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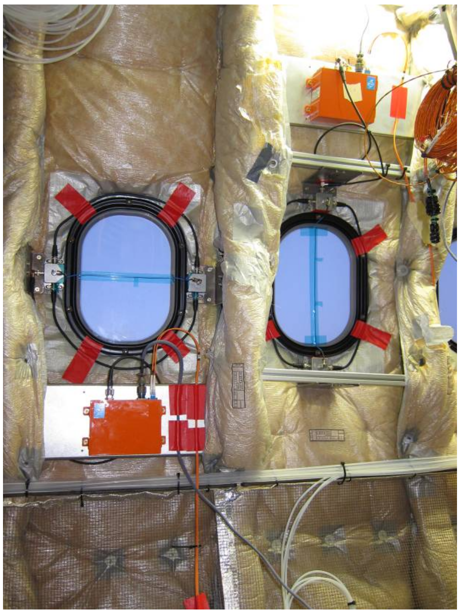
Executive summary

In-flight Lightning Measurement System ILDAS: System architecture definition, based on analysis of first flight data



Problem area
On average, lightning strikes an individual commercial aircraft about once per year. Although nowadays not a safety hazard, the strikes may cause damage to the aircraft, resulting in inspection and maintenance costs and flight delays or cancellations.

Description of work
With long-term goals of improving scientific knowledge of aircraft-lightning interaction and of improving aircraft post-strike maintenance, the ILDAS programme objective is to develop a configuration for in-flight measurement of lightning strikes. In the ILDAS-2 project, which Airbus has launched with EADS-IW and NLR as a follow-up to the ILDAS-1 FP6 EU project ILDAS, the measurement system is matured so that it can operate on board Airbus test aircraft.

Results and conclusions
Flight tests were performed on A340 in 2011 (limited installation) and in 2012 (full installation) for system validation. The next stage will be deployment on an Airbus A350XWB during its icing trials.

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Author(s)
A.I. de Boer
S.M. Bardet
A.P.J. van Deursen
J.F. Boissin
F. Flourens

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In-flight Lightning Measurement System ILDAS: System architecture definition, based on analysis of first flight data

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 88 511 31 13, Fax +31 88 511 32 10, Web site: www.nlr.nl

Nationaal Lucht- en Ruimtevaartlaboratorium

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In-flight Lightning Measurement System ILDAS: System architecture definition, based on analysis of first flight data

A.I. de Boer, S.M. Bardet, A.P.J. van Deursen[1], J.F. Boissin[2] and F. Flourens[2]

[1] TU Eindhoven

[2] Airbus

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IN-FLIGHT LIGHTNING MEASUREMENT SYSTEM ILDAS: SYSTEM ARCHITECTURE DEFINITION, BASED ON ANALYSIS OF FIRST FLIGHT DATA

A.I. de Boer[1], S.M. Bardet[1], A.P.J. van Deursen[2], J.F. Boissin[3] and F. Flourens[3]

[1] National Aerospace Laboratory, NLR
Anthony Fokkerweg 2, 1059 CM Amsterdam, The Netherlands
e-mail: adeboer@nlr.nl

[2] Eindhoven University of Technology TU/e
P.O. Box 513, 5600 MB Eindhoven, The Netherlands
e-mail: a.p.j.v.deursen@tue.nl

[3] Airbus Operations, Flight and Integration Test Centre
316 route de Bayonne, St Martin, 31060 Toulouse, France
e-mail: jean-francois.boissin@airbus.com, franck.flourens@airbus.com

Abstract

At the previous SFTE-EC Symposium, the history of the In-flight Lightning Damage Assessment System (ILDAS) programme was presented (ref. [1]). The goal of the programme is to (a) extend knowledge on the interaction between lightning and aircraft in flight, with the aim of improving reliability and maintenance, (b) to be able to correlate events during flight tests with lightning characteristics, and (c) to investigate the use of in-flight lightning data for optimisation of post-strike maintenance. Within the ILDAS-2 project the goal is to have an operational lightning measurement system on board the A350 XWB test aircraft during its icing campaign flights. An initial, limited-scale 'engineering setup' was installed on an Airbus A340 aircraft in March 2011, which performed several flights through lightning. The data from these flights were analysed to verify the performance of the sensor and acquisition system in a real lightning environment, and to assess algorithms for lightning strike detection. The results of the engineering test phase allowed the final decisions to be made on the architecture for the final application on the A350. The paper highlights several key findings from the 2011 campaign and describes the resulting architecture of the system. A validation test campaign was conducted in March 2012 where a full-architecture implementation was on board, but results of this campaign are not available yet.

1 INTRODUCTION

On average, lightning strikes an individual commercial aircraft about once per year (ref. [2]). The strikes may cause damage to the aircraft, but are not a safety hazard due to the immunity engineered into the aircraft. The safety track record for lightning-caused aircraft accidents is nowadays excellent. For a variety of reasons, explained in sections 1.1 and 1.2, there was a strong desire to know more about the lighting-aircraft interaction. This resulted in the ILDAS research programme: ILDAS-1 (2006-2009) and ILDAS-2 (2009-2013).

1.1 The ILDAS-1 project

The ILDAS-1 project was an EU-supported FP6 research project to validate the principle of an in-flight lightning strike measurement and damage assessment system for fixed-wing aircraft and helicopters, with long-term goals of improving scientific knowledge of aircraft-lightning interaction and of improving aircraft post-strike maintenance (ref. [3]). In ILDAS-1, a system called ILDAS was defined, developed, and successfully verified during both a rig test campaign and a ground test campaign on an A320 aircraft in 2009.

1.2 The ILDAS-2 project

Due to the promising results of ILDAS-1, Airbus decided to continue the ILDAS programme by launching the ILDAS-2 project in 2010 with one primary objective: to use the ILDAS system for the flight test campaign of the Airbus A350 XWB (ref. [4]). The following three benefits were expected:

1. Validation of the ILDAS system's compatibility with an airframe that is mainly composed of carbon-fibre composite materials.
2. Improvement of lightning knowledge (medium-term): Only several tens of in-flight lightning measurements were ever described in literature. Measuring numerous strikes per icing campaign flight enables the composition of a comprehensive strike data base. Better knowledge of the phenomenon characteristics will allow optimising the structural protection of the different aircraft zones, with a positive impact on post-strike airline operations. Beyond pure safety aspects, for which the current regulation suffices, this knowledge of the threat statistics will help to define the appropriate protection robustness with respect to airframe maintainability and unscheduled repair.
3. For maintenance and repair organisations (long term): a commercial adaptation of the ILDAS system could be installed in airliners and be used as a real-time lightning damage assessment system. It would inform the organisations immediately after the strike, thus enabling anticipative maintenance actions. The inspection time can be significantly reduced, as can flight delays and flight cancellations.

To make the ILDAS technology suitable for in-flight measurement of actual strikes to aircraft, it had to be taken from technology readiness level (TRL) 3 ("analytical and experimental critical function and/or characteristic proof-of-concept"), at which the ILDAS-1 project ended, to TRL 6 ("system/sub-system model or prototype demonstration in a relevant environment"). The focus of the project was on delivering an in-flight system with full in-flight measurement functionality (reliable triggering, all sensors installed and data recording without missing strikes), and to post-process and analyse the data on ground, after the flight.

In order to incrementally mature the ILDAS system for the flight test campaign of the Airbus A350XWB, a three-stage flight test approach was planned:

1. In-flight "engineering testing" with a limited two-sensor system (one magnetic-field and one electric-field), and continuous, relatively low-rate data capture, to validate the operation of the hardware while in flight and subjected to a true lightning environment. This campaign was conducted in 2011 and the results have been analysed. They are described in section 4 of this paper.
2. System in-flight validation, using a complete system, and triggered high-rate data capture. This campaign was conducted in 2012, as described in section 5, but the results are not yet available.
3. Deployment of the validated lightning measurement system on an Airbus A350 XWB test aircraft during icing test flights, planned for 2013.

2 SYSTEM CONCEPT

The purpose of the ILDAS system is to determine the electrical current waveform of the lightning channel and the points of attachment on the aircraft. To do this, synchronous measurements of the magnetic field are performed on various parts of the aircraft using the specially-developed ILDAS data acquisition system. The resulting data from multiple sensors is subsequently processed by a numerical toolkit to determine the lightning attachment points and to reconstruct the lightning current waveform, see Figure 1.

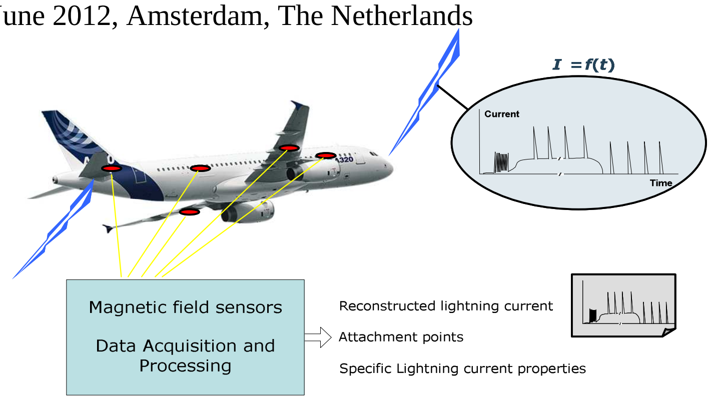

Figure 1 – Reconstruction of the lightning channel current

2.1 Sensor locations

In ILDAS-1, the sensor locations were on the fuselage, in the cabin, on the wings in flap track fairings, and on the horizontal and vertical tail plane (see Figure 3). The in-cabin window sensors, described in section 2.2, were a new development. Their performance was shown to be as good as external sensors, without requiring installation outside the (pressure and temperature-controlled) cabin, as for the other sensors. For ILDAS-2, an ambitious implementation goal was set: make the system cabin-only, meaning a sensor configuration that employs only window sensors. This configuration greatly simplifies installation, and relaxes environmental compatibility requirements. Clearly, such a configuration would reduce the amount of information, so it had to be studied how well the waveform reconstruction could be, especially for attachment scenarios involving a wing or parts of the tailplane.

2.2 Window sensor for magnetic field

Within the ILDAS-1 project, the Eindhoven University of Technology developed a novel cabin-window-mounted magnetic-field sensor (ref. [5]). The measurement principle is that the lightning current generates a magnetic field outside and around the aircraft. A simple but effective sensor to determine that field strength employs the penetration of the field through openings in the fuselage, in particular the cabin windows. A single wire antenna that spans the window at mid-height inside the aircraft senses the magnetic field variation through the window, see Figure 2.

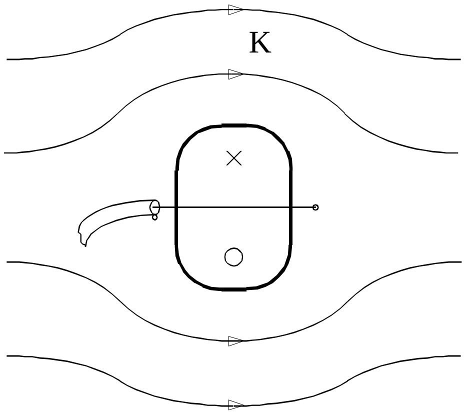

Figure 2 – Principle of the window sensor, with lightning current density K through the aircraft fuselage. The magnetic-field penetration of the window is indicated by × and ○.

2.3 Acquisition system

Dedicated sensor assembly electronics units perform the data acquisition. The electrical signal is the time-derivative of the magnetic field strength; signal integration is performed in the analogue domain. Two different integrators are used, each with its own time constant, which provides two signal processing channels with different gains to allow a large dynamic range (about 96 dB). The outputs of the integrators pass analogue signal processing stages to reach a high-speed Analogue-to-Digital Converter (ADC). The bandwidth of each sensor channel is:

Magnetic-field sensor: 100 Hz – 10 MHz
Electric-field sensor E1: 100 Hz – 500 kHz (later extended to 10 Hz, see §5.1)
E2: 100 kHz – 1 MHz

Digital signal processing for the three measurement channels takes place in a field-programmable gate array (FPGA), which writes measurement data in a 1.2 second ring buffer memory. Upon detection of a strike, all sensor assembly electronic units are simultaneously triggered with high time synchronicity (10 ns). Each ring buffer stores 0.2 seconds of data before the trigger and 1.0 seconds thereafter. A spare buffer is available to prevent data loss when a second strike occurs before the first buffer is emptied. Buffer contents are transferred through a fibre-optic Ethernet network to an onboard central control and storage system.

2.4 Processing – The inverse method

The objective of the ILDAS inverse method is to reconstruct the lightning current and the lightning impact scenario, using magnetic-field measurements from multiple sensors. The inverse method is part of an electromagnetic toolkit developed by EADS IW, based on their ASERIS-FD software. Since the impact scenario is unknown before the reconstruction, the measured signals are processed for each individual impact scenario. Subsequently, the scenario is chosen that presents the smallest error between the provided measurements and a reconstruction based on a database of lightning response signals for the particular aircraft and aircraft configuration. The database is constructed with a detailed electromagnetic model of the aircraft and a list of the most probable scenarios, established by Airbus in-service operational experience. Reference [4] contains more detail on the algorithm.

3 A320 CAMPAIGN 2009 – GROUND TEST

A ground test of the concept prototype system with six sensor assemblies was performed on an Airbus A320 test aircraft in 2009 within the FP6 EU project, as described in reference [3].

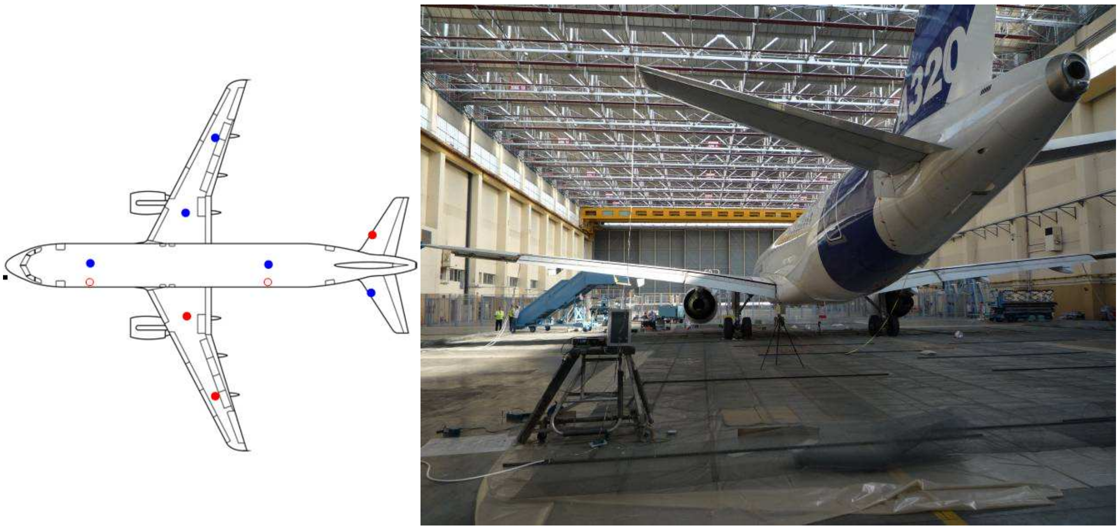

Figure 3 – Left: overview of the 12 positions of the sensors on the Airbus A320 aircraft during the 2009 ILDAS ground test. Red are ILDAS sensor assemblies, blue are additional sensor assemblies based on digital oscilloscopes. Right: a lightning waveform generator injects 3 kA pulses into the horizontal stabilizer of the aircraft. Current return occurs through a metal mesh on the ground.

4 A340 CAMPAIGN 2011 – IN-FLIGHT ENGINEERING TEST

The campaign was conducted in March 2011 in southern Europe and consisted of three flights through lightning, resulting in the recording of 30 strikes. The goal of the campaign was (a) to validate the operation of the hardware while in flight and subjected to a true lightning environment, and (b) to obtain measurement data for verifying and optimizing the lightning strike detection (trigger) algorithm.

4.1 Architecture

The ILDAS system is designed for triggered measurement of lightning-induced fields at an acquisition rate of 100 MS/s for a duration of 1.2 seconds. No flight-proven trigger algorithm existed, so the engineering test phase was based on measuring continuously throughout the entire flight, with a reduced amount of data. Two sensor assemblies were deployed in this test; one for magnetic field and one for electric field, see Figure 4.

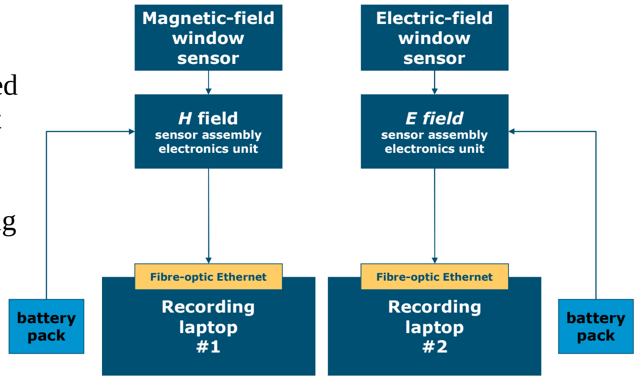

Figure 4 – Architecture for the engineering test phase

The field-programmable gate array (FPGA) inside the electronics units down-samples the 10 ns-sampled data to intervals of 2.5 µs. The resulting data was continuously streamed over a 100 Mb/s fibre-optic Ethernet link to two Linux-based data storage computers. For each reporting period of 2.5 µs, the following parameters were recorded: (1) maximum value, (2) minimum value, (3) average value, (4) extreme value (max or min), filtered for spikes, as a backup in case measurements would be disturbed by spurious errors, and (5) results of the candidate trigger algorithm, as developed by ONERA within the ILDAS-1 project based on the experience from an in-flight lightning campaign performed in the 80's (ref. [6]).

4.2 Installation in the aircraft

Airbus performed the installation of the ILDAS measurement equipment in an Airbus A340 factory test aircraft. The position of the equipment in the aircraft was in the left forward part of the cabin, about half-way between the nose and the leading edge of the wing. Figure 5 shows the installation of the magnetic-field window sensor on the leftmost window, and the electric-field window sensor on the second window. Below the windows is a mounting frame for the two sensor assembly electronic units (orange boxes), mounted to the (vertical) aircraft frames. On the cabin floor is a rack with the two data recording computers and batteries for the electronic units.

Figure 5 – Installation of the test setup in the Airbus A340 aircraft. The leftmost window has the magnetic-field sensor, the second window the electric-field sensor. The orange box is one of the two acquisition units performing signal conversion and short-term data storage. The laptops record all data during flight.

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4.3 Measurement results

Figure 6 shows an overview of the measured waveforms for the flight that took place on 29 March 2011. For each data point, a line is plotted from the minimum value in that interval to the maximum value. The units on the *x* axis are seconds; the graphs cover a complete flight. The units on the *y* axis are arbitrary units (unscaled output values of the ADC).

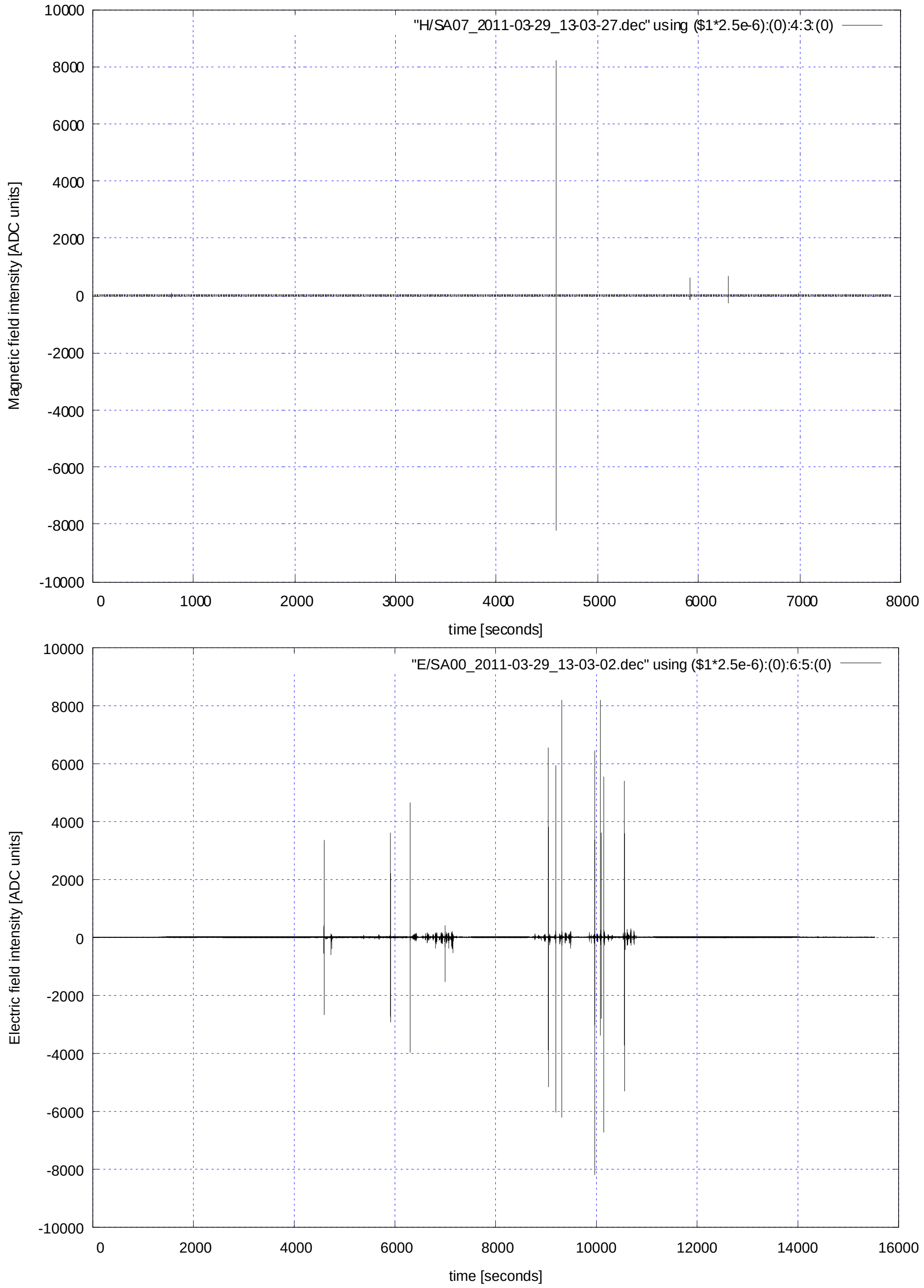

Figure 6 – Overview of 29 March flight; magnetic field HF1 above, electric field E1 below. Note the dissimilar x axes; due to depletion of a battery the magnetic-field recording stopped before the end of the flight.

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4.4 A detailed look at one event

In this section one event is presented in some detail: the first strike of the last flight, which contains the largest magnetic-field peak observed in the A340 2011 campaign. The recording exceeded the measurement range of the acquisition electronics' first, high-accuracy measurement channel, and was correctly measured with the second, high-range channel. Figure 7 below shows data from the high-accuracy channel, which clipped at its maximum level of 8191. Results from the high-range channel are shown later in this section. The magnetic-field data is at the top, the electric field in the bottom part of the graph. For the electric-field data two channels are displayed: the black line is the wideband signal (100 Hz – 500 kHz) with its units on the left axis in black; the red line is the high-frequency signal (100 kHz – 1MHz) with its units on the right axis in red. The units on the *x* axis are seconds (synchronised between both recordings), the units on the *y* axis are arbitrary units (unscaled output values of the analogue-to-digital converter).

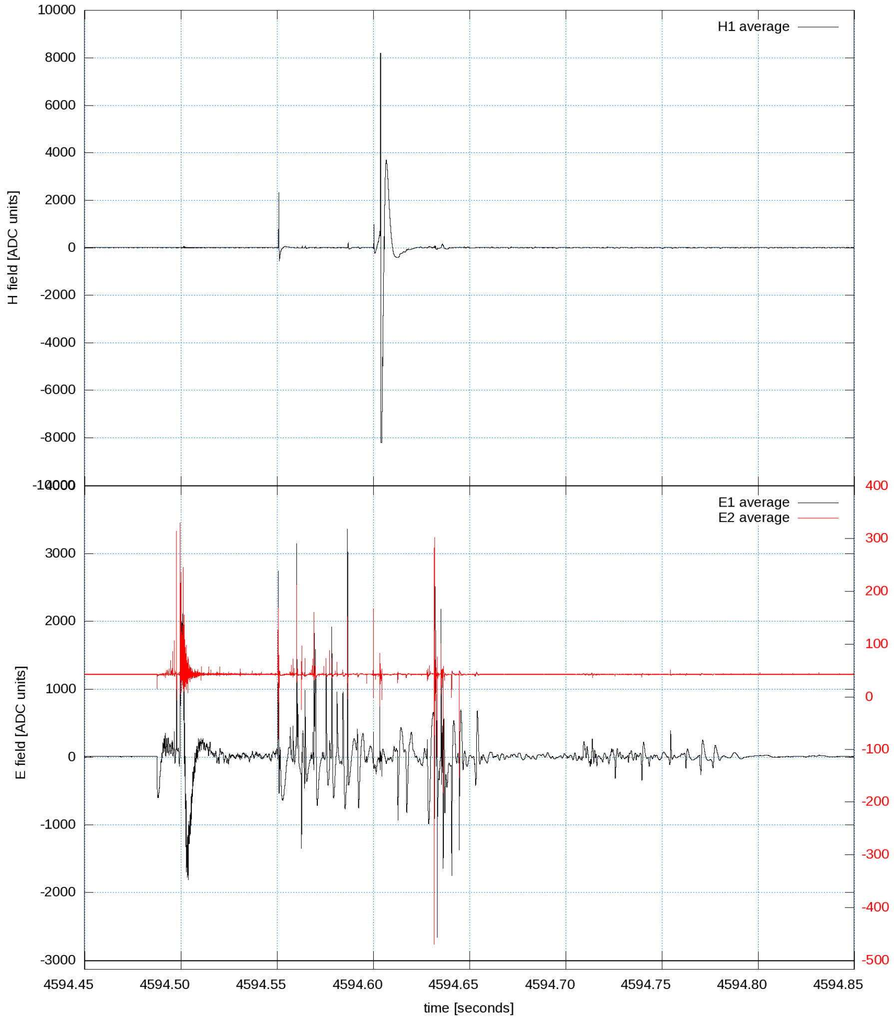

Figure 7 – First strike of last flight: 400 ms recording cutout (50 ms/div)

Figure 7 above shows several stages of the development of this lightning strike:

1. Around 4594.50, pre-burst activity consists of a characteristic development of the electric field, without any high-amplitude activity of the magnetic field. This stage is associated with the development of a positive leader from the aircraft towards the charge centre in the thunderstorm. Figure 8 shows this stage in more detail.

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2. Around 4594.55, so about 6 ms after the development of the leader, the first return stroke occurs. The stroke causes a major peak in the fuselage current, which was measured with the ILDAS magnetic-field window sensor (see Figure 9).
3. Around 4594.60, the second and largest return stroke occurs, see Figure 10.

4.4.1 Leader development

The first activity, around 4594.50, is the leader development stage. This shows only minor magnetic-field activity, but considerable electric-field signal. Although magnetic-field levels are relatively low (note the difference in *y* axis scaling in this graph compared to the previous graph), this stage is known for the fast rise time of the current waveform. This stage therefore causes a considerable amount of interference on the aircraft-internal domain due to the frequency-dependent nature of the coupling between the lightning current and the internally induced current. Due to the relatively low reporting speed of 2.5 µs during this campaign, the rise time of the signals cannot be accurately determined.
400 Hz signals generated by the aircraft electrical power system can also be seen in the magnetic-field recording. These are caused by fuselage currents, due to the fuselage being used by the aircraft power system as neutral conductor for electrical loads. The fuselage current causes a true magnetic field signal, which is truthfully measured by the sensor.

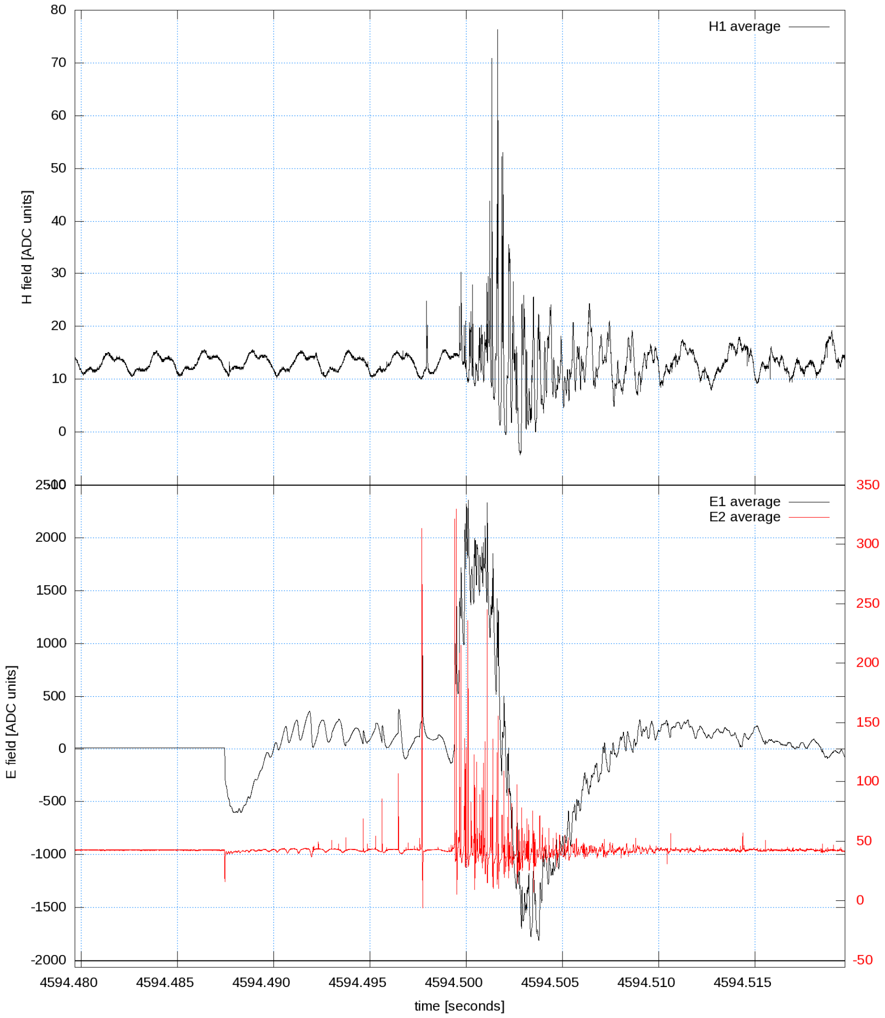

Figure 8 – The leader development stage of the strike (40ms cutout, 5 ms/div)

4.4.2 First return stroke

The first significant H field activity (around *t* = 4594.56) is shown in Figure 9. The peak value is about 2400 ADC units, representing about 11 kA of current flowing in the cross section of the fuselage at the location of the sensor.

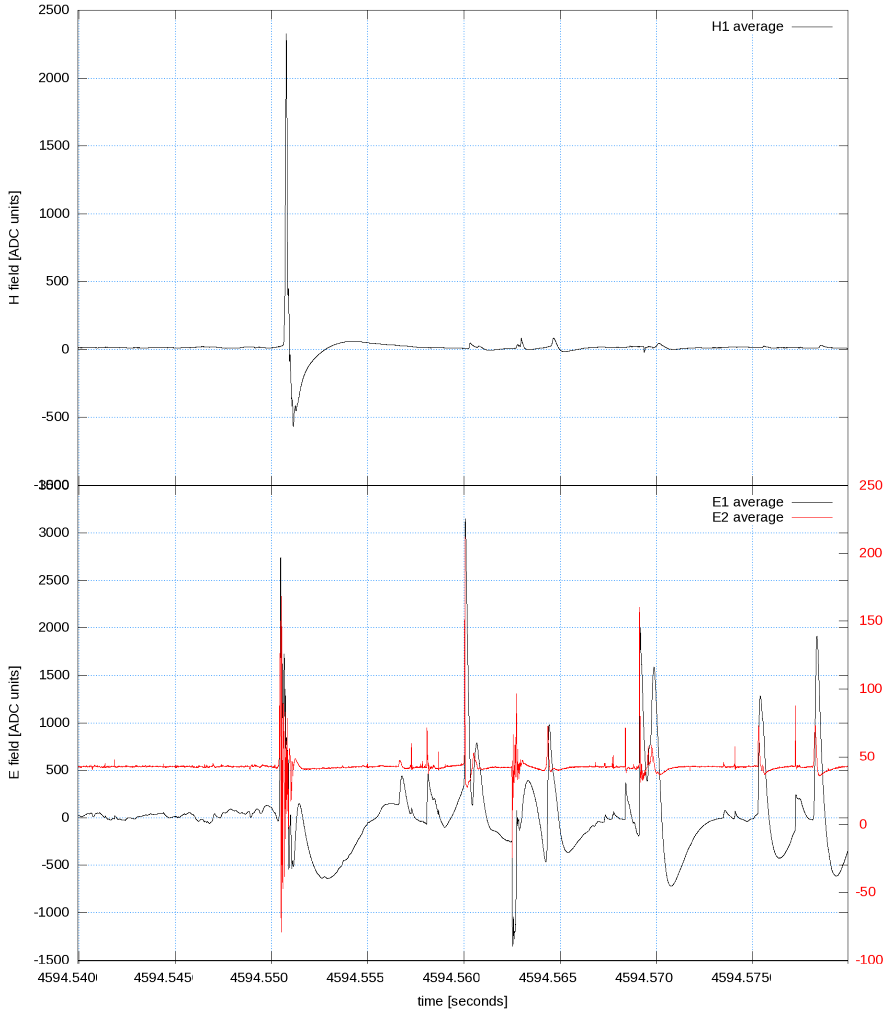

Figure 9 – First return stroke (40ms cutout, 5 ms/div)

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4.4.3 Second return stroke

Figure 10 shows the high-intensity peak as measured by the large-range data acquisition channel. The event is zoomed in to 4 ms total duration. It should be noted that all figures presented in section 4.4 show a 100 Hz high-pass filtered version of the true magnetic-field signal. The measurement principle – based on the time-derivative of the magnetic field – does not allow measurement of the lowest-frequency signal components. The most visible consequence in Figure 10 is the apparent negative part of the signal after $t = 4594.604$, which was not present in the original signal. Also the peak amplitude of the original signal was larger than the peak in the high-pass filtered data. The measured value of 1388 units on the large-range channel (which has a lower gain than the high-resolution channel used in section 4.4.2) represents about 125 kA of current flowing in the cross section of the fuselage at the location of the sensor. The peak value in the original signal has not been calculated.

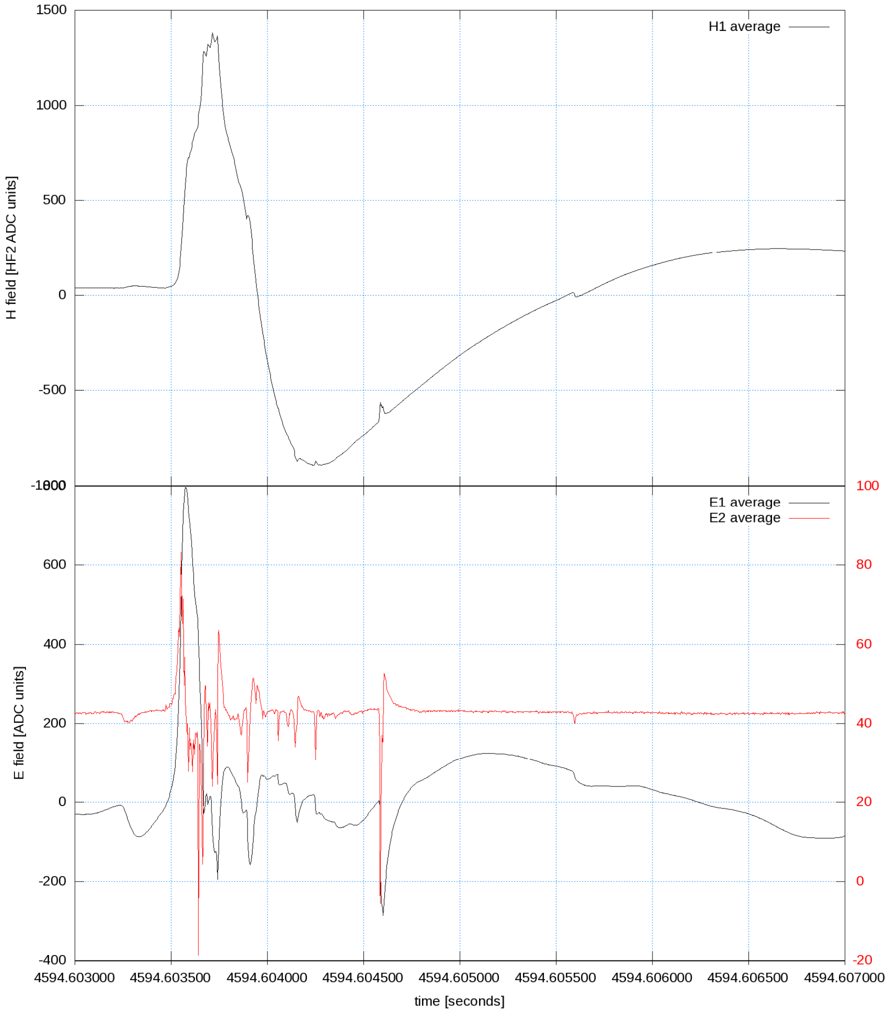

Figure 10 – Second, largest return stroke (4 ms cutout, 500 µs/div)

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4.5 Triggering

An important goal of the 2011 flight tests was the verification and the validation of the conceptual strike detection (trigger) algorithm. This algorithm is based on the characteristic shape of the electric field waveform during the initial leader development: an initial rise followed by a sharp stepwise collapse (refs. [2], [6]). From the strike recording presented in section 4.4, the measured electric field is shown in red in Figure 11. This signal was high-pass filtered at 100 Hz by the acquisition system. The bump-shaped signal observed between t = 4594.387 and t = 4594.400 is observed on most strikes and appears remarkably similar. However, the intensity is lower than useful for the foreseen strike detection (triggering) algorithm. With numerical post-processing, the effect of the high-pass filter was later numerically corrected (which is possible for short time spans only), shown in green in Figure 11. This reveals the original full-spectrum signal, of which the low-frequency components were attenuated, but still available in the measured signal. Since measurement down to DC is not possible for practical reasons, an alternative high-pass frequency of 10 Hz instead of 100 Hz was analysed, shown in blue in Figure 11. This alternative is feasible from a measurement perspective and provides sufficient waveform detail for the trigger algorithm.

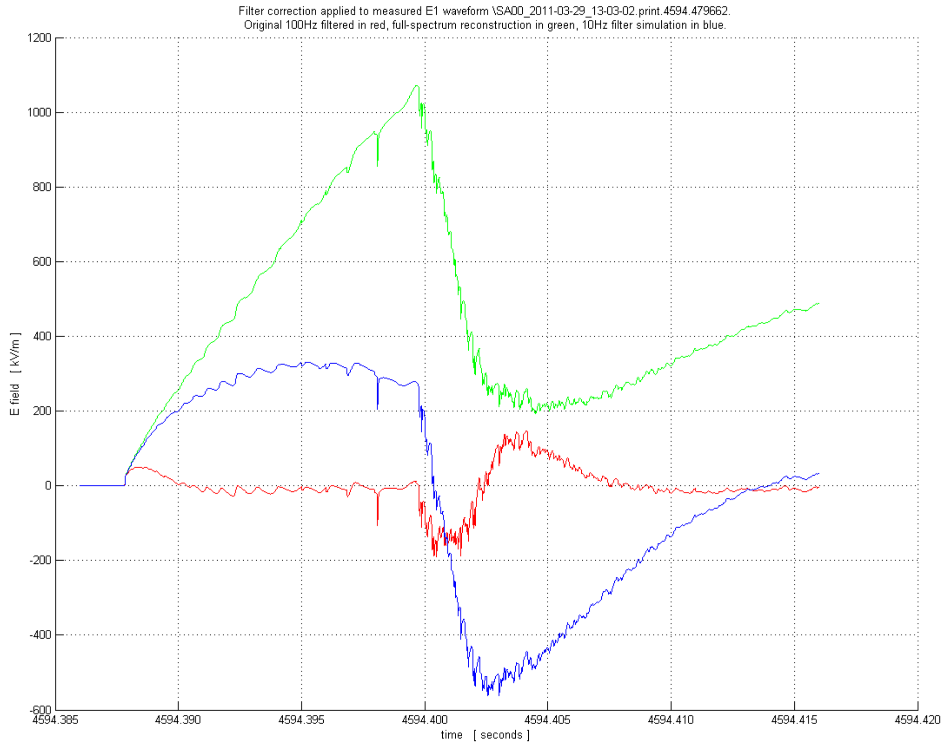

Figure 11 – Leader development phase: Electric-field 100 Hz high-pass filtered recording (red), full-spectrum numerical reconstruction (green) and numerical simulation of a 10 Hz filter (blue). (5 ms/div)

4.6 Strike frequency

The continuous recording yielded valuable input for the ILDAS system architecture. One unexpected finding was that the frequency at which the strikes to the aircraft occurred was higher than expected. At a certain point in the flight campaign, six strikes were recorded in a period of 1000 seconds, so on average 167 seconds between strikes. This meant that a triggered system must be capable of collecting the strike data from all sensors and free the system well within this time period. The ILDAS system architecture was initially based on a worst-case scenario of two strikes in quick succession, followed by a relatively long time of lightning inactivity, allowing the system ample time to store the captured data. For an application in commercial flights, where pilots try to avoid lighting storms, it may be argued that this is still a valid assumption, but it is now clear that it is not a valid assumption for flight test application. With this finding, the architecture was adapted to prevent losing data during campaigns that use triggered acquisition.

5 A340 CAMPAIGN 2012 – IN-FLIGHT SYSTEM VERIFICATION

After analysis of the 2011 campaign data, the ILDAS system architecture was adapted (described in section 5.1), and additional system components were manufactured. As validation of the system a complete setup was installed in the Airbus A340. It consisted of eight magnetic-field and one electric-field sensor assembly and employed triggered data capture at a high sample frequency, as described in section 5.2. A flight campaign was conducted in March 2012 in South America, during which the aircraft was struck by lightning multiple times. However, at the moment of writing, the ILDAS data recordings were not released yet.

5.1 Architecture

The ILDAS system architecture was adapted based on the results of the engineering test phase. The main modification was an optimisation of the trigger concept. The lower frequency of the electric-field sensor was extended from 100 Hz down to 10 Hz, for which the need was described in section 4.5. Instead of triggering only on electric-field signals, a hybrid system allows any one of the sensor assemblies, electric-field or magnetic-field, to generate a trigger. The observed higher strike frequency, described in section 4.6, was handled by increasing the number of central computers and allowing for simultaneous downloading of data from multiple sensor assemblies to each computer. The adaptations required a modification of network architecture, and a dedicated fibre-optic Ethernet network switch was developed, which handles (a) data communication between the sensor assemblies and the central computers, (b) handles distribution of trigger messages, and (c) performs high-accuracy time synchronisation between the sensor assemblies. The resulting architecture is shown in Figure 12. For the validation, the current probe sensor assemblies and the (IRIG) synchronisation with the flight-test instrumentation were not implemented.

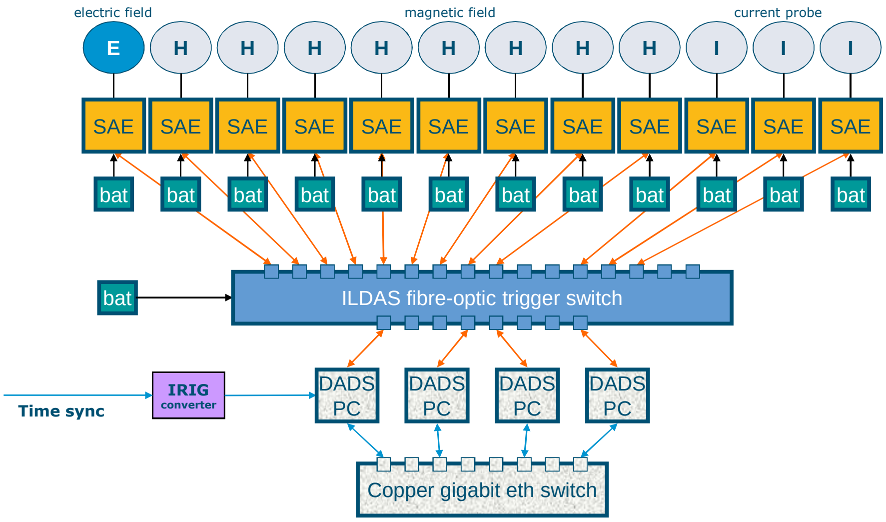

Figure 12 – ILDAS on-board system architecture

5.2 Installation

The ILDAS system consisting of one electric-field and eight magnetic-field sensor assemblies was installed into the Airbus A340 test aircraft. The magnetic-field sensors were installed symmetrically on left and right sides of the aircraft. Two sensors were placed about halfway in the fuselage section between the nose and the leading wind edge, two in the section between the trailing wing edge and the tail, and four in the middle of the aircraft, above the wings. The over-wing sensors covered two directions, one sensitive for magnetic fields caused by nose-to-tail currents, and the other for wing-to-wing currents, see Figure 13 right-hand side. The electric-field sensor was also placed in the forward section. The central control and data storage system, consisting of the Ethernet switches and three laptops, were installed in the middle of the aircraft, see Figure 13 left side.

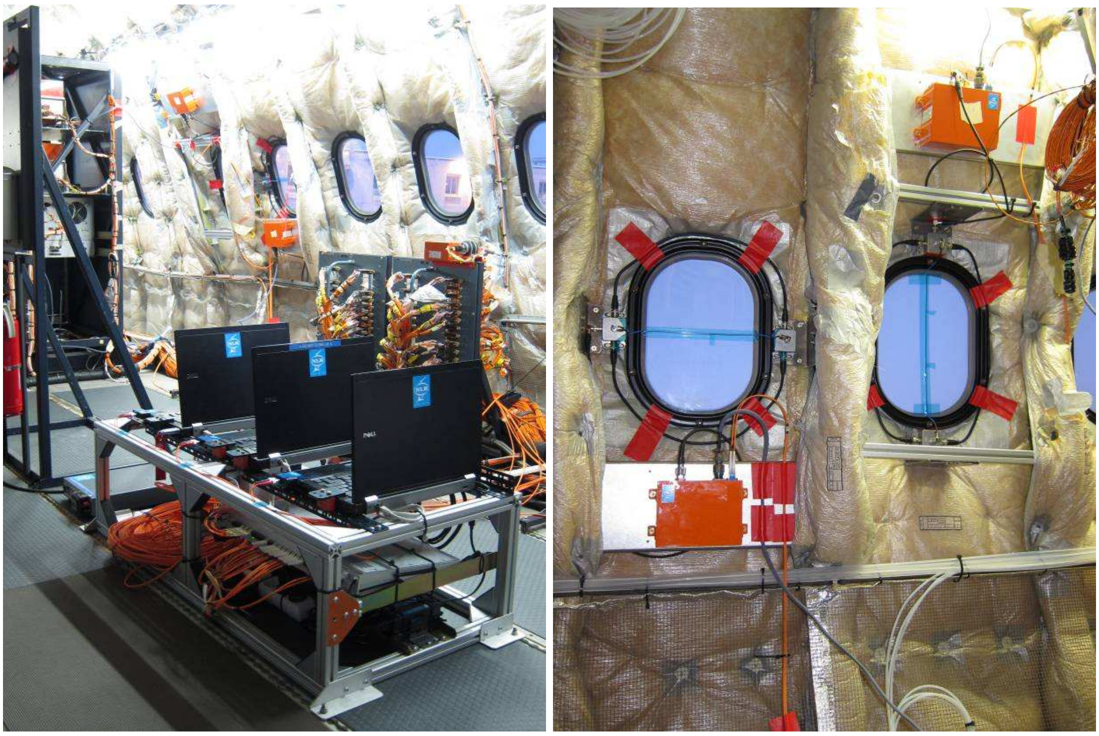

Figure 13 – ILDAS installation for system verification onboard the Airbus A340

6 CONCLUSIONS AND FUTURE CAMPAIGNS

As part of ILDAS programme, flight tests were performed on a system capable of in-flight lightning measurement. The system was installed completely inside the aircraft cabin. Preliminary in-flight testing was done in March 2011 for verification of system components including compatibility with the in-flight environment during a lightning strike. The data from these flights were analysed to verify the performance and to assess algorithms for lightning strike detection. The results of the engineering test phase allowed the final decisions to be made on the architecture for the final application on the A350 XWB. A validation test campaign was conducted in March 2012 where a full-architecture implementation was on board, but results of this campaign are not available yet.

The next stage will be the deployment of the lightning measurement system on an Airbus A350-900 XWB test aircraft during icing trials. Icing trials are flown in conditions with a very high probability of lightning strikes, and aircraft are typically struck several tens of times during the trials. The results allow correlation of events during flight tests with lightning characteristics and extension of the general knowledge on the interaction between lightning and aircraft in flight. This knowledge may be employed in the medium term to optimise the aircraft lightning protection provisions while complying with the high safety standards adopted in civil aviation. An application in the long term may be a commercial system carried onboard during regular airline operations that allows improved maintenance speed or efficiency after an airliner suffered an in-flight lightning strike.

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