



Executive summary

Optical Air Data System Flight Testing

Problem area

Within the NESLIE (NEw Standby Lidar InstrumEnt) project, an innovative optical air data system was developed, built and tested. This system was further developed in the DANIELA (Demonstration of ANemometry InstrumEnt based on LAser) project. The system applies the LiDAR technique to measure the air speed vector of the aircraft. The failure modes of this system are different from those of the currently used pitot-static system. Therefore, flight safety is expected to increase. This new system was evaluated during flight tests on-board NLR's Cessna Citation II research aircraft in polar, moderate and tropical regions.

Description of work

The air speed system was successfully integrated in the research aircraft and the flight test campaigns were flown during the Springs of 2009 (NESLIE) and 2011 (DANIELA). A total of 46 flights were performed, accumulating over 100 flight hours. 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 the air data source from the research aircraft.

Results and conclusions

This paper i) introduces NLR's flight test facility, ii) describes the standby air data system under test, iii) describes system integration in the research aircraft, iv) gives an overview of flight test operational activities and v) presents some results of the analysis of recorded data.

The results of these projects show that the system can be operated in normal and extreme conditions (clear air, big rain droplets and dust particles). The DANIELA processing algorithms for different atmospheric conditions have been improved when compared to the NESLIE project.

Applicability

No show-stoppers have been identified for further development of the system. The LiDAR technique is a promising technique for air data measurements.

Report no.

NLR-TP-2012-068

Author(s)

M.J. Verbeek
H.W. Jentink

Report classification

UNCLASSIFIED

Date

February 2012

Knowledge area(s)

Vliegoperaties
Vliegtuigsysteemontwikkeling

Descriptor(s)

Flight test
Research aircraft
Lidar
Air data
Airspeed measurement

UNCLASSIFIED

Optical Air Data System Flight Testing

Nationaal Lucht- en Ruimtevaartlaboratorium, National Aerospace Laboratory NLR

Anthony Fokkerweg 2, 1059 CM Amsterdam,
P.O. Box 90502, 1006 BM Amsterdam, The Netherlands
Telephone +31 20 511 31 13, Fax +31 20 511 32 10, Web site: www.nlr.nl

UNCLASSIFIED



NLR-TP-2012-068

Optical Air Data System Flight Testing

M.J. Verbeek and H.W. Jentink

This report is based on a presentation to be held at the Avionics Europe 2012 Conference, Munich, Germany, 21-22 March 2012.

The contents of this report may be cited on condition that full credit is given to NLR and the author(s).

Customer	European Commission
Contract number	212132
Owner	NLR
Division NLR	Air Transport
Distribution	Unlimited
Classification of title	Unclassified
	February 2012

Approved by:

Author	Reviewer	Managing department



Contents

1	Introduction	7
2	Flight Test Facility	8
3	Set-up	10
3.1	Aircraft	10
3.2	Experimental Equipment	10
3.3	Aircraft Modification	12
3.4	Flight Test Equipment and Data Recording	15
4	Flight Operation	16
4.1	General	16
4.2	Preparation	16
4.3	Execution	18
5	Flight Test Analyses and Results	19
5.1	Introduction	19
5.2	Laser Signal Families as Function of Atmosphere	19
5.3	Laser System Coherence with Aircraft Data	20
5.4	Improvements	22
6	Conclusions	24
7	References	25
Acknowledgements		26



Abbreviations

AAB	Angle of Attack from Boom
ACM	Air Cycle Machine
ANSI	American National Standards Institute
AOA	Angle Of Attack
ARINC	Aircraft Radio Incorporated
ATM	Air Traffic Management
CFD	Computational Fluid Dynamics
EC	European Commission
FL	Flight Level
GPS	Global Positioning System
IEC	International Electrotechnical Commission
IRS	Inertial Reference System
KIAS	Knots Indicated Air Speed
LiDAR	Light Detection And Ranging
MMI	Man Machine Interface
MPE	Maximum Permissible Exposure
NATO	North Atlantic Treaty Organization
RTO	(NATO) Research and Technology Organization
SFTE	Society of Flight Test Engineers
SSA	Side Slip Angle
TAS	True Air Speed
UTC	Universal Time Coordinated



Abstract

Within the NESLIE (New Standby Lidar Instrument) and DANIELA (Demonstration of ANemometry InstrumEnt based on LAser) projects, which are both supported by the European Commission, an innovative air data system was developed, built and tested. The system applies the lidar technique to measure the aircraft's TAS (true airspeed), AOA (angle of attack) and SSA (side slip angle). The developments resulted in a test system of a future generation standby instrument for commercial aircraft. This system has no probes protruding in the air contrary to traditional pitot-static air data systems. The laser-based instrument will have drastically different failure modes compared with traditional systems, reducing the probability of common failures, which increases flight safety. The test flights were performed under responsibility of NLR's flight test facility, using its Cessna Citation II research aircraft, which had been modified for the occasions. Flight test periods were in April - May 2009 and March - May 2011. The system was evaluated from North Pole to Equator in 46 flights covering over 100 flight hours. A large data set of measurements was created in the flight test campaigns. This paper will i) introduce NLR's flight test facility, ii) describe the standby air data system under test, iii) describe the integration of the system in NLR's Cessna Citation II research aircraft, iv) give an overview of flight test operational activities and v) present some results of the analysis of recorded data.



This page is intentionally left blank.



1 Introduction

A short-range innovative lidar-based air data system was developed, built and tested in the NESLIE (New Standby Lidar Instrument) and DANIELA (Demonstration of ANemometry InstrumEnt based on LAser) projects that are supported by the European Commission. The DANIELA project is a follow-up of the NESLIE project. The developed 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 and DANIELA consortia which consisted of following participants: THALES Avionics (coordinator, France), THALES Research & Technology (France), AIRBUS (France), DASSAULT Aviation (France), EADS CRC (Germany), AWI (Germany), TEEM Photonics (France), IMEP (France), Cranfield University (United Kingdom), XenicS (Belgium), ITI-CERTH (Greece) and NLR (Netherlands).

The in-flight evaluation was performed in the NLR Cessna Citation II research aircraft during the springs of 2009 (NESLIE) and 2011 (DANIELA). The objective of the flight test campaigns was to evaluate:

- the performance of the system as a function of particle concentration, size, type and mixture, for which flight test altitudes, weather conditions, visibilities and locations/routes were varied.
- the correlation between the system output and aircraft reference data derived from standard aircraft systems and specific flight test instrumentation.

A prerequisite for the flight test was to prepare and execute the NESLIE and DANIELA flight tests in such a way that the required data could be obtained safely, effectively and efficiently.

2 Flight Test Facility

The National Aerospace Laboratory (NLR) operates two research aircraft (see below) to test new technology and procedures. The aircraft are well suited to test new sensors, but are also used for testing in the field of aerodynamics, atmosphere, avionics, Air Traffic Management (ATM), flight test methods, system tests, flight inspection of navigation aids and Airborne Remote Sensing.

Cessna Citation II

The PH-LAB is a Cessna Citation II, a twin-engine jet with a load capacity of 1400 kg. Thanks to its turbofan engines, the aircraft can fly to an altitude of 13 km (43,000 feet) and carry out measurements at speeds of up to 262 KIAS. This aircraft can also fly at extremely slow speeds, should an experiment require it. The aircraft has recently received a cockpit/ avionics upgrade, enabling, amongst others, flight evaluation of new display formats from the right hand seat in the cockpit (see Figure 1).



*Figure 1 Cockpit of NLR's Cessna Citation II research aircraft.
The right and middle display can be used to evaluate new display formats under real flight conditions*



Fairchild Metroliner II

NLR's Fairchild Metro II, PH-NLZ, is a twin turboprop aircraft, modified for aerospace research. It has a 17 m³ pressurized cabin and a large cargo door. The maximum altitude for the aircraft is 7,5 km (25,000 ft) and its maximum speed is 248 KIAS. The aircraft also has a 610 x 610 mm² camera hatch with 40 mm optical quality glass, which can be replaced by metal plates for mounting special equipment.



Figure 2 NLR's Fairchild Metro II research aircraft

Modifications

For modifications to the laboratory aircraft, NLR operates a Part-145 Maintenance and modification organisation. The Part-145 organisation has capabilities for line/base maintenance, component maintenance, design and approval of modifications for flight testing, executing of aircraft modifications and fabrication of parts for flight testing.

3 Set-up

3.1 Aircraft

NLR's Cessna Citation II research aircraft (Figure 3) 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 (see section 2).



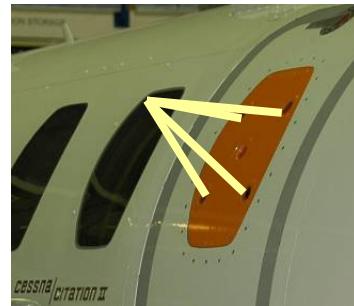
Figure 3 NLR's Cessna Citation II research aircraft ready for a NESLIE test flight from Amsterdam Airport Schiphol with the modified emergency hatch and noseboom

3.2 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 4). 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 (see section 5).

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

- Wavelength: 1.55 µm
- Optical power range: 1 W
- Measurement distance: 35 cm



*Figure 4 Alignment of the four LiDAR beams outside the aircraft's fuselage.
See Figure 3 for the orientation of the orange coloured plate in the
emergency hatch with respect to the aircraft*

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.

In NESLIE, the system is housed in two avionics boxes, one for the optical system, the other for data acquisition purposes. In DANIELA, the two boxes were integrated into one box, making the total volume smaller. The boxes are attached to the seat tracks in the cabin (Figure 5). Furthermore, the system comprises a control and annunciator panel 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. An impression of the laser system MMI is given in Figure 6.



Figure 5 Impression of cabin layout with white-coloured avionics boxes attached to the seat tracks. (Left: NESLIE. Right: DANIELA.)

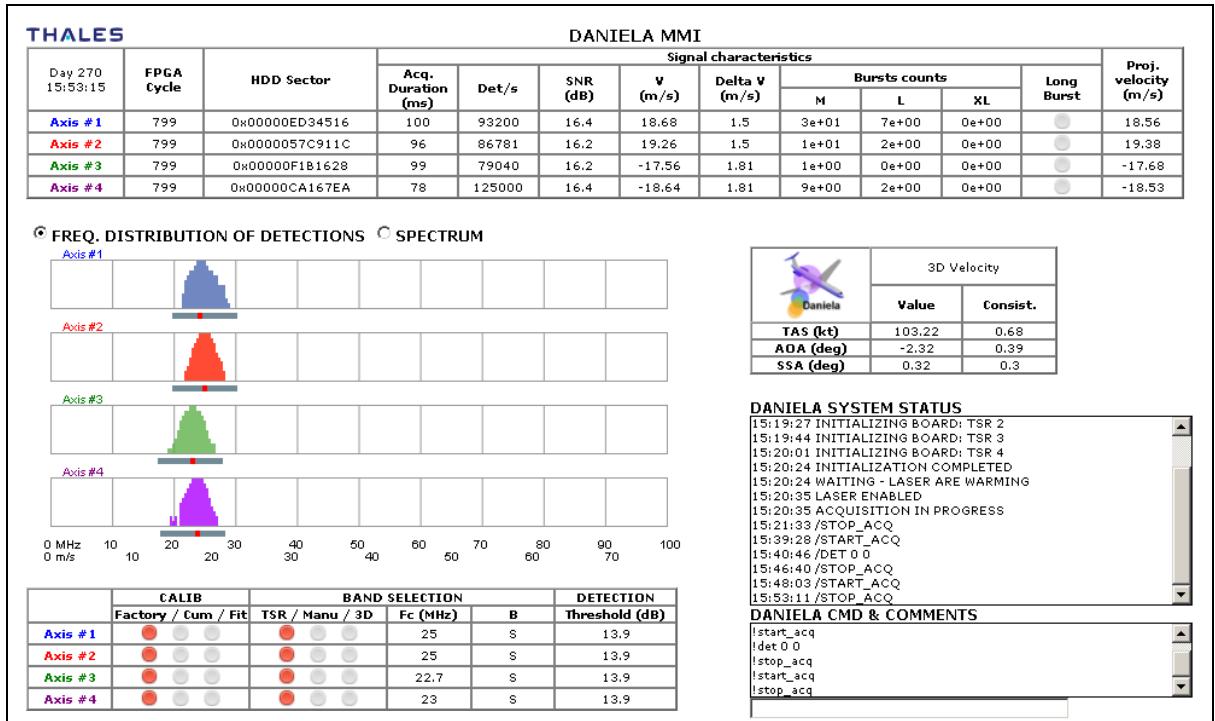


Figure 6 Impression of DANIELA system MMI with color-coded laser axes signals

The laser light is guided through glass fibre cables to the optical heads (Figure 7), that focus the beams on the measurement volume (Figure 4). 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 3.3.

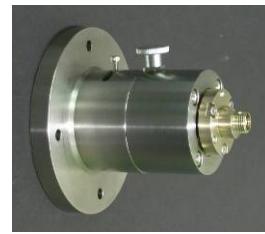


Figure 7 The optical head of which four are installed on a frame in the aircraft.

3.3 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 8), 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 8). The expected AOA is however less straight-forward to determine. According to aerodynamic theory (ref. 1), 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.

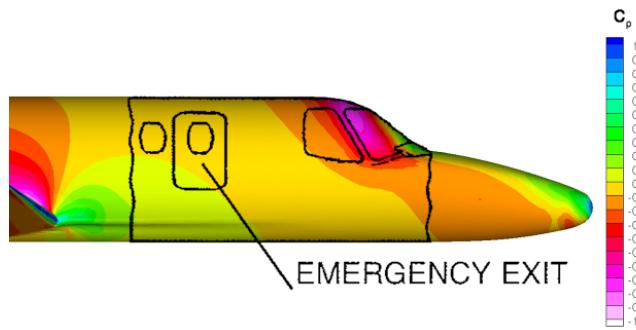


Figure 8 Pressure distribution relative to free-stream along the aircraft's fuselage (low level cruise conditions). The $c_p=0$ boundary, which just touches the emergency hatch at the lower left side, indicates free-stream pressure and thus free-stream speed

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 laser 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 9). Provisions for the attachment of a frame, which had to accommodate the four optical heads, were realised during the milling process.

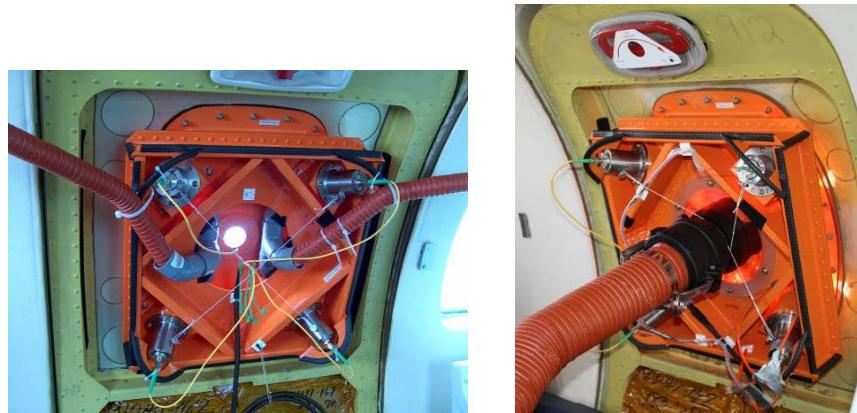
The main requirement for the attachment of the optical heads is that they should be very stiff with regard to each other. This stiffness is required in order to determine the aircraft's air speed with sufficient accuracy. The four heads together are allowed to be more flexible. The resulting frame, made from an aluminum base plate and sheet parts, clearly shows diagonal inner plates to meet the stiffness requirement (see Figure 10).



Figure 9 Impression of the manufacturing process of the laser windows plate

Finally, during NESLIE the four laser windows were anti-iced by ducted air taken from the overhead ventilation outlets, later to be improved during DANIELA with air taken directly from the Air Cycle Machine (ACM) (see Figure 10).

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



*Figure 10 Frame accommodating the four optical heads and anti-icing ducts.
(Left: NESLIE. Right: DANIELA.)*



3.4 Flight Test Equipment and Data Recording

The aircraft was equipped with a data logger system. This data logger system developed by NLR consists of an analogue and digital PC-based multiplexer/digitizer. The data logger is capable to multiplex eight ARINC and analogue signals with sampling rates high enough to meet the requirements. The data is stored on a hard disk recorder. All recorded data is time tagged (UTC) with a resolution of 0.0001 sec. Inertial reference (from IRS), air data and GPS data are available in the system in ARINC 429 format.

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 and in what type of clouds.

For part of the test flights in NESLIE, a noseboom with alpha (AOA) and beta (SSA) vanes was installed (Figure 3). This noseboom is among NLR's standard flight test equipment and can easily be mounted or removed from the aircraft's nose.

Additional flight test equipment in DANIELA comprised of a humidity sensor, a hot-wire liquid water content sensor and an Iridium set for (emergency) voice communication.



4 Flight Operation

4.1 General

As reflected in the objectives in section 1, the flight tests covered two fields of interest.

First there was the interest in the sensor side of the system, which focused on the particle concentration and size in the air as a function of different atmospheric conditions (altitude, clouds, visibility, etc.) over sea, countryside and urban areas as well as in polar, moderate and tropical climates. The polar region was selected to find extremely clear air, while the tropical region was selected to find relatively large particles: sand, dust and tropical rain. Different atmospheric conditions require different processing of the recorded data in order to compute the correct speed in the measurement volume just outside of the aircraft's fuselage.

Second interest was in comparing the system's air speed solution with the air speed measured by the aircraft's reference system. The manoeuvres in this part also included dynamic ones like side slips and some zero-g manoeuvres in which a large range of speed and AOA are covered in a short period of time.

4.2 Preparation

Modification/installation

In NESLIE, the modification design, manufacturing and certification as well as the installation were performed in February and March 2009. Almost all of these modifications could be reused in DANIELA.

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 and a suitable procedure to perform these tests was defined.



Special attention was given to the preparation of the flight test campaigns to Svalbard (North Pole) and Accra (Ghana). The former is a remote airfield, while the latter is surrounded by politically less stable countries.

Laser safety

During the preparation phase, it was also evaluated how the laser-based system could be operated in a safe way on ground and in the air. In terms of ref. 2, 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. 2) and American standards (ref. 3 and ref. 4) 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 system in the NLR Cessna Citation II, safety measures were observed depending on the conditions of the system and the aircraft. Inadvertent operation of the lasers is prevented by system design, among which is a manually operated mechanical 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. Finally, the anti-icing duct could be stowed upon take-off and landing.



4.3 Execution

In NESLIE, 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.

In DANIELA, another 67 flight test hours were accumulated in the period from March 31 through May 12, 2011. A total of 29 flights were flown over 16 countries, covering approximately 30.000 km and ranged from North Pole to Equator. All required atmospheric conditions were encountered at least once.



5 Flight Test Analyses and Results

5.1 Introduction

Both the aircraft reference data (including nose boom in certain flights) and the NESLIE/DANIELA system data were processed off line and evaluated by different partners in the consortia. Following aspects are addressed in the next sections: Laser signal families as function of atmosphere (section 5.2), laser system coherence with aircraft data (section 5.3) and assessment of improvements in DANIELA over NESLIE (section 5.4).

5.2 Laser Signal Families as Function of Atmosphere

In order to get speed signals with good integrity and reliability from the laser system, the system should be able to function correctly in different atmospheric conditions. Therefore, flight tests have covered different parts of the world (see section 4.3) in which many atmospheric phenomena have been encountered.

Table 1 gives an overview of the encountered situations for DANIELA (those encountered in NESLIE are a subset of Table 1).

The encountered conditions have been categorised into signal families. Each family requires it's own way of signal processing, in order to extract the correct airspeed. The evaluation of suitable processing algorithms has been the subject of post-flight data analyses.

*Table 1 Overview of encountered atmospheric conditions during DANIELA.
(Green = encountered, yellow = not encountered.)*

Main goals	Important goals	Valuable goals	Valuable goals but potentially unsafe
Extremely clear air	Snowflakes	Supercooled water droplets	Volcanic ashes
Stratosphere	Ice crystals	Cirrus	Sand wind (formation step)
Arctic aerosols	Arctic haze	Cirrocumulus	Cumulonimbus
Sand wind (transportation step)	Jet stream (turbulences)	Cirrostratus	Hail
Over desert (no sand)	Sand wind (evolution step)	Altocstratus	Rain mixed with hail
Tropical rain (moderate)	Smoke	Altocumulus	Storm
Oceanic long range		Nimbostratus	
Mediterranean rain (heavy)		Stratocumulus	
Tropical rain (heavy)		Cumulus	
		Stratus	

5.3 Laser System Coherence with Aircraft Data

In this section, the coherence between the output of the laser system and the Citation air data is shown. In the coherence analysis, calibrations of the TAS and AOA outputs from the laser system were 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. 5 and 6), but that is not the case for the laser system developed in NESLIE and DANIELA. 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.

First, an example is given for the AOA coherence as found during a straight-and-level, acceleration-deceleration segment of one of the NESLIE flights. Figure 11 shows the NESLIE system AOA versus the reference AOA from the aircraft. For the latter, the AOA from the nose boom has been taken, after it has been calibrated for installation effects.

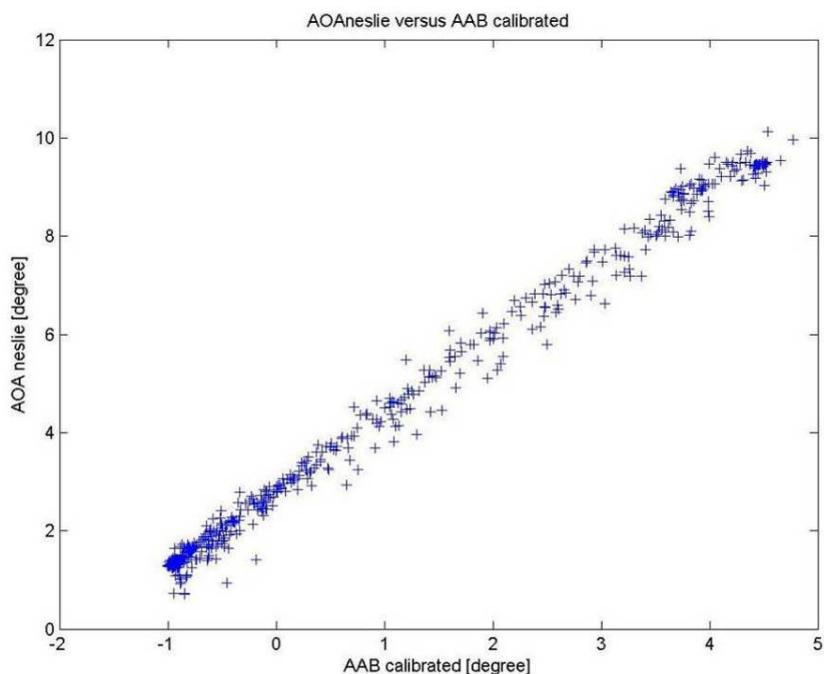


Figure 11 Relationship of Angle Of Attack from NESLIE (AOA neslie) with the Angle of Attack derived from the boom vane and calibrated for installation effects (AAB calibrated)

As can be seen from Figure 11, coherence is already high. A simple calibration function could therefore be found with a bias and linear correction.

Fitting the NESLIE True Air Speed (TAS) air data with aircraft TAS for the same flight segment leads (Figure 12) to the same conclusion as for the AOA: high coherence, which allows a simple calibration with bias and (minor) linear correction. Figure 12 also shows that the NESLIE speed is higher than the aircraft speed, which is as expected (section 3.3).

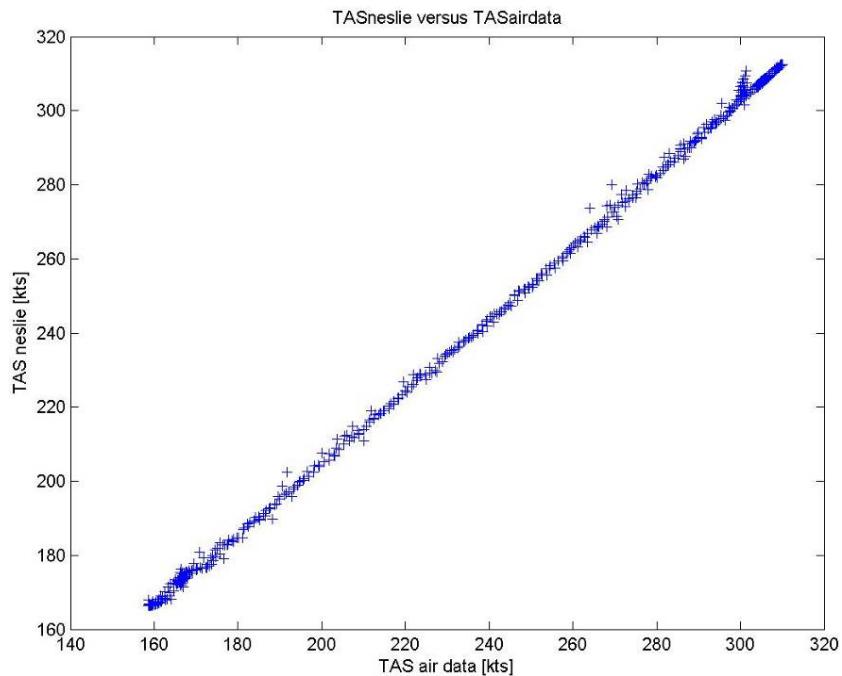


Figure 12 Relationship of True Air Speed from the NESLIE system with the True Air Speed of the air data system of the aircraft

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 13 shows measurements during five parabolic flight segments. The airspeed varies over a much larger range than in the acceleration-deceleration flight segment.

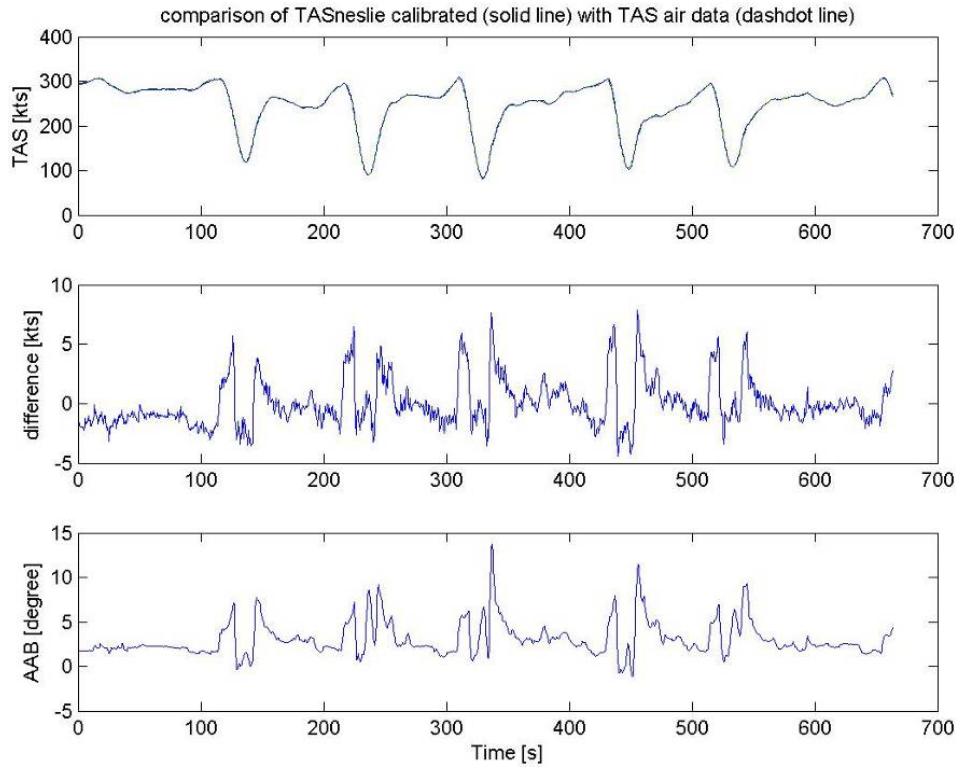


Figure 13 *Top: Both NESLIE calibrated speed based on straight-and-level segment as well as aircraft reference speed (plots overlap). Middle: Difference between both speeds. Bottom: AOA from nose boom vane. Flight segment with parabolic flight manoeuvres.*

The NESLIE airspeed used in Figure 13 was calibrated based on the straight-and-level flight segment. The difference signal between the NESLIE speed and the aircraft speed (picture in the middle) has a strong correlation with the AOA of the aircraft (bottom picture). Furthermore, it appears that there is a small time delay between the signals, which is caused by the sampling rate. As a result, the calibration function was expanded with two terms: AOA and acceleration. The improved result for this calibration is illustrated in Figure 14.

5.4 Improvements

In the DANIELA project, the system has been improved including that the different signal families have been processed with improved processing algorithms. The resulting airspeed errors were compared with NESLIE data. Latter means that the collected DANIELA data has been processed with the algorithms as developed within the NESLIE project. NESLIE trials already showed very good velocity results in clear air conditions and clouds composed of small particles.

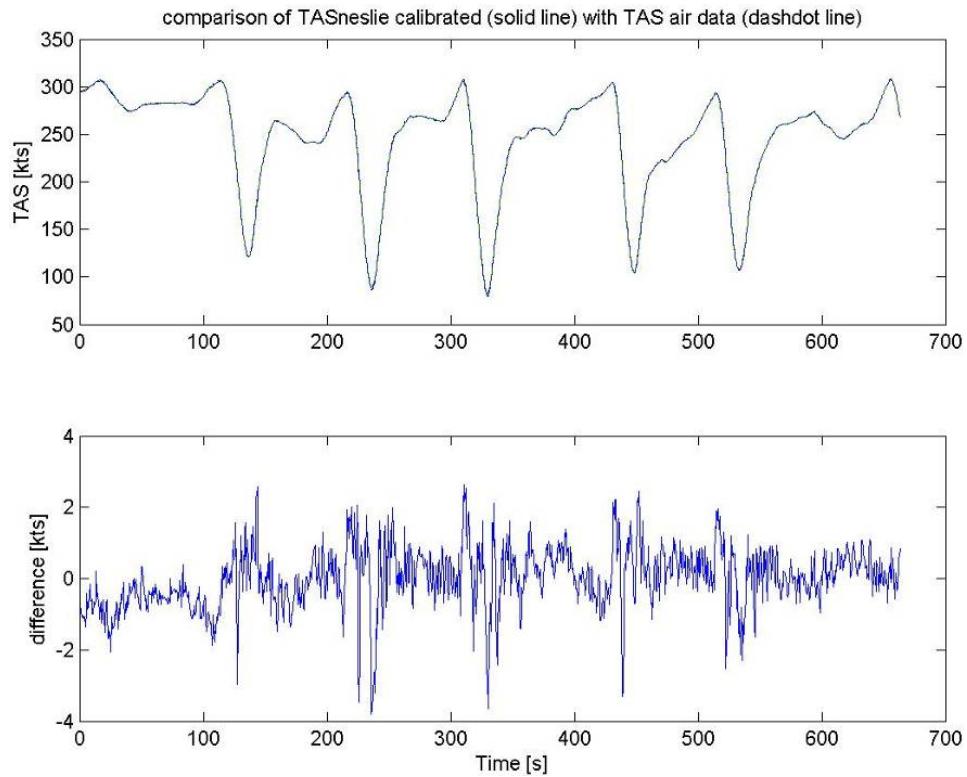


Figure 14 Top: Both NESLIE calibrated speed as well as aircraft reference speed (plot overlap). Bottom: Difference between both speeds

The main DANIELA goals were to improve sensitivity, output rate and accuracy, as well as to improve signal knowledge in extreme adverse conditions. These four goals were achieved:

1. Sensitivity improvement by a factor 3 leading to an “anytime-anywhere” availability (including extremely clear or dry air).
2. Velocity refresh rate improvement up to the product specification (10Hz).
3. A significant accuracy improvement (factor 2 to 5) in dense clouds or in presence of very big particles like large droplets, snowflakes or hailstones.
4. A detailed description of the signal characteristics over periods during which a lack of accuracy was noticed (some percent of the overall flying time). This knowledge is very valuable for further research.



6 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 show that the system can be calibrated for installation effects at the selected position. After implementation of some system improvements, it was flight tested again in the DANIELA project. The results of this project show that the system can be operated in extreme conditions with respect to particle conditions (clear air, big rain droplets and dust particles). The processing algorithms for different signal families have been improved, leading to better system performance in the DANIELA project.



7 References

1. I.H. Abbott, A.E. von Doenhoff, "*Theory of Wing Sections – Including a Summary of Airfoil Data*", Dover Publications Inc., New York, 1959, p. 41-42.
2. IEC 60825-1:2007, "*Safety of laser products – Part 1: Equipment classification and requirements*".
3. ANSI Z136.1-2007, "*American National Standard for Safe Use of Lasers*".
4. ANSI Z136.6-2005, "*American National Standard for Safe Use of Lasers Outdoors*".
5. H.W. Jentink, R.K. Bogue, "*Optical air flow measurements for flight tests and flight testing optical flow meters*", SFTE (EC) - RTO SCI-162 Symposium "Flight test – Sharing Knowledge and Experience" Warsaw, Poland, 9-11 May 2005, paper 11, also publ. as NLR TP-2005-256 and RTO-MP-SCI-162 paper 11.
6. F. Alonso, "*Anemometric calibration test methods for Airbus A330/340*", Proceedings ETTC 91, 25-26 June 1991, Toulouse, France, p. 2-7.



Acknowledgements

The work described in the paper is executed as part of the NESLIE and DANIELA projects which have been co-funded by the European Commission, 6th respectively 7th Framework Programme, EC contract 30721 respectively 212132.

Following participants took part in the development and evaluation of the system: THALES Avionics (coordinator, France), THALES Research & Technology (France), AIRBUS (France), DASSAULT Aviation (France), EADS CRC (Germany), AWI (Germany), TEEM Photonics (France), IMEP (France), Cranfield University (United Kingdom), XenicS (Belgium), ITI-CERTH (Greece) and NLR (Netherlands).