment of the four LiDAR beams outside the aircraft's fuselage. See Figure 1 for the orientation of the orange coloured plate in the emergency hatch with respect to the aircraft.**

The system is housed in two avionics boxes, one for the optical system, the other for data acquisition purposes. The boxes are attached to the seat tracks in the cabin (Figure 3). Furthermore, the system comprises a control and annunciator panel (accommodated in the FTE console) with which, amongst others, the power can be switched off directly in case of an emergency. Finally, a laptop is connected to the system for configuration and data management, calibration and testing.

Figure 3 **Left: Impression of cabin layout with the two white-coloured avionics boxes attached to the seat tracks. Right: One of the boxes opened in the workshop.**

The laser light from the optical box is guided through glass fibre cables to the optical heads (Figure 4), which further focuses the beams on the measurement volume (Figure 2). The optical heads are installed in the cabin, whereas, obviously, the measurement volume is outside the aircraft's fuselage. How the four laser beams find their way through the fuselage is described in section 4.3.

During the flight test campaign, NESLIE system data were recorded, both in a raw format and as averages over half second time intervals.

Figure 4 The optical head of which four are installed in the aircraft.

4.3 Aircraft Modification

In order to guide the laser beams from the avionics box in the cabin to the measurement volume just outside the aircraft, the aircraft needed to be modified. During the definition phase, a proper location for the laser beams to pass through the aircraft fuselage had to be found. Pressure distributions (based on CFD calculations) were studied (Figure 5), which resulted in the most forward usable cabin window – being the one in the emergency hatch on the right hand side – as the best location to realise the pass-through. This location is least disturbed by the presence of the wings and the boundary layer at this location is thin. Local air speed at this location is expected to be only slightly higher than free-stream values (Figure 5). The expected AOA is however less straight-forward to determine. According to aerodynamic theory (ref. 6), the AOA at the sides of an infinite cylinder placed in an airflow is exactly twice the free-stream AOA due to upstreaming airflow on the sides. However, the actual situation mainly differs in three ways from this theory. First, the Citation's cabin is finite. Second, the window is not exactly at the maximum cabin width, but slightly more upward and thirdly, the measurement volume is situated at a certain distance from the fuselage and not right at the skin. Given the above, the AOA is expected to be somewhere in-between free-stream and double free-stream values.

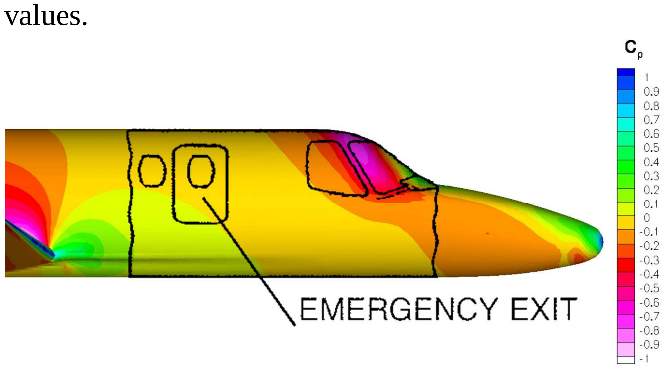

Figure 5 Pressure distribution relative to free-stream along the aircraft's fuselage (low level cruise conditions). The cp=0 boundary, which just touches the emergency hatch at the lower left side, indicates free-stream pressure and thus free-stream speed.

The choice of a measurement location at the side of the fuselage is less favourable to determine the free-stream SSA. A local SSA is of course measured, however, this angle will always be small due to the influence of the fuselage, which guides the airflow alongside itself. Selection of a measurement location on top of the fuselage would result in the opposite situation: good SSA measurement, but less favourable for AOA determination.

The four lasers beams would be distorted by a standard aircraft window as it is not optically flat. As a result, the existing window was replaced with four optically flat glasses mounted in a plate. This plate has the same contour as the original window and was milled out of a block of aluminum at NLR (Figure 6). Provisions for the attachment of a frame, which had to accommodate the four optical heads, were realised during the milling process.

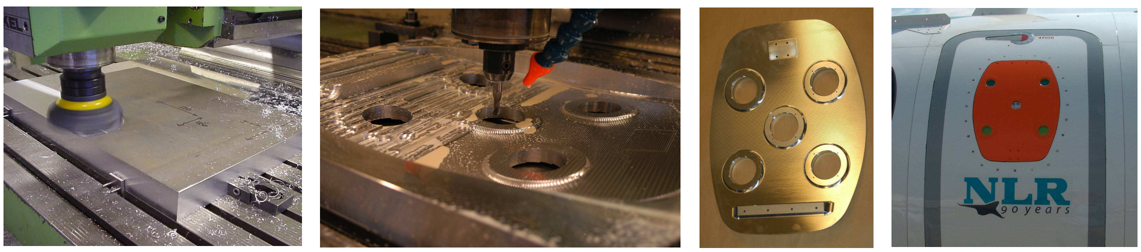

Figure 6 Impression of the plate manufacturing process.

The main requirement for the attachment of the optical heads is that they should be very stiff with regard to each other. This stiffness is required in order to determine the aircraft's air speed with sufficient accuracy. The four heads together are allowed to be more flexible. The resulting frame, made from an aluminum base plate and sheet parts, clearly shows diagonal inner plates to meet the stiffness requirement.

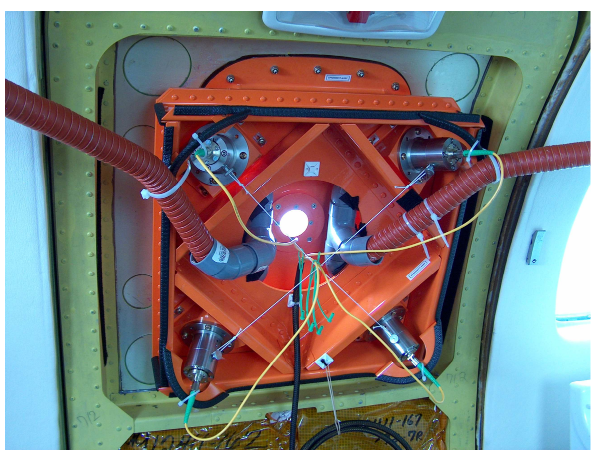

Figure 7 Frame accommodating the four optical heads.

Finally, the four laser windows were anti-iced by ducted air taken from the overhead ventilation outlets (see tubing from left and right in Figure 7). A fifth, not anti-iced, window was accommodated in the middle of the plate to test specific coatings.

Classification of the emergency hatch modification was such that certification of it was performed internally by NLR's approved inspectors.

4.4 Flight Test Equipment and Data Recording

The aircraft was equipped with a data collection system (CMS) for recording of the reference data. This reference data is used for comparison with the data from the NESLIE system (see section 6). The CMS data collection system consists of analog and digital multi-plexer/digitizer unit (PCU). The PCU is capable to multiplex several hundreds of digital and analogue signals with sampling rates high enough to meet the requirements. The data was stored on a S3DR solid state recorder. All recorded data had a time tag (UTC) with a resolution of 0.0001 sec. Inertial reference, air data and GPS data are available in the system in ARINC 429 format. The data collection system is a fully qualified for airborne operation.

For part of the test flights, a noseboom with alpha- (AOA) and beta (SSA) vanes was installed (Figure 8). This noseboom is among NLR's standard flight test equipment and can easily be mounted or removed from the aircraft's nose.

A cockpit mounted, forward looking camera was used for post-flight evaluation. With the recordings it could be determined when the aircraft was flying in clouds.

Figure 8 Noseboom with alpha- and beta vanes.

5 FLIGHT TEST OPERATION

5.1 Test Matrix

The test matrix consists of two main parts. Part one (called 'Backscattering measurement') was dedicated to the sensor side of the system and focused on the particle concentration in the air as a function of different atmospheric conditions (altitude, clouds, visibility, etc.) over sea, countryside and urban areas. Part two (called 'Performance measurement') was dedicated to comparing the system's air speed solution with the air speed measured by the aircraft's reference system (including noseboom sensors). The manoeuvres in this part included dynamic ones a.o. side slips and some zero-g manoeuvres in which a large range of speed and AOA are covered in a short period of time. Table 1 gives a concise overview of the test matrix.

Shakedown	Step climbs to max altitude
Backscattering measurement	Step climbs to max altitude
	Constant max altitude
	Sea, countryside, dense urban area
	Stable conditions
	Turbulent conditions
Performance measurements (with noseboom)	Side slips, AOA variations with flaps
	Rapid speed changes
	Parabolic flights (0-g manoeuvres)
Backup flights	As required

Table 1 Overview of NESLIE test matrix.

5.2 Preparation

Modification/installation

The modification design, manufacturing and certification as well as the installation were performed in February and March 2009. Following the installation of all equipment, integration tests were performed on the ground, including the determination of the laser beam orientation with respect to the aircraft. Latter was performed by levelling the aircraft on hydraulic jacks and measuring the angles of the frame on the emergency hatch by using an inclinometer. Furthermore, the laser output power in the measurement volume was checked.

Flight safety

The flight test operational preparation was straightforward except for the sideslips. For the evaluation of the NESLIE system it was requested to fly prolonged sideslips. When flying prolonged sideslips, there is a risk of fuel starvation and subsequent engine flame-out of the low-wing engine. The rate with which the fuel moves into the direction of the wingtip was hard to establish beforehand (the Citation is not equipped with a collector tank). Therefore, a dedicated test flight was performed. During this flight a ‘fuel low level’ warning came up after about 1 min. Continuation of the sideslip for another 45 sec did not lead to an engine flame-out. Nevertheless, when back on the ground, the strategy on how to perform the prolonged sideslips during the project (i.e. with partners on board) was reconsidered. Another approach to fly prolonged sideslips is to use cross feed. Both methods were compared with each other (Table 2) in terms of acceptable risk. Whereas, on the one hand, using cross feed has a higher severity (i.e. dual engine flame-out in case the engines are fed from the wrong tank), not using cross feed has, on the other hand, a higher probability (of a single engine flame-out). Both methods were assessed as virtually equal in terms of risk. The cross feed was finally chosen as the method to be used during the test flights.

		Risk assessment regarding fuel starvation as result of prolonged sideslips	
		SEVERITY	PROBABILITY
X-FEED	YES	dual engine flame-out (higher severity)	improbable
	NO	single engine flame-out (low severity)	more likely

Table 2 Relative risk assessment for sideslip induced fuel starvation as function of use of cross feed.

Laser safety

During the preparation phase, it was also evaluated how the laser-based NESLIE system could be operated in a safe way on ground and in the air. In terms of ref. 7, the four laser beams are Class 4 laser beams (the category with the highest safety risk). For lasers with wavelengths between 1.4 and 1000 µm the classification is Class 4 if the power is larger than 0.5 W. Operation of Class 4 lasers is connected to hazards for burning skin or the outer parts of the eye and strict safety measures should be taken. The retina is not particularly in danger.

The IEC (ref. 7) and American standards (ref. 8 and ref. 9) express the limit for skin exposure by stating a Maximum Permissible Exposure (MPE) of 1000 W/m^2 for these wavelengths. This MPE is defined for a measurement aperture of 3.5 or 7 mm diameter. For the laser beams of the laser units the 1000 W/m^2 is at 2.9 meter from the focal lens and with an extra margin the laser beams will generate a lower than MPE exposure at distances larger than 3.5 m from the unit.

For operations with the NESLIE system in the NLR Cessna Citation II, safety measures were observed depending on the conditions of the system and the aircraft. The main measures for on-ground operation in the hangar consisted of clearly marking the 3.5 m danger area with tape and signs, presence of a technician responsible for laser operation and presence of an NLR ground engineer. The main measure for operation on the platform is that the system is only operated after engine start, which guarantees no one is closer than 3.5 m from the emergency hatch. For obvious reasons, taxi-, runway- and airborne operations pose no problems to the NESLIE laser operations.

Inadvertent operation of the lasers is prevented by system design, among which is a manually operated shutter in each optical head. Furthermore, the design of the frame and the way it is attached to the emergency hatch, prevent direct laser reflections to enter the cabin.

Cabin safety

As the emergency hatch was chosen to be the location where the laser beams would leave the aircraft cabin, meaning that a construction would be fitted to it, some measures were taken in order not to impair cabin safety. These measures consisted of design requirements on the one hand (restrictions on installation weight and volume) as well as additional safety means on the other hand. The glass fibre wire, being the only part that connects the frame with the NESLIE system, was taken sufficiently long in order not to obstruct emergency hatch throw-out and furthermore, a 'cable cutter' was directly accessible on the hatch.

5.3 Execution

About 40 hours flight test time has been accumulated with NLR's Cessna Citation II research aircraft in the period from April 9 through May 14, 2009. During this period, a large measurement data set was collected over Northern Europe between ground and FL410. A total number of 17 test flights were performed (one – the prolonged sideslip test flight – was flown in March, 2009) in various meteorological situations and flight conditions. All items of the test matrix could be covered, which – given the high level of weather dependency – was a good performance. The reserved backup test flights could be used for additional tests rather than for repeating less successful test flights. The backups were used to test different laser output powers and different focal lengths.

All test flights were performed safely. Use of cross feed for prolonged sideslips worked well. No unsafe situation occurred with regard to airborne and on-ground laser operations. Laser window anti-icing was satisfactory, although some window icing occurred during the initial flights when the ducted air flow was too small. Modifications to further improve the system will be evaluated in NESLIE's follow-up project DANIELA (2008-2011).

6 FLIGHT TEST ANALYSES AND RESULTS

6.1 Introduction

Both the aircraft data (including nose boom in certain flights) and the NESLIE system data were recorded and processed off line. Data was processed and evaluated by different partners in the NESLIE consortium with respect to different aspects, which are addressed in the next sections.

6.2 Number of Detections

The NESLIE system was operational and provided air speed measurement for the whole flight campaign, in all altitude and atmospheric conditions. In addition, the number of detections complies with the models describing the aerosol content in the atmosphere. However, in specific conditions the number of detections dropped. The low detection rate events were not encountered at high altitudes (as one might expect), but in one flight at FL160 and in another flight at FL90. Although no conclusive meteorological explanation is available for these low particle densities, the conditions are associated with particles being washed out by the rain before the measurement was done.

The NESLIE system sensitivity for future experiments or developments should be kept at least equal to the current sensitivity of the system, or should even be increased, in order to obtain a minimum number of detections in all meteorological conditions and over the entire altitude range.

6.3 Consistency of NESLIE System Measurements

The so-called consistency parameter represents the coherence between the 4 velocity measurements on the 4 axes. Only velocity measurements on 3 axes are needed for a TAS determination, while 4 measurement axes are available, giving redundant TAS data. The consistency parameter ΔTAS corresponds to the maximum deviation between the value obtained from a least squares optimum TAS value and the four TAS_i values that are calculated omitting the velocity measurement on one axis.

$$\Delta TAS = Max \left\{ \left| TAS - TAS_i \right| \right\} \quad for \;\; i = 1, 2, 3, 4 \qquad (1)$$

The parameter has been used as the main criterion to assess data availability and validity.

Taking into account all the flights, it is found that 85% of the NESLIE system measurements show a consistency better than 2 kts. Analysis shows the following dependencies of consistency on flight conditions:

- Small differences in the wavelength of the different lasers have no impact on this consistency. This complies with the expectations.
- The laser power has an influence on the consistency: the higher the power, the higher the consistency (this point also corresponds to the expectations).
- The altitude influences the consistency:
    - below FL300, 87% of the measurements have a consistency better than 2 kts.
    - above FL300, only 76% of the measurements have a consistency better than 2 kts.
- Meteorological conditions have an influence on the consistency: the better consistency is obtained with haze (95% below 2 kts), then clear conditions (85% below 2 kts) and finally in clouds (73% below 2 kts).
- Geographical location was not found to have a significant influence on consistency.
- Finally, a high number of detections is not necessarily associated with a good consistency of the measurements.

6.4 NESLIE System Coherence with Aircraft Data

In this section, the coherence between the output of the NESLIE system and the Citation air data is discussed. In the coherence analysis, calibrations of the TAS and AOA outputs from the NESLIE system are searched for. The idea behind this investigation is that in general all air data systems on an aircraft need a calibration. The only exception is the LiDAR system measuring speed at a relatively long range (see ref. 1 and 5), but that is not the case for the NESLIE system. Calibrations can be applied as long as there is a unique relation between the output parameters of an air data system and the actual aircraft TAS and AOA. Only an air data system that can be calibrated will provide adequate TAS and AOA information for the pilot and aircraft systems and therefore the existence of valid calibrations indicates that the system is useful.

Only the averaged NESLIE system outputs over 0.5 second intervals are evaluated in the analysis. The evaluation is against the CMS measurement system on the Citation, which comprises the standard Citation air data system, an inertial measurement system plus, for some flights, the information of vanes on the aircraft noseboom. First the vanes on the aircraft itself are calibrated utilizing the inertial system and the air data system on board. The TAS can not be calibrated in such a simple way. Here we rely on the information of the aircraft manufacturer and indications that this information is correct within the order of +/- 1 kts as was derived from other investigations in which wind fields were measured.

Segments are chosen in the flight data for this analysis. Calibration results are reported below that reflect the different significant influences of parameters on the calibrations. In these segments the consistency factor was well below 2 kts. For the segments with a consistency factor higher than 2 kts the coherence is considerably less.

The calibration of the NESLIE angle of attack is derived by fitting the parameter on Angle of Attack derived from the boom vane and calibrated for installation effects ($AAB_{calibrated}$) and is given in Figure 9. The analysed flight segment is a level straight flight with acceleration and deceleration. This manoeuvre was considered effective to get an indication of the NESLIE AOA and TAS behaviour. This leads to the following calibration equation:

$$AOA_{calibrated} = 0.64\, AOA_{Neslie} - 1.78 \quad [\text{deg}] \qquad (2)$$

The factor 0.64 is between the factor 1, expected for a free-stream (without aircraft) condition, and a factor 0.5 expected for a cylinder as described in section 4.3.

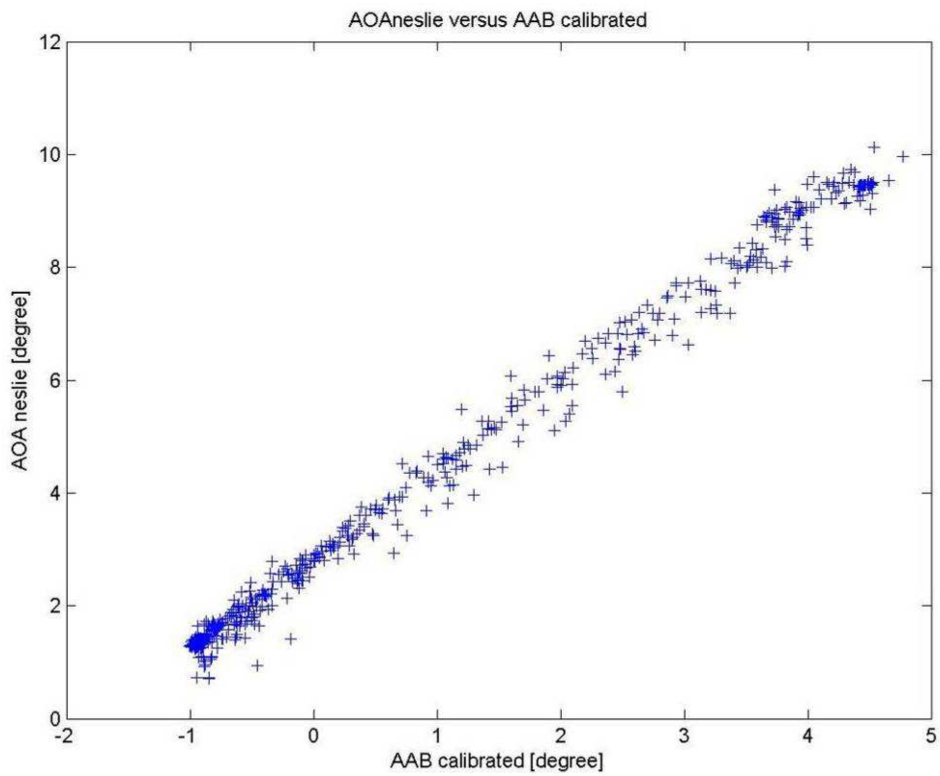

Figure 9 **Relationship of Angle Of Attack from NESLIE (AOA_{neslie}) with the Angle of Attack derived from the boom vane and calibrated for installation effects ($AAB_{calibrated}$).**

Fitting the NESLIE True Air Speed air data with aircraft TAS for the same flight segment with level straight flight with acceleration and deceleration leads (Figure 10) to the following calibration equation, which – as expected (section 4.3) – shows a NESLIE speed slightly higher than free-stream (i.e. $TAS_{calibrated}$):

$$TAS_{calibrated} = 1.03\, TAS_{Neslie} - 11.2 \quad [kt] \qquad (3)$$

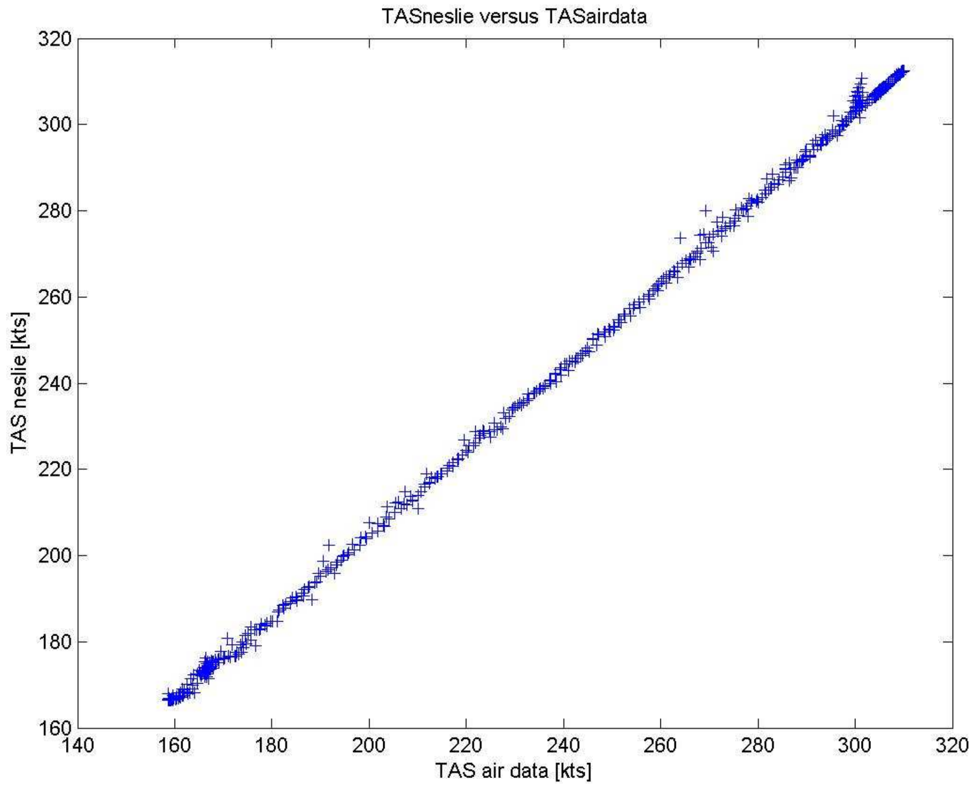

Figure 10 Relationship of True Air Speed from the NESLIE system with the True Air Speed of the air data system of the aircraft.

Dynamic behaviour was investigated in a flight segment with five parabolic (zero-g) manoeuvres. These manoeuvres were considered effective to get a quick indication of the system behaviour over a large range of conditions.

Figure 11 shows measurements during the parabolic flight segments. The airspeed varies over a much larger range than in the acceleration-deceleration flight segment. The calibration derived from this segment, equation (3), was applied to calibrate the NESLIE TAS. The difference signal between NESLIE TAS and aircraft TAS (picture in the middle) has a strong correlation with the AOA of the aircraft (bottom picture). A correction term was introduced. Furthermore, it appears that there is a small time delay between the signals. For an averaging process leading to 2 samples per second data, this should be expected and by fitting the signals the time delay was determined.

The improved calibration equation (4) results in much smaller differences between the calibrated NESLIE TAS and the aircraft TAS (see Figure 12).

$$TAS_{calibrated} = 0.98\, TAS_{neslie} - 0.014\,\frac{dTAS}{dt} - 0.97\, AAB + 3.4\ \ [kt] \qquad (4)$$

Different methods have been used to attempt to calibrate the NESLIE system versus the aircraft data, for specific flights where the boom was used and then both Side Slip Angle (SSA) and Angle Of Attack (AOA) were available. It was found that in general the aerodynamic conditions have a significant influence, as it was expected:

- SSA has an influence on the AOA calibration
- There is no significant influence of the SSA on the TAS calibration
- The flap setting TO/Approach and the Landing configuration have an influence on both AOA and TAS calibration

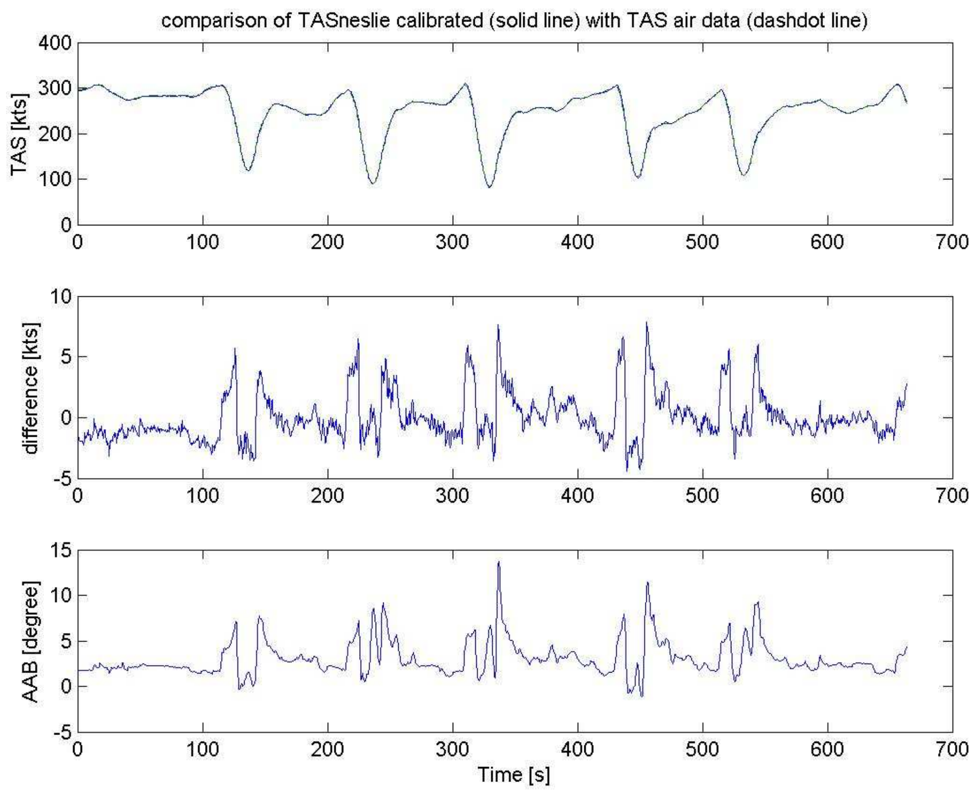

Figure 11 Top: True Air Speed measured with the NESLIE system, calibrated with equation (3) and the True Air Speed from the air data system from the aircraft (plots overlap).

Middle: The difference between these two parameters.

Bottom: The Angle of Attack from the boom vane during the flight segment with five parabolic flight manoeuvres.

In general it is concluded that the AOA and TAS output of the NESLIE system can be calibrated with a good agreement with the aircraft data, except for the periods when the consistency parameter has a too poor value.

6.5 Signal Processing Performances

The dependency of performance of the NESLIE system on different processing parameters was analysed in post flight processing using the recorded raw signal data. These dependencies include the following:

- Different algorithms to estimate air data from raw measurements have been established. The consistency of resulting air data of the NESLIE system appears to be dependent on the applied algorithm. For example, using the median instead of averaging appears to increase the quality of the estimation in most cases.
- The initial NESLIE measurements were performed with a 2 Hz update rate. Different update rates (10 Hz, 20 Hz, 26 Hz and 40 Hz) were tested by post processing of the data, for two different flights. As was expected, the availability of valid NESLIE air data decreases as the update rate increases. The consistency of data is however not or only slightly impacted for the periods when the valid NESLIE air data is available.
- In conditions with a decreased consistency, for instance in adverse atmospheric conditions like dense clouds, raw data recording indicates that the optical set-up in combination with the processing algorithm is not optimised. The processing algorithm will be improved.

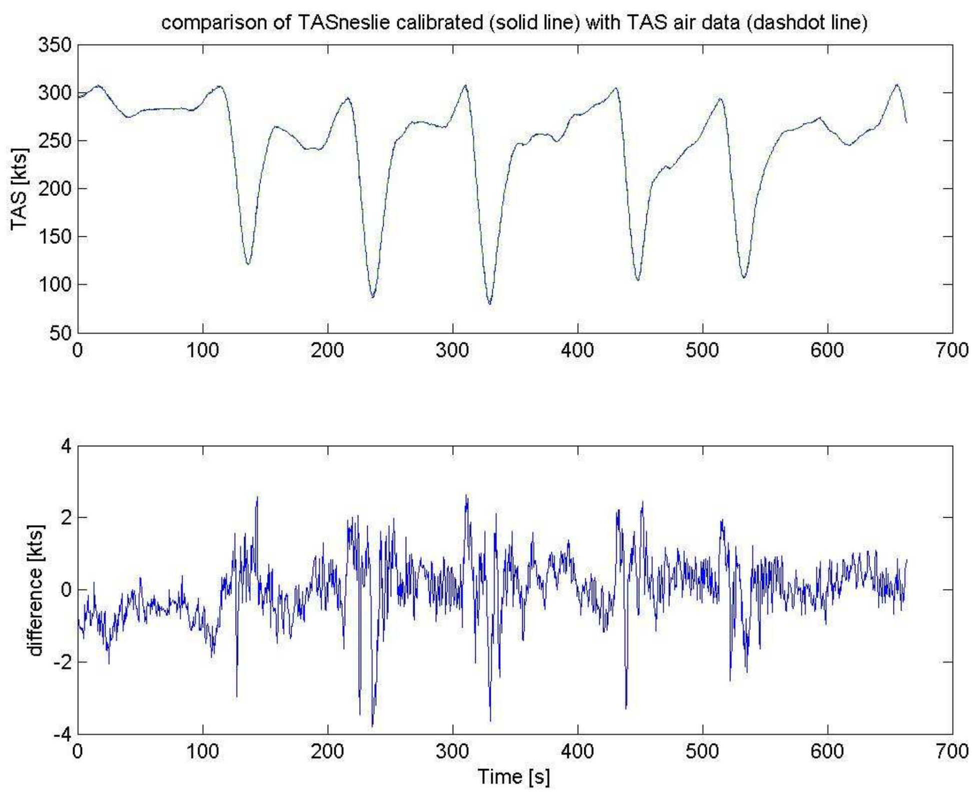

Figure 12 Top: True Air Speed measured with the NESLIE system calibrated according to equation (4) and the True Air Speed from the air data system from the aircraft (plots overlap).

Bottom: The difference between these two parameters.

7 CONCLUSIONS

In the frame of the NESLIE project, an optical system for measuring air data with the LiDAR technique has been developed and flight-tested. The system was successfully integrated in the NLR Cessna Citation II research aircraft and a flight test campaign was flown. A large data set of measurements was gathered and evaluated. The evaluation results are very promising and show that the system can be calibrated for installation effects at the selected position. A large progress was made with respect to the state of the art in optical air data systems. Flight testing of the system in an already instrumented and relatively easy-to-modify research aircraft, embedded in an experienced flight test organisation, as presented proved to be effective and efficient.

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