Free Flight Boundary Layer Investigations by means of Particle Image Velocimetry

Christina Politz1,*, Christoph Roloff1,2, Reinhard Geisler1, Andreas Schröder1

1: Institute of Aerodynamics and Flow Technology, Department of Experimental Methods, German Aerospace Center, Göttingen, Germany
2: now at Institute of Fluid Dynamics and Thermodynamics, University of Magdeburg, Magdeburg, Germany
* Correspondent author: Christina.Politz@dlr.de

Abstract A comprehensive flight test study comprising three different measurement techniques operating simultaneously is herewith presented. This experimental campaign aimed at demonstrating the applicability of PIV under free flight conditions. The PIV system itself consisted of two stereoscopically aligned PIV cameras as well as a mobile and robust laser system. One crucial novelty to PIV measurements in general was the usage of naturally occurring cloud droplets as seeding material. This particularity emerged to be the most restricting and indeterminable factor of the measurement chain of this campaign with respect to the accuracy of the PIV method but also to the flight test strategy. On account of this, two additional reference systems were also integrated inside the aircraft. On the one hand, a single-point measurement method based on differential pressure probes was installed close to the PIV field of view to allow a comparative determination of the local velocity inside the fuselage boundary layer of the aircraft. On the other hand, a laser based particle sizing technique by means of Interferometric Laser Imaging for Droplet Sizing (ILIDS) was also designed, certified and embedded inside the aircraft cabin of a Dornier Do 228 – 101. This method enabled the determination of the cloud droplet sizes and the number density as an input for the analysis of particle dynamics. This paper gives a brief overview of the overall system design and integration. The presented results and the following discussion however focus primarily on the PIV data.

1. Introduction

Applying complex measurement techniques to flight test conditions often increases the level of uncertainties regarding the reliability and accuracy of an experiment. A realisation and evaluation of the PIV technique under these conditions was up to this campaign as part of the European research project AIM and its successive project AIM² (Advanced In-flight Measurement Techniques) still outstanding (Politz et al. 2010). Before those first attempts similar methods for flow quantification like Laser Doppler Anemometry (LDA) were adjusted for in-flight applications. In this regard Becker et al. (2000) reported about a LDA flight experiment with a small fixed wing aircraft. The aim of this experiment was to study the boundary layer transition on the wing under the influence of an excitation source with the help of an optimised LDA system. The integration of such a system with high energy light sources and intense data transfer especially inside small aircrafts like the used motor glider is often more difficult because of the limited space and power supply. A similar LDA study with a Do-128 research aircraft was presented by Grosche et al. (2000). For both experiments the given aerosol distribution and characterisation was one of the driving factors for the system design.

The PIV method on the other hand with its unique abilities is able to extend the information density of a flow measurement compared to single-point measurement techniques extensively. This advantage should be recognised because compared to most industrial wind tunnel facilities the available testing time, the degree of reproducibility and the possibilities of instantaneous corrections and adjustments during the flight test is rather limited or even non-existing. Therefore, the PIV technique promised to be an attractive tool for flight test applications in particular with its ability to capture velocity vector field information containing a wide range of spatial scales in the flow. Moreover, the PIV technique can provide significant experimental data for the validation of numerical flow simulations or for scaled wind tunnel tests.

However, it is not always possible to meet certain requirements regarding the laser operation, accessibility to the desired field of view, larger scales or even establishing sufficient basic boundary conditions for the PIV setup by for example providing almost ideal seeding particles when conducting the experiments under free
flight conditions. Hence, a careful evaluation of all possible impacts on the method itself but in particular on
the accuracy and reliability should be carried out before the flight test. On account of this, the herewith
presented flight test campaign did not only comprise the PIV installation but also two additional reference
systems.

The assigned task of this experimental study consisted of two parts. On the one hand, an Interferometric
Laser Imaging for Droplet Sizing (ILIDS) tool and a traversing rake with two differential pressure probes
were installed and operated simultaneously to obtain reference data for the PIV method. A precise
knowledge about the particle size distribution close to the field of view of the PIV method allocated valuable
information for the estimation of the particle dynamics. On top of that the two differential pressure probes
attached to a traversing stem were also placed close to the field of view of the PIV system. These pressure
probes were specifically adapted to velocity measurement within the vicinity of a rigid surface. The obtained
velocity data served as potential reference information for the PIV results. On the other hand, the second task
of this flight test campaign was the physical characterisation of wall bounded flows by means of PIV and
differential pressure probes. The investigated area was very close to the fuselage surface of the research
aircraft.

In the following, the experimental installations as well as the research aircraft are introduced. The presented
results and the subsequent discussion are focused solely on the outcome of the evaluated PIV data. The
significance and the influence of the utilisation of cloud droplets as seeding source is further analysed based
on the obtained data and gathered experiences.

2. Flight Test Installation & Certification

The experimental test bed was a modified research
aircraft type Dornier Do 228 – 101 of the DLR
Flight Department in Braunschweig. This aircraft
possesses two turboprop engines which enable short
take-off and landing abilities. The Dornier Do 228-
101 is a high wing airplane with a wing span of
16.97 m and a fuselage length of around 15 m. It is
designed to carry 18 passengers for a maximum
range of around 1300 km and is therefore classified
as a commuter aircraft. The Do 228 cabin is in
general not pressurised. This circumstance restricted
the maximum altitude of this flight test to around
10.000 ft. Nevertheless, the maximum achievable flight altitude of this type of aircraft is 25.000 ft MSL and
the maximum velocity up to an altitude of 15.000 ft MSL is specified with 200 KIAS.

This particular research aircraft with the call sign D-CODE was subsequently modified to allow manifold
flight test installations. For example, an additional experimental power supply distributed by several
connector panels inside the cabin provided a maximum capacity of approximately 7 kVA allocated by the
generators of the engines. Furthermore, several cut-outs along the fuselage allow miscellaneous external
installations like specific antennas or sensor systems. On top of that, the aircraft has its own Inertial
Reference System which can provide valuable data about the flight attitude as well as atmospherical and
aircraft parameters. These data sets were acquired with the help of a suitable unit provided by the DLR
Institute of Flight Guidance. Several flight parameters of this system were made available and could be used
to check and supplement the PIV flight test data set thanks to the support of the colleagues of the DLR
Institute of Flight Guidance.

The installation of this particular experimental system led to a major modification of the aircraft. The cabin
was equipped with two racks. A first rack in the front of the cabin was housing the data acquisition and
control units for the PIV, ILIDS, pressure probe rake and further flight test devices. A second rack in the rear
part of the cabin held the PIV laser including light sheet optics, power supply, synchronisation unit and
power supply of the PIV cameras. This rack and hence the PIV laser was located right in front of the last
window on the right hand side of the aircraft. This window possessed a spherical shape (see Figure 2) which
enabled an orientation of the laser light sheet parallel to the aircraft fuselage pointing in flight direction and
passing by the penultimate window. The divergence of the laser light sheet was around 9° (see Figure 1).
A pressure probe traverse as well as a camera stand with two stereoscopic PIV cameras and an ILIDS camera were placed in front of the penultimate window on the right hand side of the fuselage. In order to enhance the optical access of the cameras the standard cabin window was replaced by a rigid aluminium frame housing a high quality optical glass pane and a cut-out for the pressure probe stem. The stem of the traversing probe supported two Pitot probes with differential pressure sensors and was able to move 100 mm out- and inwards (Figure 4). The lower so called boundary layer probe had a flattened opening which was at the tip of a curved tube to reduce deviations of the true total pressure caused by the specific finite size of the probe body in the immediate proximity of the wall. The second Pitot tube possessed a larger inner and outer diameter compared to the boundary layer probe. The probe tip of the Pitot tube had a nearly elliptical shape to reduce the yaw sensitivity caused by oblique flow angles occurring in the flow. The total motion of the pressure probe traverse allowed a determination of the velocity profile of the boundary layer between 4.5 mm and 144.5 mm distance from the fuselage surface. The relative location of this measurement window was 10 m downstream from the aircraft nose which resulted in a boundary layer thickness of more than 100 mm at the point of the experimental installations.

The field of view of the PIV camera was approximately 50 mm above the pressure probe stem and covered an area of 75 x 100 mm² depending on the configuration (see Figure 4). The observation distance between the laser light sheet and the cameras was around 164 mm. For the last flight test the laser light sheet was moved 30 mm closer to the aircraft fuselage surface to obtain additional PIV data from a different position inside the boundary layer.
The PIV setup was based on standard components which proved to be robust and reliable over a series of wind tunnel tests. Two pco.1600 cameras with a resolution of 1600 x 1200 pixels were attached to an X95 stand. The lower camera was aligned horizontally relative to the light sheet under a scattering angle of around 90°. This camera was defined as the reference camera. The upper camera was tilted by a stereoscopic viewing angle of around 45° degree also at a scattering angel of 90°. The PIV laser was a Big Sky CFR 400 laser with a specified pulse power of around 200 mJ while emitting green light at 532 nm. The repetition rate is 10 Hz which was also the recording frequency of the PIV and ILIDS system. The certification process of the flight test installation and procedures was an essential and probably the most cumbersome part of this project. In particular the safe operation of a high power laser during the flight could only be managed based on the introduction of several restricting procedures and safety installations.

The particle sizes and concentrations were recorded by means of an ILIDS method. This technique was chosen because an Interferometric Laser Imaging for Droplet Sizing (ILIDS) probe turned out to be the most suitable system for this PIV campaign due to its simplicity and high cost efficiency compared to other probes. The main components of an ILIDS system are a high energy, polarised and monochromatic light source, a camera including macro lens and of course the particles under investigation. The most profound advantage of an ILIDS system for PIV flight tests is the fact that an integration of such a system can be easily done. This simplification is traded off by a lower resolution and lower dynamic range compared to commercially available airborne particle sizing techniques. An ILIDS setup was compiled, tested and certified by DLR. For ILIDS data processing, the Particle Master IMI Sizing software developed and allocated by LaVision GmbH was used.

The PIV and the ILIDS system were running with 10 Hz while the differential pressure probes acquired data with a sampling rate of at least 10 kHz. The synchronization was realized with the help of a sequencer.

![Figure 4: Overall arrangement and relative positions of the measurement areas of each applied experimental technique](image)

<table>
<thead>
<tr>
<th>F/T No. Date</th>
<th>No. of Measuring Points</th>
<th>Illumination</th>
<th>Recording Medium</th>
<th>Observation Distance [mm]</th>
<th>Field of View [mm²]</th>
<th>Record. Freq. [Hz]</th>
<th>Pulse delay [µs]</th>
<th>Seeding</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 07.06.13</td>
<td>8</td>
<td>Nd: YAG Laser Big Sky CFR 400: 2 x 200 mJ / Pulse, 532 nm (Double Pulse)</td>
<td>PIV 2 x CCD camera, pco.1600, resolution: 1600 x 1200 pixel, 14 bit dyn. range</td>
<td>160 (67°)</td>
<td>72 x 97</td>
<td>PIV 30</td>
<td>Cloud droplets originating of haze, layer clouds (e.g. Stratus, Stratocumulus), Cb, Cumulus</td>
<td></td>
</tr>
<tr>
<td>2 16.10.13</td>
<td>8</td>
<td>Nd: YAG Laser Big Sky CFR 400: 2 x 200 mJ / Pulse, 532 nm (Double Pulse)</td>
<td>ILIDS CCD camera, AVT GX 3300, resolution: 3296 x 2482 pixel, 14 bit dyn. range</td>
<td>163.5 (72°)</td>
<td>75 x 100</td>
<td>PIV 30</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>3 17.10.13</td>
<td>6</td>
<td>Nd: YAG Laser Big Sky CFR 400: 2 x 200 mJ / Pulse, 532 nm (Double Pulse)</td>
<td>PIV 2 x CCD camera, pco.1600, resolution: 1600 x 1200 pixel, 14 bit dyn. range</td>
<td>163.5 (72°)</td>
<td>75 x 100</td>
<td>PIV 30</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>4 21.10.13</td>
<td>9</td>
<td>Nd: YAG Laser Big Sky CFR 400: 2 x 200 mJ / Pulse, 532 nm (Double Pulse)</td>
<td>ILIDS CCD camera, AVT GX 3300, resolution: 3296 x 2482 pixel, 14 bit dyn. range</td>
<td>163.5 (72°)</td>
<td>69 x 95</td>
<td>PIV 30</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>5 23.10.13</td>
<td>7</td>
<td>Nd: YAG Laser Big Sky CFR 400: 2 x 200 mJ / Pulse, 532 nm (Double Pulse)</td>
<td>ILIDS CCD camera, AVT GX 3300, resolution: 3296 x 2482 pixel, 14 bit dyn. range</td>
<td>133 (41.5°)</td>
<td>65 x 85</td>
<td>PIV 30</td>
<td></td>
<td>-</td>
</tr>
</tbody>
</table>

* Distance between wall (aircraft fuselage) and light sheet.
3. Flight Test Procedure

A total of 5 flights with an overall flight time of 13:37 hours were conducted in June and October 2013. The decisive factors for the flight path, level and duration were the availability and characteristics of the present seeding, i.e. cloud genus. Depending on the quality of the existing seeding and the stabilisation of the flight conditions each test flight comprised between 6 to 9 measuring points defined by different indicated velocities and flap settings. The altitude during the time within the flight test area was almost kept constant and bank as well as yaw angle were set to a neutral position as far as possible. All flights were conducted during night time to avoid the negative influence of the sunlight on the PIV and ILIDS images and to simplify the flight test procedures with respect to the laser safety.

The recording strategy of each measuring point was aiming on two different objectives. After entering a cloud layer and ensuring the safe operation of the laser, the sequence of the measuring point was activated. During the first approximately three minutes during the recording time the PIV, ILIDS and the pressure probe measurements were running and recording simultaneously. At that time the traverse was positioned at one predetermined distance from the fuselage surface very close to the light sheet and hence close to the field of view of the PIV measurement area inside the boundary layer. The objective of this simultaneous run was the deduction of the comparability between the derived velocities from the PIV and the pressure probe system at the same position inside the boundary layer. After the three minutes run the PIV and ILIDS system were stopped and the pressure probe traverse was now solely moving through the whole boundary layer of the aircraft fuselage to obtain the velocity profile within the proximity of the wall.

4. Results and Discussions

4.1 PIV Results of Different Aircraft Configurations

Every test flight consisted of several measuring points with different flight settings. The changed parameters were mainly the air speed and the flap position. Between the flight tests the altitude and of course the type of cloud as seeding source also constituted variable factors. The changes of the aircraft configuration aimed essentially on impressing different conditions upon the boundary layer flow to determine their impact.

Figure 5 presents two arbitrary PIV images of different measuring points recorded during the fourth flight test on the 21st of October 2013 (see Table 1, F/T No. 4). Even if the first acquired sequence of images encountered a low seeding density the total amount of PIV images with sufficient seeding concentration was comparably high, probably because of a complex frontal system which was constitutive for the experimental condition of that day. Broken Cumulus (CU) and Stratocumulus (SC) cloud layers were forecasted for the predetermined flight test area. Therefore, layer clouds mainly SC with a large spatial extension yielded easily accessible experimental conditions. The presented PIV result on the left hand side of Figure 5 was recorded while flying with an indicated airspeed of 120 kt ($u_\infty \approx 68\ m/s$) and with extended flaps. The PIV image on the right hand side depicts an averaged flow field within the boundary layer (both at a distance of 72 mm away from the fuselage) defined by an indicated airspeed of 180 kt ($u_\infty \approx 105\ m/s$) with retracted flaps. The presented PIV results of both measuring points were averaged over a sequence of 200 images.

Both runs were evaluated with an interrogation window size of 64 x 64 pixels in combination with a window overlap of 75 %. The initial window size of the grid – refinement sequence was 192 x 192 pixels. The figures only show every fourth horizontal and every third vertical vector to increase the clarity of the plots. The most severe difference beside the consistent velocity deviations is given by the increased downward velocity component exposed by the measuring point with extended flaps. Even if the flaps are approximately half a meter above the measuring window their influence is still clearly detectable. The mean value of the horizontal velocity component of the first measuring point was around $u_{120kt} \approx 57\ m/s$ with a mean downwind component of $V_{120kt} \approx -11\ m/s$. On the contrary to that the averaged horizontal velocity of the second measuring point was around $u_{180kt} \approx 99\ m/s$ with a clearly smaller downwind magnitude of $V_{180kt} \approx -5\ m/s$. 
4.2 Flow Quantification at Different Wall Distances

The final flight of the campaign was devoted to the investigation of an alternative light sheet position within the fuselage boundary layer. The objective of this approach was to emerge the different features of the flow in the immediate vicinity of the aircraft surface. On account of this, the light sheet was moved around 30 mm closer the fuselage towards a wall distance of 41.5 mm by repositioning the mirror of the light sheet optics and repeating the calibration procedure (see Table 1, F/T No. 5). The readjusted field of view of the PIV system was now reduced to a size of around 65 x 85 mm² at a working distance of approximately 133 mm. It should be noted that the dimension of the ILIDS images are not reduced by definition and are therefore maintaining the magnification factor and the probe size.

This last modified flight test was conducted on the 23\textsuperscript{rd} of October 2013. At that day a cold front was passing by over Germany during the course of the day. By the time of dusk most clouds of this frontal system were outside of the operating distance of the aircraft over the western part of Poland. Therefore, mostly thin layers of haze with presumably isolated Stratocumulus clouds remained as seeding sources for the PIV measurement. Most of the recorded images showed therefore a very low seeding concentration with comparable small particle sizes. In total, 7 measuring points could be recorded at an altitude of around 5000 ft MSL. To compare a particular measuring point with a similar true airspeed flown during another flight test with the light sheet at the ‘72 mm’ position, the flight parameters should be compared carefully especially regarding the altitude, static air temperature and static pressure. For the purpose of this discussion a measuring point recorded during the second flight test (see Table 1, F/T No. 2) conducted on the 16\textsuperscript{th} of October 2013) was chosen for this comparison. The true airspeed of the two selected measuring points with different light sheet positions was approximately $u_\infty = 70$ m/s and the flaps were retracted.

Figure 6 presents the magnitude of velocities as well as the RMS values averaged over a series of images. The presented PIV results obtained during a flight with a light sheet distance relatively to the fuselage of 72 mm (F/T No. 2) was derived over 20 images, because only this short series of images exhibited an expedient number density of cloud droplets inside the field of view. The pulse delay during this flight was set to be 30 µs. Still, a low density resulted in larger final interrogation windows during the evaluation process with a size of 128 x 128 pixels starting by means of multi – grid refinement at 256 x 256 pixels. The window overlap was chosen to be 75 %. The aircraft velocity was almost kept constant during the course of this measuring point. The averaging of the PIV results of the last flight test (F/T No. 5) was based on 231 images which were recorded throughout a SC layer with a pulse delay of 10 µs. During that time noticeable velocity changes of the aircraft could be detected. The true airspeed decreased from $u_\infty = 72,3$ m/s to $u_\infty = 68,9$ m/s probably due to atmospherical turbulences inside the cloud or piloting inputs. The number density of the particles was still comparable low and hence the interrogation window size was set to be 96 x 96 pixels starting with 160 x 160 pixels.
The averaged results depicted in Figure 6 indicate a velocity deviation of approximately 3 m/s between the 41.5 mm (F/T No. 5) and 72 mm (F/T No. 2) light sheet position. An estimation of the boundary layer height based on for example the 1/7 power law at this air speed yields $\delta \approx 110 \text{ mm}$. Even though this law is more accurate for lower Reynolds numbers it seems to agree quite well with the pressure probe data. Based on this theory and the first preliminary results of the pressure probes a deviation of the velocities of the different light sheet positions and hence wall distances of around 5 m/s would be more likely. However, it should be taking into account that the determination of the averaged PIV results as well as the pressure probe data is based on small samples which were in addition strongly influenced by external perturbations like atmospheric turbulences, air speed changes or probably particle dynamics.

A rough idea about the intensity levels of the turbulent boundary layer under investigation can be deduced with the help of the RMS values of the velocity fluctuations. The right diagram of Figure 6 depicts the root–mean–square values of the fluctuations averaged over the same number of images and therefore under the same flight conditions and evaluation parameters. Note that the RMS values of the 41.5 mm – FOV are generally higher with respect to the fluctuation strength but smaller regarding the dimensions of the detected turbulent structure. The consistent location of certain structures over the averaged series of PIV images may indicate a statistically stationary behaviour of the turbulences at this point. But it has to be pointed out that the number of considered samples is not high enough to provide a robust result to support these assumptions.

4.3 Naturally Occurring Cloud Droplets as Seeding for PIV

The utilisation of naturally occurring cloud droplets as seeding sources for PIV measurements proved to be an approach which precipitated an undeterminable uncertainty to the measurement. The particle diameters tend to be generally larger compared to nearly ideal tracer particles injected for example into the measuring section of a wind tunnel with especially designed seeding generators. A first glance at the preliminary ILIDS results indicated an average particle size of around 16 µm in Stratocumulus (SC) and Cumulus (CU) clouds which are the most commonly occurring cloud types not only during the measurement but also in general. Several measuring points recorded during different flights in humid haze layers showed presumably smaller particle images but also a lower number density compared to SC clouds. From these observations followed that often in times the seeding conditions are characterised by a compromise between a sufficient seeding concentration and a viable particle diameter.

Figure 7 presents a raw PIV image captured during the first flight test (see Table 1, F/T No. 1). The meteorological conditions forecasted a high pressure area which increased its influence over Germany and caused a decreased tendency of cloud development. Only isolated Cumulus and Cumulonimbus (CB) clouds
with thunderstorms occurred. This resulted in a long test flight of almost 4 hours over a distance of 1130 km towards Berlin and the polish border. Only single events of significance could be recorded in clouds with a small horizontal dilatation but large vertical dimension. These CB clouds are often characterised by very strong up- and downdrafts which could result in precipitation or even thunderstorms. Therefore the seeding concentration turned out to be very inhomogeneous. Not only with respect to the seeding density within one PIV image but also in between two subsequent PIV recordings (see Figure 8).

![Figure 7](image1.jpg) Left: Variation of seeding concentration, Right: Research aircraft entering a potential seeding source

These higher turbulence levels which can occur in every genus of clouds further complicated the attempt to compare the PIV results with the pressure probe data. The measured boundary layer profile of the pressure probe rake was often in times strongly disturbed by changes of the flow or airspeed changes of the aircraft. These conditions make a differentiation of the individual contributions to the acquired flow field by the atmospherical or aircraft dynamics from the inherent turbulent structures of the boundary layer flow almost impossible. In addition, a consequential treatment of the PIV and pressure probe data for the purpose of comparison emphasises the fundamental difference between single-point measurement technique and methods with a high spatial resolution such as PIV. Averaging the velocity at one discrete time step over the whole PIV image to derive the corresponding absolute value of the velocity and compare this value to the mean velocity within this time interval is not a viable approach. Figure 6 gives an idea of the resulting RMS values within the PIV images. The strength of theses fluctuation can cause severe deviations from the underlying mean velocity and of course also from the averaged pressure probe velocity at that time step.

Artificial seeding sources would allow a decoupling of the airborne PIV measurement from clouds as seeding sources and hence flights in calm air might be possible. However, integrating those complex and often pressurised devices upstream would induce a perturbation of a different kind.

![Figure 8](image2.jpg) Subsequent changes of seeding concentration within 0.1 seconds.
5. Summary

Flight tests with such complex measurement techniques like PIV necessitate a comprehensive study of the interactions of each single link as part of the measurement chain. Even the installation of an independent reference system should be reasonable to allow a validation of the recorded data. The herewith presented measurement campaign aimed on pursuing this task. A PIV, ILIDS and pressure probe traverse were integrated inside a DLR research aircraft to enable boundary layer measurement under free flight conditions. Over a course of 5 test flights conducted in June and October 2013 a comparably large amount of data was acquired. A restricting factor of this campaign was the utilisation of cloud droplets as seeding sources. Nevertheless, a first glance at the results confirmed the feasibility of PIV for flight test applications if the correspondent system design and validation has been carefully adjusted to the unique boundary conditions of flight testing.

6. Acknowledgment

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7. References