ADVANCED FLOW DIAGNOSTICS FOR AERONAUTICAL RESEARCH

AFDAR

Project Final Report

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Project no.	265695
Instrument:	Collaborative Project (STREP)
Thematic Priority:	FP7-AAT 2010-RTD-1
Start date of project:	1 November 2010
Duration:	42 months
Classification:	PU

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PROJECT FINAL REPORT

Grant Agreement number: 265695

Project acronym: AFDAR

Project title: Advanced Flow Diagnostics for Aeronautical Research

Funding Scheme: FP7-RTD-STREP

Period covered: **from** 2010-11-01 **to** 2014-04-30

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1 Final publishable summary report

1.1. Executive summary

The objective of AFDAR is to develop, assess and demonstrate new image-based experimental technologies for the analysis of aerodynamic systems and aerospace propulsion components. The main development focus is on new three-dimensional methods based on Particle Image Velocimetry (PIV) to measure the flow field around aircraft components, and on the high-speed version of the planar technique for the analysis in time-resolved regime of transient/unsteady aerodynamic problems.

The progress beyond the state of the art with respect to current technologies is summarized by three aimed breakthroughs: 1) three-dimensional volumetric measurements over wings and airfoils; 2) time-resolved measurements and aerodynamic analysis several orders of magnitude faster than today; 3) turbulence characterization in aerodynamics wind-tunnels at resolution orders of magnitude higher than today by Long-Range Micro-PIV. The project ultimately aims to support the design of better aircraft and propulsion systems by enabling the designer to use experimental data during the development cycle of unprecedented completeness and quality. The work also covers the simultaneous application of PIV-based techniques and other methods to determine aero-acoustic noise emissions from airframe and to improve combustion processes to lower NOx, CO2 and soot emissions from engines.

The consortium is led by a Dutch Technical University and lists 10 partners including a Russian research Institute and an Australian University. Industries are involved in this work providing testing facilities. The project delivers a detailed analysis of the new measurement systems and a number of technology that validate these concepts in industrial environments.

The results are widely disseminated from small scale (consortium meetings, AFDAR workshops) to large scale (international symposia and conferences) and by scientific publications. A worldwide initiative to assess the state-of-the-art of PIV (www.pivchallenge.org) is initiated under AFDAR and will run beyond the time-frame and scope of the project.

1.2. Summary description of project context and objectives

The objectives of the AFDAR project are intended to contribute within the wider scope and context of the EU efforts towards reaching a Greener and Sustainable Air Transport.

The need for radical improvements in the efficiency and reliability of air transportation has been clearly identified by the European commission in FP7 and through the launch of the Clean Sky Joint Technology Initiative. European aeronautics is committed to play a prime role in shaping aviation for this new age. Technological innovation and the development of better aeronautical systems require a significant effort in terms of upstream research to further extend the base of available technologies used in the development cycle of aircrafts.

In particular Europe seeks to build safer, greener and smarter aircraft and has agreed in 2007 on targets to cut greenhouse gas emissions by at least 20% until 2020. For that purpose, the objective is:

to reduce fuel consumption and CO2 emissions by 50%; to reduce NOx emissions by 80% during landing and take-off. Last but not least, according to Europe strategic research agenda in aeronautics (ACARE), acoustic emissions should be reduced such to achieve 50% perceived external noise.

These objectives require significant improvements in the design of propulsion systems and external aerodynamics for the aeronautical industry, which in turn make necessary advanced verification tools for flow physics, including complex processes like combustion and aeroacoustics by means of experiments and computer simulations.

Development cycle innovation in aerospace

Despite of the impressive progress in the field of applied fluid mechanics and aerodynamics, the analysis and design of specific aircraft subsystems require more and more reliable approaches. This is particularly true when considering wings with high lift devices deployed or for the prediction and control of acoustic noise both from engines and from the airframe. Moreover the issue of NOx emissions is more commonly addressed downstream of the propulsion devices and breakthroughs may only be achieved if the flow processes occurring within the propulsion system are well understood by experimental visualizations in order to devise appropriate simulation schemes. It is therefore important to support the analysis of these specific configurations by appropriate diagnostic tools.

Beside the potential improvements in cruise flight drag, significant benefit can be expected from a better understanding of transient flight phases (e.g. take-off and landing). The high lift configurations often operate in presence of large flow separation where predictive models fail to return reliable estimates of the flow and detailed experiments are mandatory to validate CFD codes. As an example the activities performed in the EU FP6 C-WAKE and EU FP7 FAR-WAKE projects showed that advanced measurement techniques like PIV play a key role to understand and predict large transport aircraft vortex wakes. Moreover the overall efficiency of air transport relies heavily on modern propulsion systems. The improvement of jet engines is nowadays based on iterative aerodynamics and aerothermodynamics optimization of components such as compressor, combustor and turbine. These optimizations increasingly rely on the complete understanding of the complex interaction between primary and secondary flows present in these systems.

Image based flow diagnostics

Advanced experimental techniques provide improved physical knowledge of critical aerodynamic phenomena, in turn leading to better control strategies (e.g. improving performance of simpler designs such as single flap instead of double). It was clear already in FP6 that research programmes for the development of advanced flow diagnostics had a considerable impact in the innovation of aeronautical design processes. The last two decades have seen the exponential growth of image-based non-intrusive measurement techniques and in particular the development of digital particle image velocimetry (Willert and Gharib, 1991) sets a milestone in the area of flow diagnostics especially for experiments conducted in aeronautical wind-tunnels.

Given the high potential of this technique early European projects conducted in the 90s such EUROPIV and EUROPIV 2 have allowed to bring significant improvements to the PIV technique, but most importantly, to transfer PIV from the laboratory to realistic industrial application (Stanislas et al., 2000-2004). Subsequently the PIVNET and PIVNET 2 European thematic networks have enabled European researchers to establish world-wide leadership in the development and application of advanced concepts for flow measurements based on the Particle Image Velocimetry technique (Schroeder and Willert, 2008). As a result many European industries and laboratories support their R&D activities by the application state-of-the-art PIV during experimental verification of design concepts, resulting in improved competitiveness.

The central aim of the PIVNET II network (http://pivnet.dlr.de/, Schroeder and Willert, 2008) was to try to reduce the time to transfer PIV from the laboratory scale at research organizations, which pioneered various developments to a large variety of industrial applications. For that purpose, during the course of the network, a large variety of very successful workshops were organized around industrial demonstrations. Aside from targeting the field of aeronautics, other demonstrations focussed on turbomachinery, car aerodynamics, naval industry, household appliances, etc. Further special annual workshops were organized to foster contacts and cooperation between the major European PIV developers. Every other year this workshop took the form of an international PIV Challenge (benchmark of PIV evaluation algorithms, Stanislas et al., 2008), which demonstrated the strength of the European PIV community and its leading role worldwide in this field. These activities have been the background for the AFDAR project.

State of the art of PIV techniques and current limitations for industrial applications

One of the objectives in relation to the use of the above image-based flow diagnostics is that results obtained in the area of external aerodynamics achieved in the last 15 years by the very experts in the field, should now and in the future be realized by engineers of average expertise, in less time within industrial facilities. For instance the standard procedure to examine vortex dominated flows (aircrafts wing tip vortices, helicopters and propellers rotors) is based on experiments that make use of PIV, which have rapidly superseded previous methods based on probes or Laser Doppler Velocimetry.

The information obtained by experiments is of statistical nature meaning that ensemble or phase averaging is applied before the results are obtained. Dynamical events such a boundary layer transition, vortex breakdown or unsteady flow structure interaction could only seldom be described by experiments due to the scarce availability and low efficiency of high-speed illumination and recording systems at time.

The current capabilities of experimental methods are not capable of properly addressing a number of problems of high relevance for the industry. The points mentioned below constitute the main driver to perform the technological developments needed to progress beyond the state of the art.

- Understanding and predicting transient/unsteady phenomena: Reliable simulations of unsteady flow separation on aircraft wings, multi-element airfoils and powered engine nacelles at high Reynolds numbers still represent great challenges. The temporal motion of the separated region and the frequency and size of the shedding vortices must be known precisely for the validation of Unsteady Reynolds Averaged Simulations (URANS), Detached Eddy Simulations (DES) and Large Eddy Simulations (LES). At present, CCD technology and Nd:YAG lasers only allow to perform measurements at a typical rate of 5 to 15 Hz. In contrast the time scales involved in real flow conditions are in the order of 1000 Hz and higher. Therefore it is not possible, based on the above technology, to provide insights on the dynamical behaviour of aerodynamic flows of industrial relevance, for instance at the basis of structure vibration and acoustic noise production. So far, most experimental support to the development of CFD codes has been limited to statistical flow information (mean flow topology and averaged fluctuations).

- Analysis of small-scale turbulence: Despite the major advances performed in the last years in the area of turbulent flows simulation, a significant gap exists between the claimed potential of experimental techniques for the study of turbulent flow and what is really possible in industrial facilities. As a result, in industrial environment it is not common to perform detailed measurement of the flow turbulent structure. The main reason being the available spatial resolution, with typically a few millimetres size, fairly below that needed for high-Reynolds number flows, typical of industrial aerodynamics.
- Three-dimensional flows: In problems of practical interest, the flow exhibits three-dimensional behaviour. Above all turbulent flows always involve three dimensional motion, which can only be partly captured by the current planar PIV techniques. The dual-planar technique (Kaehler and Kompenhans, 2000) is an important step towards the measurement of 3D turbulent flows, but it remains limited to two adjacent planes. Phenomena such as transition, separation/reattachment and vortex dominated flows such as in propellers and turbomachinery require three-dimensional characterisation to fully support the validation of numerical techniques aiming at predicting the flow behaviour of these systems.
- Advances in combustion diagnostics: Combustion processes in aircraft engines require simultaneous determination of velocity, temperature and species concentration fields. Planar Laser Induced Fluorescence (PLIF) and Laser Induced Incandescence (LII) have been demonstrated to be suited to the task and separate experiments are possible at research laboratories such as those of DLR-K, CORIA and PC2A. It is however important to be able to establish the correlation between flow field and temperature and fuel concentration. The requirements for simultaneous PIV and PLIF measurements are at an early stage of development.
- Aero-acoustics and aero-elasticity: Velocity field measurements alone are not sufficient to solve the problems where flow induced vibrations (FIV) and aeroacoustics (AA) phenomena are of importance. The latter is highly relevant to the concerns raised about air traffic sustainable growth with the current level of acoustic emissions. Understanding and controlling aero-elastic behaviour has its relevance on safety when operating aircrafts in off-design conditions where flow separation and periodic vortex shedding may lead to amplification of structural vibrations. These regimes are not easily captured by current measurement techniques. PIV measurements do not follow these phenomena because of the low measurement rate. It is required that PIV measurements at high repetition rate are conducted simultaneously to surface pressure fluctuations and sound pressure level far away from the acoustic disturbance.

The objectives of the AFDAR proposal are a direct consequence of the above statements. The work starting point is the state-of-the-art of image based flow diagnostics laser techniques, which are well represented by the consortium participants. The aim is then to develop new concepts and procedures such to overcome the current limitations regarding measurement performances. The aim is not only to develop these new techniques per se but also to bring them to a level of technological readiness such that they can be usefully applied in contexts of industrial relevance. In this respect it has been essential that the partners of this project are excellent representatives of European research in this field, and each of them contributes with unique expertise and skills and specialized infrastructures.

AFDAR focal points and objectives

The AFDAR project focuses upon the following main topics, ranging from upstream research and development to industrial demonstrations:

a) Progress beyond the state of the art in PIV
- Extension to volume resolving (3D) flow field measurements (WP2)
- High frame-rate measurement in the kHz-rate for unsteady and transient phenomena (WP3)
- High resolution non-intrusive characterization of turbulent boundary layers and flow separation (WP3, WP5)

b) New application for aeronautical research
- Advanced diagnostics for the aerodynamics and aeroacoustics of high lift wing configurations (DNW-NWB is involved as subcontractor on these experiments, Model of “Community friendly aircraft” will be provided by research community around TU Braunschweig funded by German government) (WP5)
- High-resolution analysis of swept airfoil flow undergoing laminar separation and transition (WP5)
- High-resolution and 3D analysis of transonic turbine cascade (WP5)
- 3D analysis of an Ultra-Low NOx emissions combustor (AVIO collaborates providing the combustor prototype) (WP4)
- On-line high-speed diagnostics of helicopter rotor blade deformation and blade tip vortices velocity-density measurements (WP5)

c) Improvement of aircraft design tools and methodology
- Support to CFD validation by means of a specific benchmark on airfoil transition to turbulence
- Tools for visualization and exploration of experimental databases (WP4)
- Advances experimental methodologies for aeroacoustic analysis and aero-elastic verification (WP5)

1.3. Description of the main S&T results/foregrounds

1.3.1 WP2: 3D Tomographic PIV

Tasks 2.1 to 2.3

The current state-of-the-art algorithm (MART) has been investigated for possible optimization (e.g. sparse analysis, pixel/voxel ratio, relaxation coefficients, and weighting functions) of the accuracy and efficiency of the reconstruction. The influence of parameters like the background noise, the number of particles and of the cameras (***Figure 1***), their locations and the depth of field has been investigated.

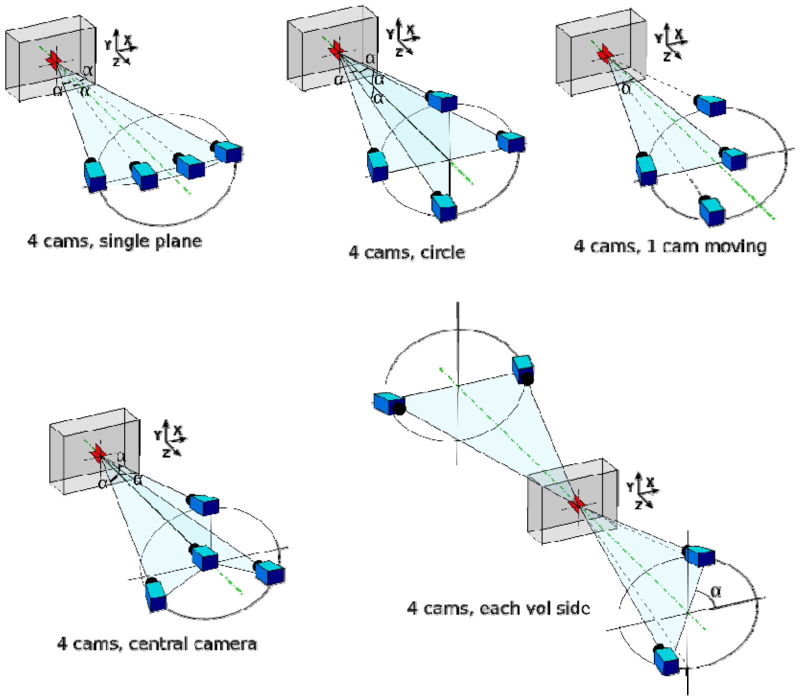

4 cams, single plane
4 cams, circle
4 cams, 1 cam moving
4 cams, central camera
4 cams, each vol side

Figure 1 *Example of tested configurations for tomographic imaging*

Some image filtering during the reconstruction procedure has been tested and demonstrated that these kind of filter can improve this step. Additional algorithms have been developed to implement the Optical Transfer Function correction within the reconstruction to account for optical distortion effects and particle blurring due to defocusing (***Figure 2***).

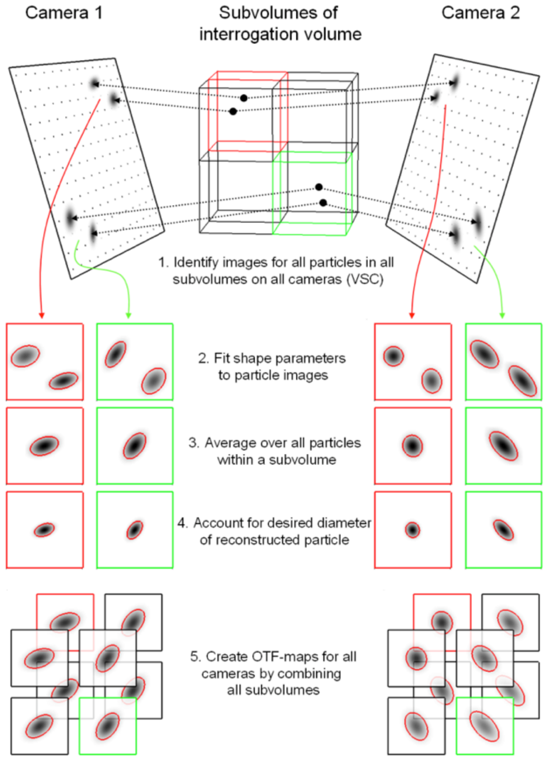


Figure 2 *Scheme of the OTF-calibration.*

Promising approaches which are reconstruction strategies that additionally make use of the time information already available from two successively recorded particle image distributions (Motion Tracking Enhancement, Novara et al., 2010) have been implemented. Various algorithms as BIMART (Block Iterative MART), MENT (Maximum Entropy), SPG (Spectral Projected Gradient) method have been also developed and tested by simulations and real measurement data. The quality factor of the reconstruction can be also improved with the number of successive recordings (***Figure 3***).

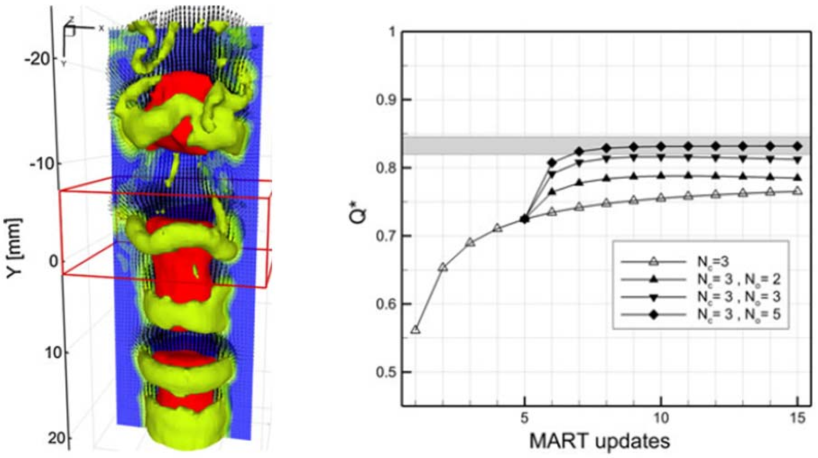


Figure 3 *Left: transitional jet flow field (iso-surfaces of axial velocity in red and vorticity magnitude in green). Right: relative reconstruction quality factor between the reference reconstructed field (MART with 4 cameras) and the 3 camera case with and without MTE (2, 3 and 5 exposures).*

A major effort was required to increase processing speed and reduce CPU memory utilization (***Figure 4***). The trade-off between the accuracy and the processing speed was explored, in order to make a substantial step towards the applicability in an industrial environment.

In relation to the above point, new data structures for 3D object storage and management have been investigated in order to lower the hardware requirements on working memory and storage capacity.

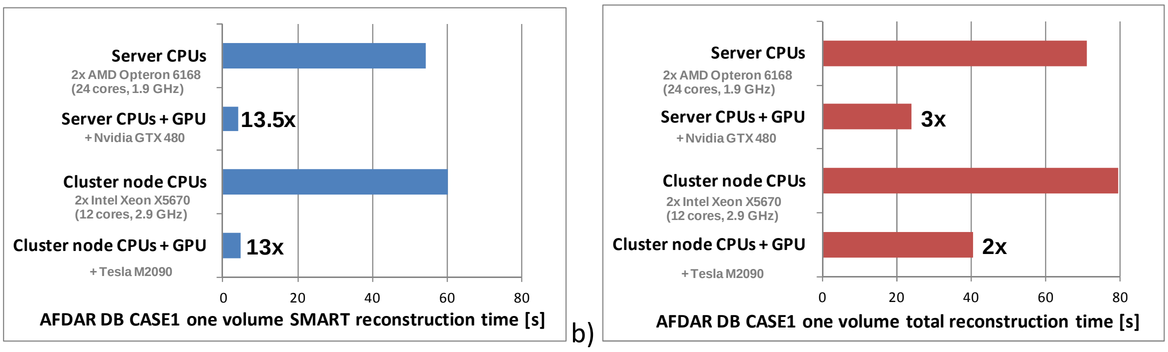


Figure 4 *A performance comparison between parallel CPU and GPU accelerated implementations of the MLOS-SMART tomographic reconstruction for a) SMART reconstruction time and b) total processing time including MLOS running time and time needed to save 3D object to a hard drive.*

Task 2.4

The interrogation of the volumetric distributions of light intensity obtained in output from the tomographic reconstruction was a crucial aspect, both for the computational cost and the accuracy. The 3D interrogation algorithms had to be optimized to handle large amount of data and, simultaneously, to exploit the more complete information on the flow structure to increase the accuracy.

The computational cost reduction strategies have been discussed. Three complementary approaches were presented. The first approach was based on optimization of the 3D cross-correlation interrogation using a software-binning based algorithm in the predictor estimation (UNINA, DLR(C) and LAVIS), optimization of the data treatment to reduce redundant calculation in case of overlapping windows (UNINA), and sparse-aided algorithms (UNINA, UNIMO). The second approach (***Figure 5***) consisted in the data reduction from 3D to 2D summing neighbouring planes of the reconstructed volumes (DLR(C) and IOT). The third strategy was based on advanced parallelization on GPUs (IOT, LAVIS), or using OpenMP-based software (IOT, DLR(C), UNINA, PPRIME). The Integration of the interrogation algorithms in the “DaVis” commercial software was performed by LAVIS (
Figure 6).

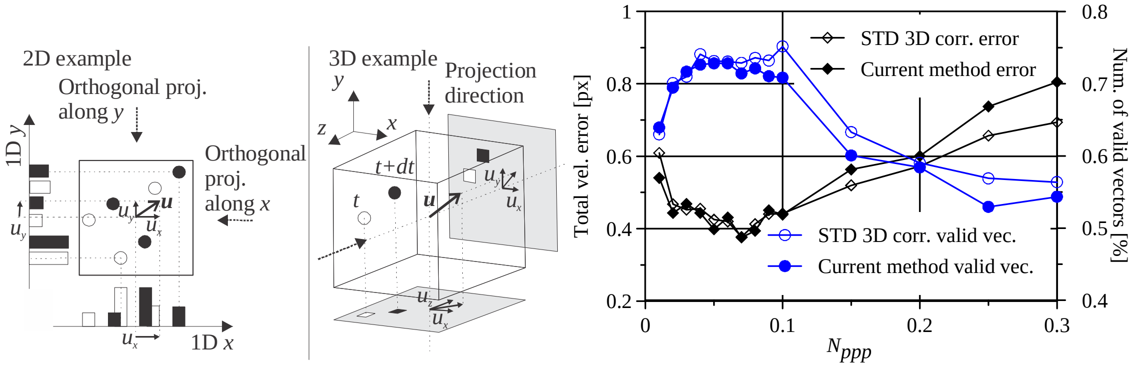
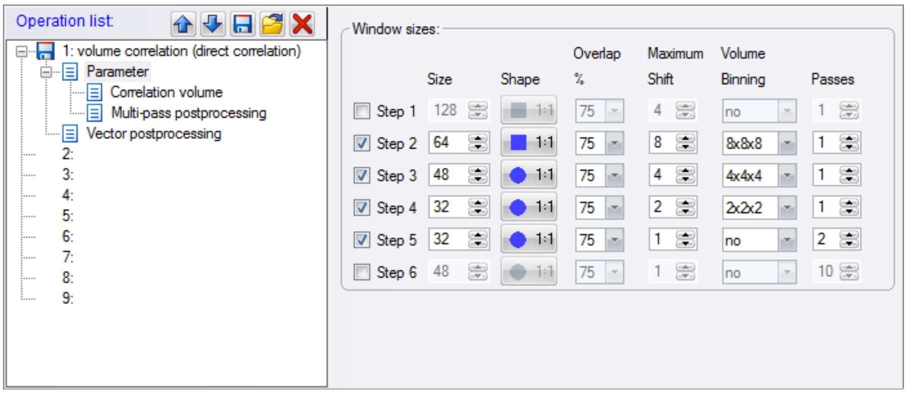


Figure 5 *An orthogonal projection scheme for an interrogation subdomain with particle images used by the proposed algorithm (2D example is given only for illustration) (left); the total velocity error and the relative number of valid velocity vectors obtained by the standard and the proposed algorithm as a function of particle concentration during the synthetic test (right).*



	Size	Shape	Overlap %	Maximum Shift	Volume Binning	Passes
☐ Step 1	128	■ 1:1	75	4	no	1
☑ Step 2	64	■ 1:1	75	8	8x8x8	1
☑ Step 3	48	● 1:1	75	4	4x4x4	1
☑ Step 4	32	● 1:1	75	2	2x2x2	1
☑ Step 5	32	● 1:1	75	1	no	2
☐ Step 6	48	● 1:1	75	1	no	10

Figure 6 *Software dialog for direct 3D correlation with down-sampling (binning) and optional round interrogation windows*

The strategies to increase the accuracy and reliability of the interrogation algorithms were also discussed. A theoretical study of the modulation transfer function of the cross-correlation algorithm and of the negative effects due to poor discretization of weighting windows in the cross-correlation step (UNINA) was reported. The possibility to calculate the full velocity gradient opened the field to new adaptive PIV strategies based on properly shaped weighting windows (TUD).

A great margin of improvement of 3D PIV was provided by time-resolved imaging. In particular, a solution to increase the measurement accuracy using properly composed correlation maps from multiple exposures was presented (TUD). Furthermore, the tracking of the particles over time can be used to measure the Lagrangian acceleration (TUD, ***Figure 7***).

Finally, an alternative approach based on optical flow methods (PPRIME) was also provided.

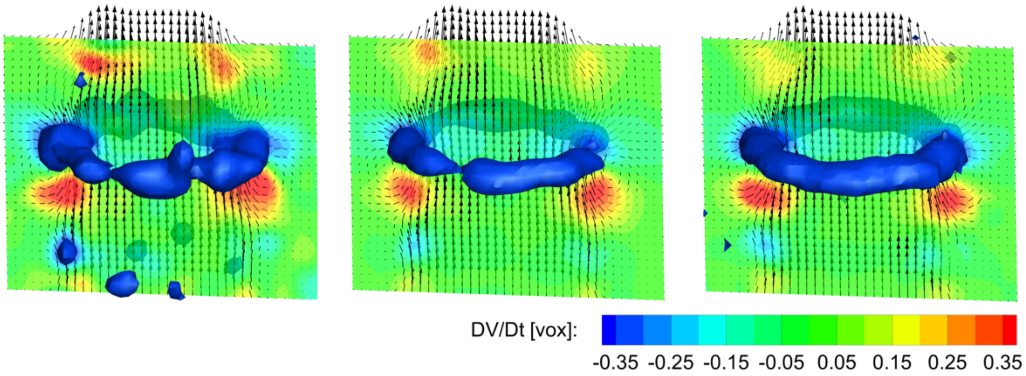


Figure 7 *Detail of a vortex ring in the jet flow at around 2 diameters downstream the nozzle exit. Iso-surface of axial component of Lagrangian acceleration (DV/Dt=-0.3 vox); velocity vectors and contours of DV/Dt on axial data slice. Left: Tomo-PIV based method with n=3. Middle: Tomo-PIV based method with n=11. Right: Tomo-3D-PTV with n=11 and p=3.*

Task 2.5

The tomographic database consists of 7 cases provided by several AFDAR contributors. It is built for the evaluation of each step of the tomographic PIV process: The calibration, the 3D reconstruction and the correlation algorithms. The "cases providers" were LML, TUDelft, UNIMO, PPRIME and DLR Köln from experiments. CORIA was "case-provider" for a computer-generated experiment.

Each team participating in a given case becomes "data contributor". The data is gathered by the case-providers through the web-interface managed by LML. The case-provider is also responsible for the analysis and comparison of data contributed to the case.

Three database cases have been evaluated by at least 3 or 4 teams and the results have been compared by the providers (LML, TU Delft and CORIA) during the workshop in Delft (June 2013) and at the final meeting of the project in Lille (February 2014).

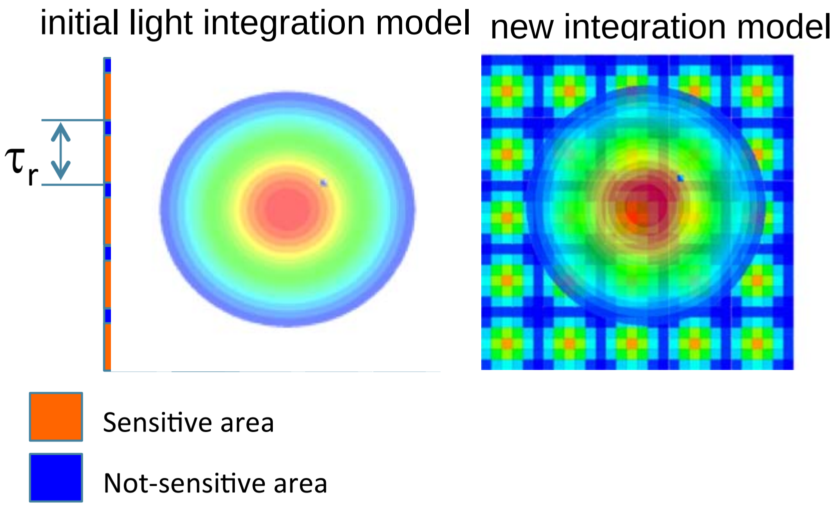
The 4th International PIV Challenge (www.pivchallenge.org) is organized by partners of AFDAR and others this year to promote the consortium and to open the comparison of the tomoPIV to others labs. This event takes place in Lisbon in July 2014 before the Lisbon laser Symposium (http://ltces.dem.ist.utl.pt/lxlaser/).

1.3.2 WP3: High-speed PIV and long-range micro-PIV

Task 3.1. Time-resolved PIV

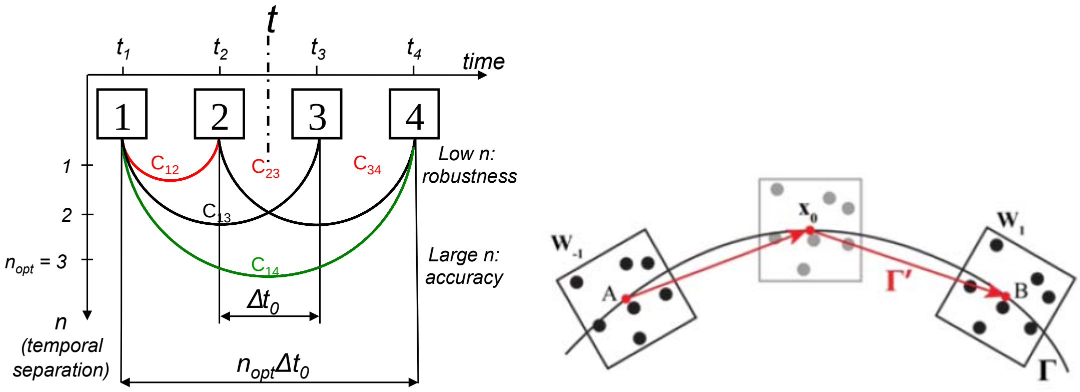
A market survey of high-repetition-rate hardware was conducted. The survey indicated the currently available components in terms of CMOS cameras and lasers and identifying most promising hardware components from the viewpoint of PIV applications.

Coria modified the SIG (Synthetic Image Generator) sources in order to allow for the implementation of image deformations, non-uniform MTFs of pixels and particle defocusing. The physical models deformation, long range microscope, CMOS response were developed in collaboration with other partners and implemented in the SIG. LML produced experimental results included in the SIG generator which was used to provide synthetic images for the qualification of the algorithms in the following tasks.



New model implemented in SIG to simulate pixels non uniform sensitivity (CORIA)

Several advanced particle tracking algorithms and correlation algorithms based on successive frames were developed. They were validated on experimental images as described in D 3.2. Among them a multi-frame pyramid cross-correlation algorithm was developed and tested that increases the robustness and accuracy of cross-correlation based PIV image analysis. Another approach is the Fluid Trajectory Correlation (FTC). The fundamental aspect of the approach, the use of a discretized model for estimating the trajectory of a fluid parcel across the sequence, allows the nonlinear motion to be tracked. The triple correlation algorithm is an extended version of the conventional pair-wise cross-correlation scheme used in PIV processing. It employs all of the state-of-the-art elements such as coarse-to-fine resolution pyramids and iterative image deformation. Concurrently, various attempts have been made to use optical flow (OF) methods. Widely used in other scientific domains, OF methods generally suffer in the scope of fluids dynamic of important drawbacks. Among them, we notice the large displacement problem and globally, an extreme sensitivity to various noise factors. To mainly avoid these drawbacks, we propose the Discrete Complete Bases Transform Optical Flow (DCBT-OF) method, an optical flow method using a multi-scale and multi-resolution transformation of the original data was developed and applied to the data. Since it was shown that PTV has some benefits in terms of spatial resolution, also a four frame particle tracking method showed superior performance over standard two frame image evaluation methods.



Left: Schematic representation of multi-frame pyramid cross-correlation algorithm (TUD).
Right: Discretized trajectory mode (TUD).

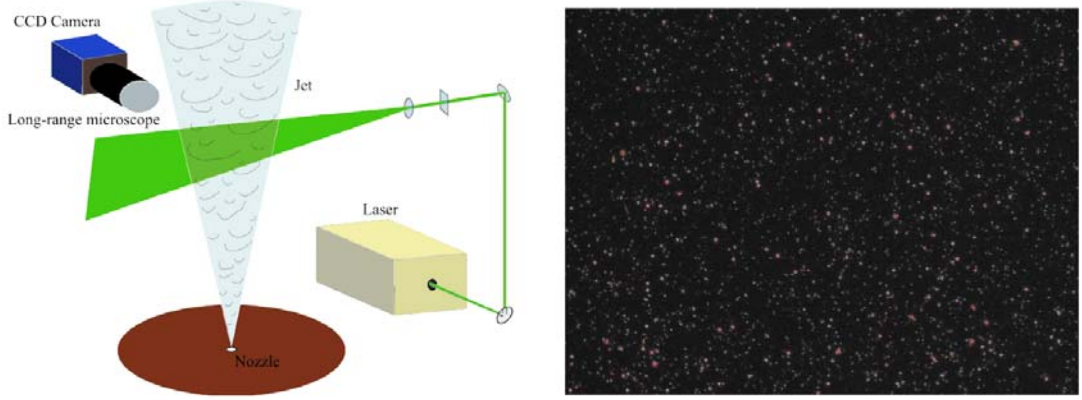
Task 3.1 was concluded with a workshop organized by UNIBW at the 8th of July 2012 in Lisbon with 18 participants of the consortium presenting and discussing the latest achievements of time-resolved PIV.

Task 3.2 High-resolution long-range PIV

The hardware was qualified for the experiments proposed in WP5. Data processing methods were developed and validated using synthetic data and experimentally obtained images. Theoretical/numerical analysis on limitations of the measurement spatial resolution were conducted.

An extensive study was performed on the achievable magnification and the corresponding image quality comparing a long-range microscope (Infinity K2) with a combination of Zeiss Makro 100 mm and 50 mm objective lenses and teleconverters. In conclusion the long-range microscope shows lower image aberrations but due to the lower numerical aperture less light is reaching the sensor. In the case of low Signal to noise ratios, the lens/teleconverter combination is therefore preferable. Furthermore two studies of the resolution limit of correlation based methods showed that the resolution is limited by the size of the particle image and particle tracking is preferable in order to achieve the maximum resolution. In addition a comparison of the image quality of the K2 Infinity microscope by UNIBW and the Questar microscope by TUD were performed. The Questar microscope show brighter particle images at lower working distances and was therefore chosen to be used in the free turbulent jet experiment at TUD.

With the single pixel ensemble correlation method reliable measurements of the averaged flow velocities can be performed. A systematic improvement and analysis showed that for particle images smaller than 3 px 500 images are sufficient to reach an error level below 0.1 px for the velocity estimate. Analysing the correlation peak itself enables the additional measurement of the averaged Reynolds stresses. An efficient algorithm was implemented and examined based on synthetic as well as experimental data. To reach an error level below 0.1 for <u'v'> at least 1000 images are necessary. However, with the developed algorithms a method for the reliable estimation of the averaged velocities and Reynolds stresses is available. A third order correction of the velocity estimation was recently implemented. However, since PTV does not show errors due to spatial averaging the developed PTV approach was also applied to the data of the free jet experiment. The results of this experiment and especially the performance of the algorithms are presented in D3.3.

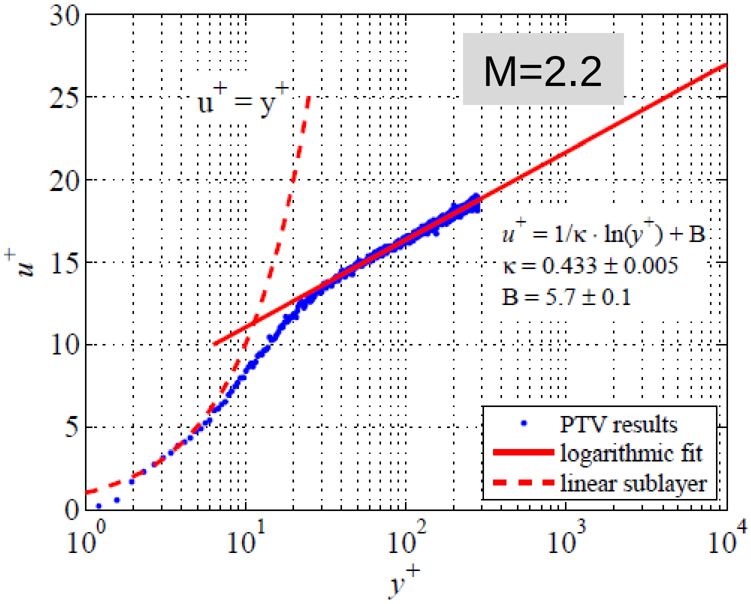


Left: Schematic representation the free jet experiment (TUD).
Right: Mico PIV image (TUD).

The single-pixel ensemble correlation was verified and validated using synthetic and experimental data. The synthetic images were used to investigate the performance and limitation in terms of accuracy and resolution in large gradient flows and close to walls. These investigations showed that the tracking of individual particles shows better results for low seeding concentrations with non-overlapping particle images. Model vibrations were investigated at the cascade wind tunnel at DLR Cologne using realistic Mach numbers. This wind tunnel will also be used for the experiments outlined in WP5.3. The analysis is outlined in report D5.3 and showed, that the highest dominant frequency occurred at ~1500 Hz. The maximum amplitude in the middle of the leading edge is about 2 pixels (150 µm), whereas the median is 0.6 pixels (45 µm). It can be concluded, that the setup is in principle suited for the high-magnification PIV measurements with a long-range microscope. Nevertheless, the images have to be pre-processed to correct for the shift of the position of the leading edge.

In order to derive design rules the experiment of WP5.2 will be investigated at UNIBW with the long-range µPIV method and time-resolved PIV. Together with DLR-G and TUD the experiment was defined to be the ERCOFTAC test case no. 81, the flow over periodic hills. This flow is of recent interest for the development of numerical methods and shows flow features such as separation, reattachment and vortex formation which are typical for aeronautical flows. The experiment was performed in May 2012. Some of the time-resolved images were taken to form a test case for the 4th international PIV Challenge. The large amount of results was already extensively discussed in international conferences (PIV 13 and TSFP8) and D5.2 and will further be examined and published in a Journal.

The imaging hardware for high-magnifications measurements in high speed flows was also tested and qualified. The resolution limit for the data evaluation methods was derived based on synthetic images and experimental data. The single-pixel ensemble correlation method was improved to estimate reliably the averaged Reynolds stresses. Model vibrations were investigated in the DLR cascade wind tunnel in Cologne. An experimental test case for the high-frequency and large-magnification measurements was defined with the project partners.



PTV analysis for high-resolution measurements in boundary layers with long-range micro-PIV (UNIBW)

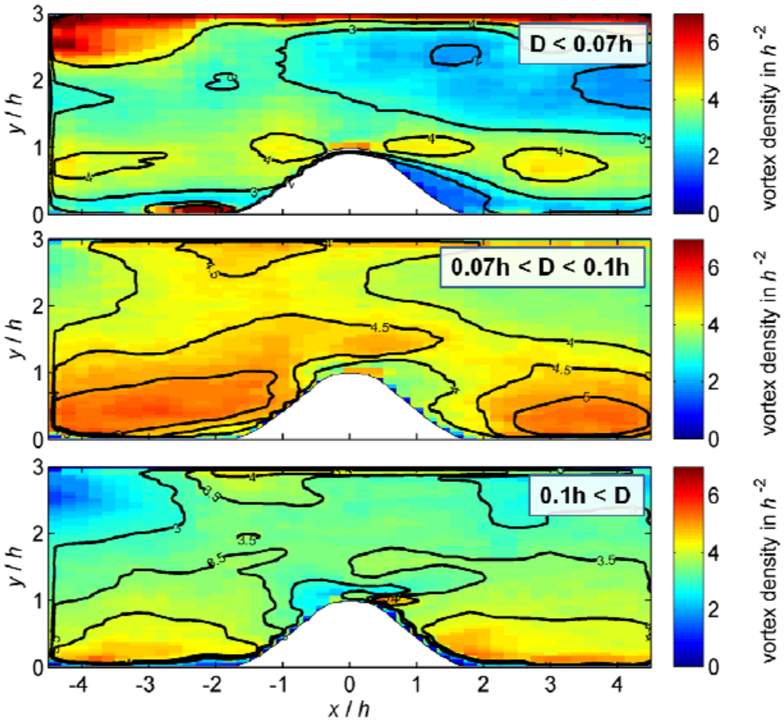
Task 3.3 Data post processing and visualisation

The qualification of estimators, as their objective definition generally allows a definite analysis to be conducted, was illustrated through an application to TR-PIV measurements of the detached flow over a NACA 0015 hydrofoil at a Reynolds number $Re=10^5$ in a water tunnel. Associated to elements of uncertainty analysis and to known statistics about the measured data, the knowledge of the properties of these estimators will allow deriving the full statistical relevance of TR-PIV based estimates. In order to assess how TR-PIV experiments may best combine accuracy, statistical relevance and high temporal resolution, independent series of multi-block TR-PIV experiments have been conducted and completed by separate LDV measurements. The behaviour of multi-block estimators were benchmarked against conventional estimates from random distributions of points using a bootstrap method applied to the LDV data. The LDV measurements have been taken for reference to extract the expected values and variances of single and multi-block estimators, demonstrating their sensitivity to the distribution of data samples. A full range of time-series analysis tools is now available, from which the quality of parametric and non-parametric analysis methods can be qualified.

The experimental configuration for this work package consists of a the flow around a NACA0012 hydrofoil. TR-PIV measurements have been performed together with hot film measurements at 7 chords downstream. An ensemble Kalman filter (EnKF) is used to obtain a dynamic estimation of the temporal prediction coefficients of the Galerkin proper orthogonal decomposition (POD) reduced order models over the entire time domain using measurements of a voltage signal obtained by the hot film sensor. In conclusion, Kalman Filtering can be used as an efficient strategy for stabilizing the evolution of experimentally identified low order dynamical systems which naturally tend to vanish or diverge. Compared to regularization procedures which need complex implementations and tuning, the Kalman filters are parameter-independent and, despite their complex underlying theoretical basis, easy to operate. The injection of external data conditioned using partial least square regression provides reliable observation terms which can be efficiently processed by the Kalman filters. It can be concluded that Kalman filters can be applied to stabilize POD-Galerkin lower order models using observable data of different nature and quality.

An extensive study to determine the instantaneous planar pressure fields from PIV velocity data in turbulent flows was performed. The principles of the pressure determination using an Eulerian or a Lagrangian approach were investigated and the performance of the proposed algorithms was tested using a synthetic flow field and by experiments conducted simultaneously with surface pressure transducers. The results show that pressure fluctuations can be captured with an accuracy up to 10% in the low-frequency range. The maximum frequency where pressure fluctuations are captured is approximately 1/3 of the recording frequency.

The identification of vortical structures can provide significant information on the overall evolution of the flow since these structures are related to mixing and momentum transfer. For the highly turbulent flow over periodic hills (D5.2) the identification was based on 22,000 planar velocity representations to reach statistical relevance. To distinguish between vorticity generated by shear and vorticity belonging to a vortical structure the D_2-criteria has been proven to be a suitable filter. In total about 5,000,000 vortices were detected with an average core size (larger axis) of about 0.09h, h being the hill height. As can be seen by the distribution, smaller vortices are more likely to appear. However, also large structures up to 0.4h were identified. The spatial distribution of the vortical structures is shown in Figure 2. At the top the smallest structures with a mean diameter of $D<0.07h$ are presented. As can be seen from the colours, these sizes are most likely to appear at the upper wall of the channel but also upstream of the hill top at the lower wall in a region where the flow is highly accelerated ($-3 < x/h -2$).



Spatial distribution of vortical structures of a mean diameter of D<0.07h (top), 0.07h<D<0.1h (middle), D>0.1h (bottom) for Re = 8,000 (UNIBW.)

1.3.3 WP4: Combined Diagnostics for combustion, aeroacoustics and aero-elasticity

Task 4.1 Flow, species and temperature mapping by PIV, PLIF and LII for combustion diagnostics

The main goal of that task for CORIA, was to demonstrate the combination of double-pulse OH fluorescence imaging and PIV to investigate turbulent flame, and especially flame stabilisation processes. The first stage of this task was devoted to the achievement of an original burner and all the all the devices for its operation. The CORIA has taken in charge the design and manufacture of the burner. It fulfils several criteria: obtain a jet flame in a protected environment, well-defined and adjustable boundary conditions, adapted to the combination of optical diagnostics used in sub-task 4.1.1 and 4.1.2.

In the second phase of the project, the CORIA has setup the optical arrangement for combining double OH fluorescence imaging with PIV. SPIV devices and two OH-PLIF devices have been combined to perform simultaneous measurements of 2D-3C velocity field and double-pulse OH PLIF. The double-pulse OH PLIF allows the determination of the OH field displacement in the laser plane, and the association with SPIV provides simultaneously the 3C velocity field in the same plane. The set-up presented in *Figure 8* shows a photography giving of an overview of all the assembly around the burner. Before the test campaign, different aspects to validate the use of the double PLIF-OH system with PIV have been evaluated and carefully checked:

- Time synchronisation of all the devices (cameras, Laser)
- Optical combination of laser and overlap of the four laser pulses in the same plane

- Calibration and accuracy of mapping functions between the four cameras
- Absence of disturbance between diagnostics

Next to these verifications, the test campaign has been realised. In accordance with the PC2A team working on the sub-task 4.1.2.

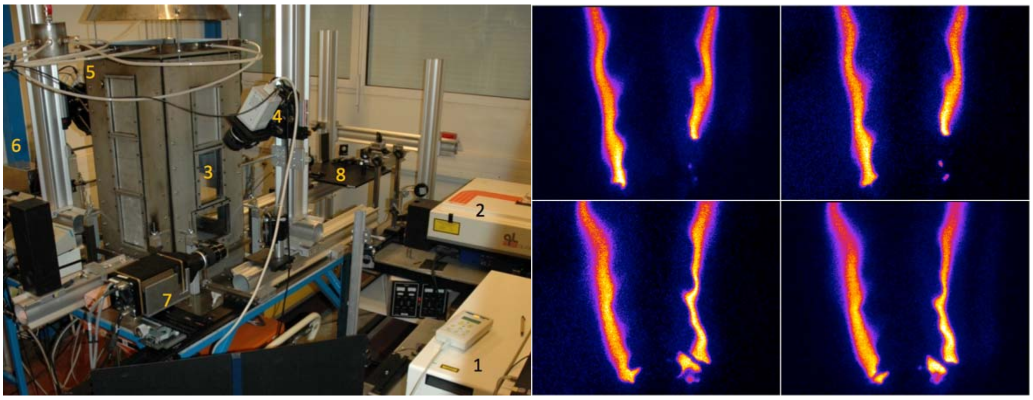


Figure 8 *OH PLIF lasers (1, 2), PIV laser (3), PIV cameras (4,5), PLIF ICCD cameras (6, 7), combination optics (8). Instantaneous OH visualization (right)*

Double image of OH radical of the flame in lifted condition for a time intervals of 200 µs are obtained. From these two examples, the flame displacement is clearly observable but also the variation of the flame shape and the appearance of small flame islands. These examples show all the interest of the combination of two UV lasers associated with two ICCD cameras, to cover a very large range of time interval between 0 and hundreds of microseconds. This adjustable time delay allows to investigate more or less all the dynamic of turbulent flame and in particular to adjust the time interval to reduce the influence of 3D flame motion in swirling condition when flames of interest for aeronautic are investigated. Using adjustable time delays between flame images combined with a statistical analysis of the flame structure modifications, these opened questions on appearance or not of local ignition sites, important to investigate the flame stabilization processes, could be addressed. This statistical analyse of flame deformation can be also conditioned with the SPIV measurements of the flow, in particular to the velocity component perpendicular to the investigation plane, indicating if a strong out-off plane flow velocity is or is not present. In *Figure 9* is presented three samples of OH image (the 1st image of the couples) overlapped to the instantaneous velocity fields in the case of a methane jet.

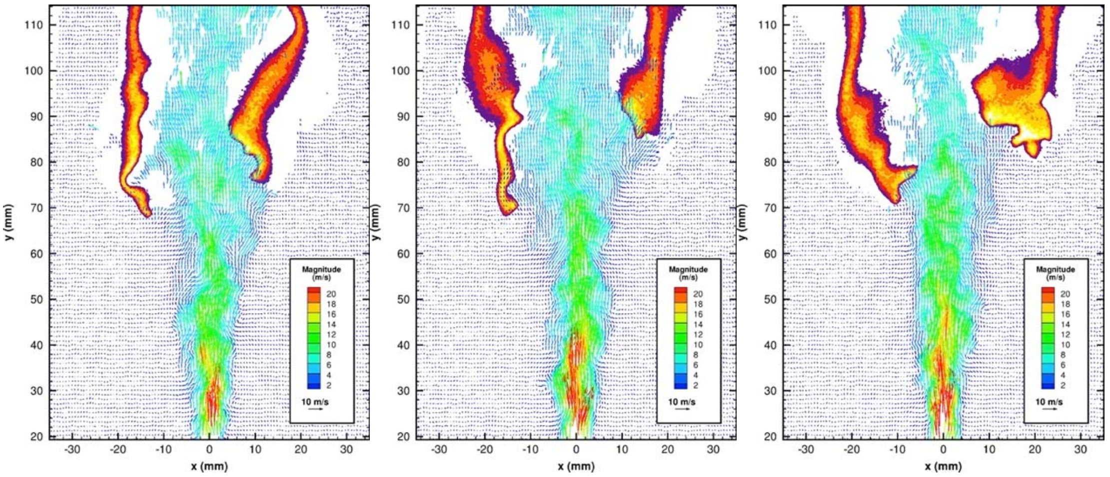


Figure 9 *Instantaneous velocity fields overlapped to the first PLIF image of OH radical*

A workshop on *Advances of Optical Diagnostics in Combustion* was held by DLR in Cologne on 15-16 October 2013. The workshop attracted 39 participants in total, mainly from Germany (29), five from France, two from Italy, one from the Netherlands and two participants from Russia. The scientific program consisted of eleven scientific presentations as well as three overview presentations, one on the AFDAR project and one introducing the hosting Institute of Propulsion Technology and one presenting the demands for optical measurement techniques in the context of combustor research and development.

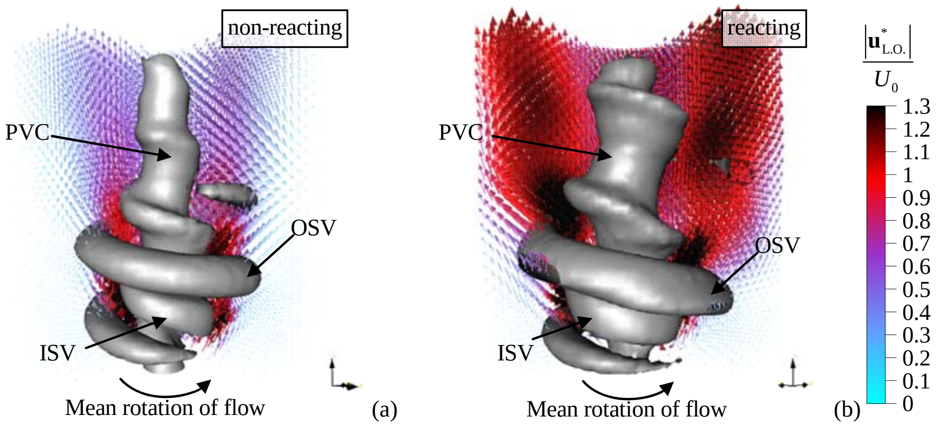


Figure 10 *Visualization of coherent structures (precessing vortex core, PVC, and inner and outer secondary vortices, ISV and OSV), extracted from POD modes for a strongly swirling (a) non-reacting jet and (b) lifted propane-air flame.*

A lean methane-air flame in a model swirl-stabilized combustor was studied by stereoscopic PIV and CH* chemiluminescence. The velocity data was processed by POD and DMD routines to extract large-scale coherent vortices in the flow. Flows low and high swirl rates were investigated. In the former case, no permanent central recirculation zone was present in the non-reacting flow. For the latter case, a pronounced breakdown of the swirling jet's vortex core took place. As a consequence, a bubble-type and cone-type central recirculation zone was present in the non-reacting and reacting flows, respectively.

Task 4.2. Combined PIV and acoustic measurements for noise source identification

Three databases are made available to the partners in task 4.2. (1) Tomographic PIV measurements (TUD); (2) Acoustic measurements (NLR); (3) Numerical calculations on an airfoil (VKI).

The research target for the collaborating partners on the experimental side within this task was to gain insight into the potential use of advanced PIV techniques for broadband noise source identification and the feasibility of PIV-based noise estimation. The experimental work focused on a flat plate of 0.6m chord with sharp trailing edge at zero incidence and forced transition on both sides, which provided the test case for broadband turbulent boundary layer-trailing edge (TBL-TE) interaction noise. This test case bears relevance for present day challenges in the wind turbine and aircraft industries.

Comprehensive acoustic phased-array measurements have been carried out at the NLR facilities and advanced beam-forming methods have been applied for noise source localization and selective source integration resulted in reliable measurements of sound power levels over large ranges of wind speeds and different boundary layer tripping devices (see *Figure 11*). Additionally, hot-wire measurements have been performed to allow for a comparison of the boundary conditions with the PIV measurements at TUD, resulting in an extensive database of TBL-TE noise data. Results of this campaign have been presented at the AFDAR “PIV in Aeroacoustics” workshop held in Delft (April 2012).

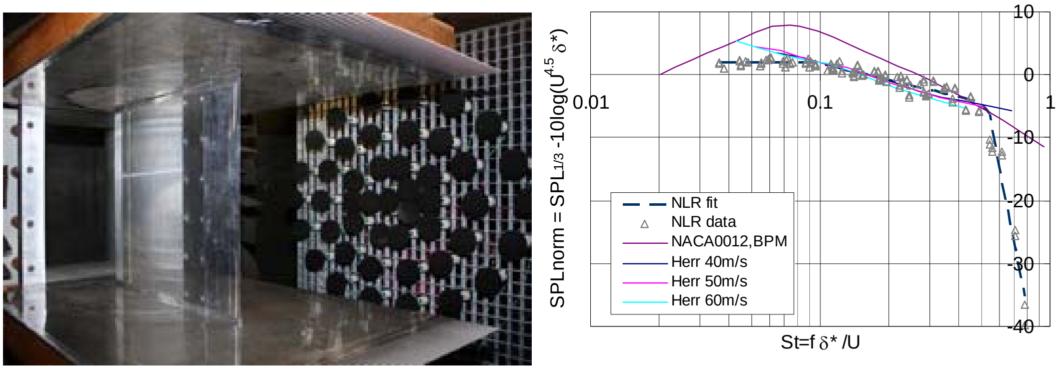


Figure 11 *Left: Flat plate configuration in NLR's anechoic tunnel; Right: Comparison of measured noise spectra with available results in literature.*

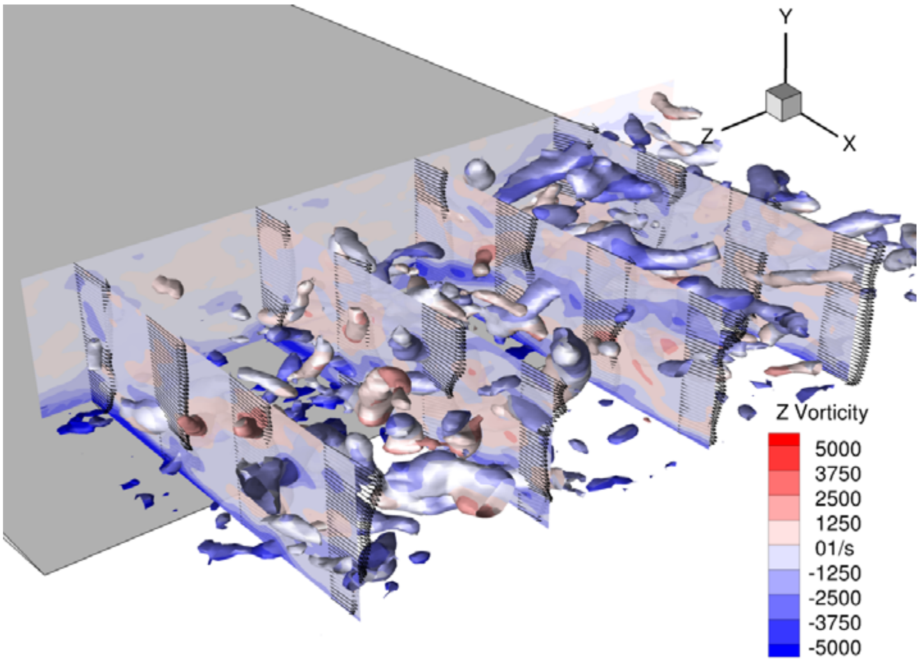


Figure 12 *Tomographic PIV measurement of turbulent boundary layer passing a trailing edge. Velocity vectors with iso-surfaces of Q, indicating vortical structures.*

Task 4.3. Time-resolved PIV and structure deformation measurements for aero-elastic investigations

A generic aeroelastic experiment has been carried out with a thin flat plate, oscillating in a flow in order to investigate the interaction of aerodynamic and structural (elastic and inertial) forces causes complex dynamic aero-elasticity problems. Part of this is the flutter phenomena, which is potentially destructive and needs to be avoided in most cases. Great effort is made experimentally and numerically in considering flutter characteristics to avoid structural failure. This includes the safety for aeronautical lightweight structures but also for buildings and bridges.

For the aeroelastic experiment, a FEM model of the thin plate has been first defined for a reasonable conception of the experiment in terms of the sizes of the involved elasticity, mass, related forces and frequencies (shear flow instability and oscillation mode). The experimental investigations of the flutter of a thin plate in a low-speed wind tunnel has been investigated by using two time-resolved optical measuring techniques.

- High speed IPCT is able to measure the position/ deformation (→ elastic forces FE) and the acceleration of the relevant surface (→ inertial forces FI) → the integral aerodynamic forces are known for each time step.
- The high speed PIV velocity vector information enables the calculation of the integral aerodynamic forces assuming 2D-flow from integrating momentum flux or solving Poisson equation for the pressure side

The acquired time-resolved data enables solving the collar-triangle of aerodynamic *A*, inertial *I* and elastic *E* forces (general aeroelastic stability problem: $A + I + E = 0$) and is also useful for computational code validation aiming in coupling CFD and CSM codes in subsonic flows.

The flow-structure-interaction experiment has been investigated in the 1m wind tunnel at DLR Göttingen using a thin rectangular plate forced to aero-elastic flutter near transitional shear flow at low speed. Two optical measuring systems have been installed to synchronously measure the flow field around (high-speed PIV) and the deformation of the plate (high-speed IPCT). Various flow velocities and thin plate models have been investigated during the campaign. The used light-sheet splitting set-up for achieving homogenous illumination of particles on both sides of the moving plate is shown.

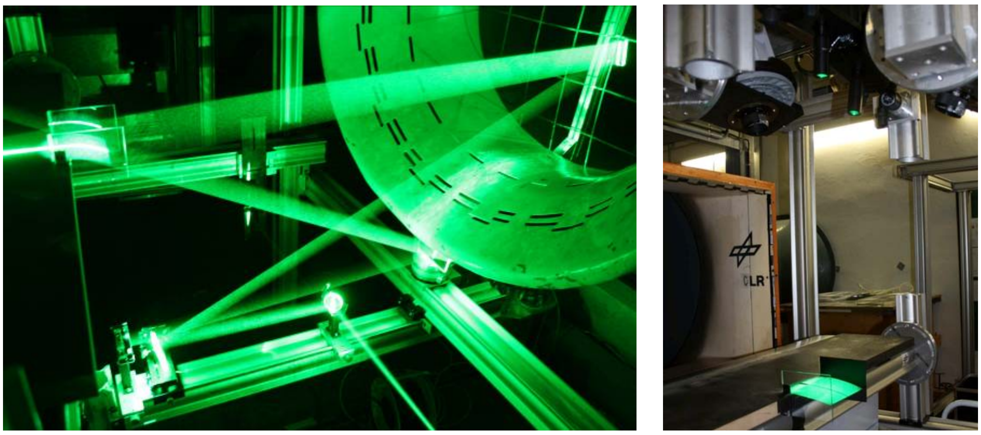


***Figure 13** High-speed PIV (5 kHz) laser light-sheet splitting and thin plate under aero-elastic forces (left) and LED pulse illumination system and stereo camera set-up for high-speed IPCT (2.5 kHz) (right) at 1m-WT of DLR in Göttingen (flow from left to right).*

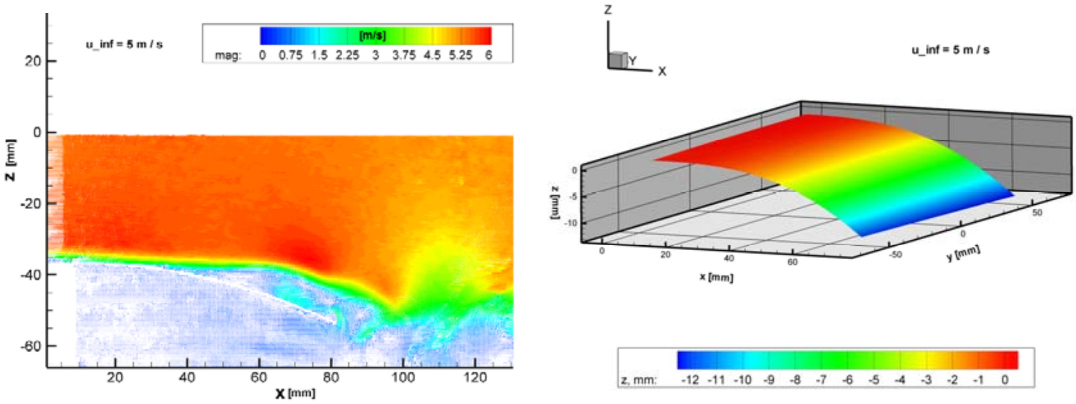


***Figure 14** Results of the HS-PIV (left) and HS-IPCT (right) measurements at the thin plate under aero-elastic forces at U = 5 m/s and at one time instant of the plate in flutter; (flow from left to right).*

1.3.4 WP5: Applications to Aeronautics – DLR

During the second period of work package 5 of AFDAR main developments achieved in the first period and recently in the second period within the work packages 2 and 3 on time-resolved and tomographic PIV have been proven to be mature for practical use within research and industrial wind tunnel facilities. In all tasks successful demonstration experiments have been carried out delivering high-quality data for scientific use.

Task 5.1. Time resolved 3D-PIV and acoustic-array technique for flap side edge noise investigation on a high-lift-configuration model in an industrial wind tunnel (NWB subcontractor)

In the frame work of the German research and development project “Buergernahes Flugzeug (BNF)” a new high-lift-configuration wing has been developed which is equipped with a low-noise large-diameter propeller and an active flap with large deflection angle (>59°) and Coanda- flow separation control at the flap along the whole span. This innovative concept model has been tested in the acoustic low speed wind tunnel of DNW-NWB in 2012 and 2013.

The DNW-NWB wind tunnel is a low speed wind tunnel facility with an anechoic plenum with 99% acoustic damping, and is certified for a frequency range from 250 Hz to 40 kHz [1]. Since its acoustic refurbishment only minimal amounts of seeding are allowed. This wind tunnel is an atmospheric wind tunnel with a closed return circuit. The wind tunnel is used in a ¾- open test section configuration (a wide floor has been installed for acoustic shielding) and has a cross sectional area of 3.25 m x 2.8 m with a contraction ratio 1:5.6.

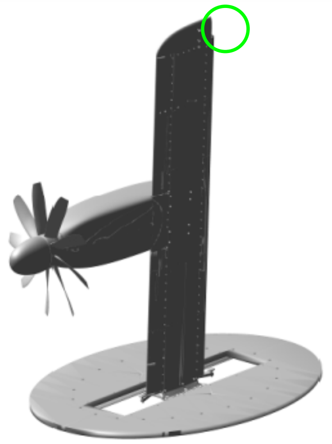


Figure 1 *CAD Drawing of the BNF model (flap edge area annotated with green circle)*

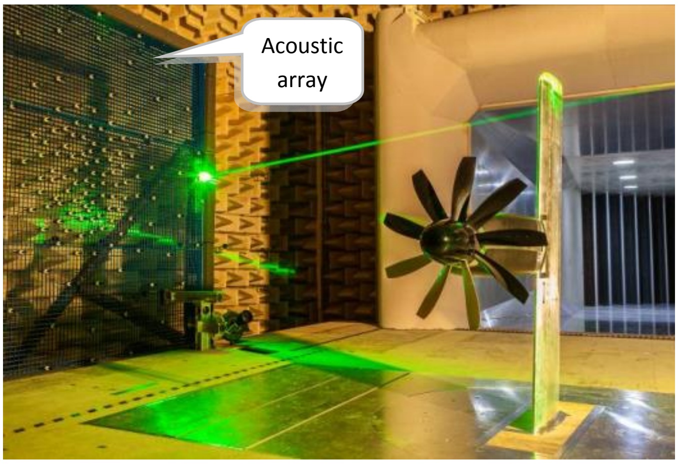


Figure 2 *Picture of the wind tunnel model with laser light volume and acoustic array in the background, the return mirror is mounted on the array.*

Figure 3 *Installation of the seeding rake at the final turning vanes just before the contraction section.*

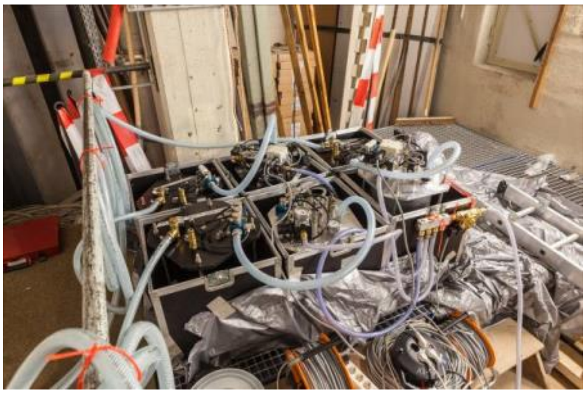


Figure 4 *Multiple connected seeding generators and impactors supplying the seeding rake with particles.*

Figure 5 *Laser light path from laser (left picture) along the flap (middle picture) towards the return mirror (right picture).*

The BNF wind tunnel model is a half model (wing span about 1.7 m) equipped with a propeller (diameter 0.66 m) driven by an electric motor and active flow control by means of Coanda blowing over the gapless flap. A CAD snapshot of the model is given in ***Figure 1***. The open test section of the DNW low speed wind tunnel facility NWB has a cross-sectional area of 3.25 x 2.8 m2. The installed model with the acoustic array (with 140 microphones) and the mounted return mirror can be seen in ***Figure 2*** and ***5***.

After proper image pre-processing the Tomo PIV evaluation using *DaVis8* was successful at least at the lower free stream velocity of U = 30 m/s. Due to large oscillations of the model occurring at U = 51 m/s for reasons of coupling eigenmodes a very laborious and time-consuming single image volume self-calibration process would have been necessary, which would at the same time have to account for the inter camera alignment as well as for the fixed model reference.

Together with the upwards-normal flow deflection on the pressure side downstream of the flap a flow exchange is organized which is caused by the pressure differences between the suction and pressure side of the wing. The overall spiralling movement of this flow exchange forms a complex vortex with a separated break-down area and strong shear-layers exhibiting large RMS resp. turbulent kinetic energy values. The main features of the vortex topology in the measured flow region are also visible in the average velocity and RMS vector volumes in ***Figure 6***. It is obvious from a fluid dynamic point of view that the strongest fluctuations appear at the shear-layer between the suction side and the separated flow region. On the other hand the region of the largest RMS values are close to, but not exactly matching the region of the largest causality-correlation values between the far-field noise and the fluctuating velocity vectors.

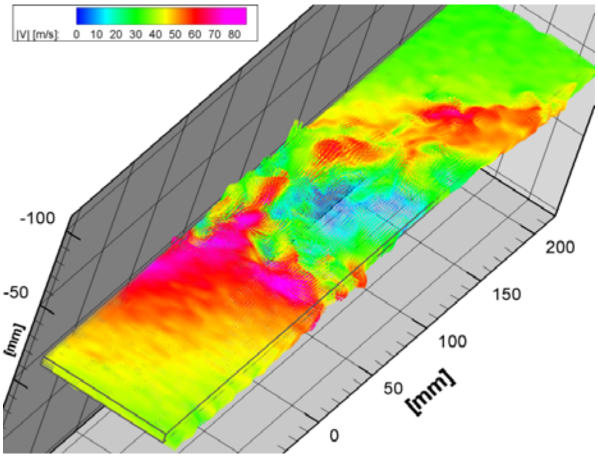


***Figure 6** Two viewing directions onto an instantaneous velocity vector volume of a high-speed tomographic PIV measurement at the BNF flap-side-edge region at U = 30 m/s.*

Task 5.2. Time-resolved 3D tomographic and high-resolution PIV for swept wing airfoil separation investigation

Initially the measurement of the flow around a swept wing airfoil was planned within the AFDAR project. During the project it was decided to select the flow over periodic hills as one of the main test cases as this flow is relevant for aerodynamic configurations but also for the validation of numerical flow simulation methods in aerodynamic research. The multitude of phenomena on different scales in both, space and time are best suited to explore the algorithms for data evaluation and analysis developed in the project. The flow over periodic hills is a common test case for the validation of numerical flow simulations (see ERCOFTAC test case Nr. 81). The numerical prediction is very difficult, since flow separation and reattachment are not fixed in space and time due to the smooth geometry (Temmerman et al., 2003; Fröhlich et al., 2005). Furthermore, the separated and fully three-dimensional flow from the previous hill impinges the next hill and results in very complex flow features.

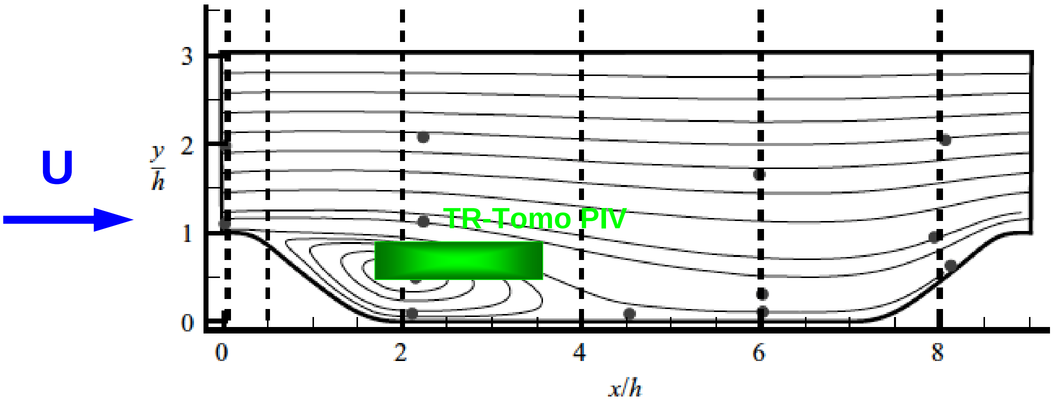


***Figure 7** Schematic of the channel with hill (height h = 50 mm) (valley) configuration (distance between hills Lx = 9h = 450 mm) submerged in the water tunnel facility with a channel height of Ly = 3.035h = 151.75 mm and a width of 900 mm (based on test case ERCOFTAC 81, for further information see Rapp and Manhart, 2011).*

Illumination was realized using a Quantronix Darwin Duo continuous laser, provided by UNIBWM. The laser beam was widened by two successive telescope optics using cylindrical lenses, resulting in an oval light profile. The profile was cut in rectangular shape by a passe-partout that was fixed at the side wall of the channel. This volume light sheet passes through the interrogation volume and is back-reflected into itself using an end-mirror located directly outside of the opposite wall of the tunnel (Schröder et. al, 2008). A second passe-partout is installed there. This setup enables all cameras to be in forward scattering and thus gather a maximum of light. In order to assure sufficient contrast for the imaged particles, a sheet of black adhesive foil was installed below the illuminated area. ***Figure 8*** (right) shows the volume light sheet, illuminating the measurement area.

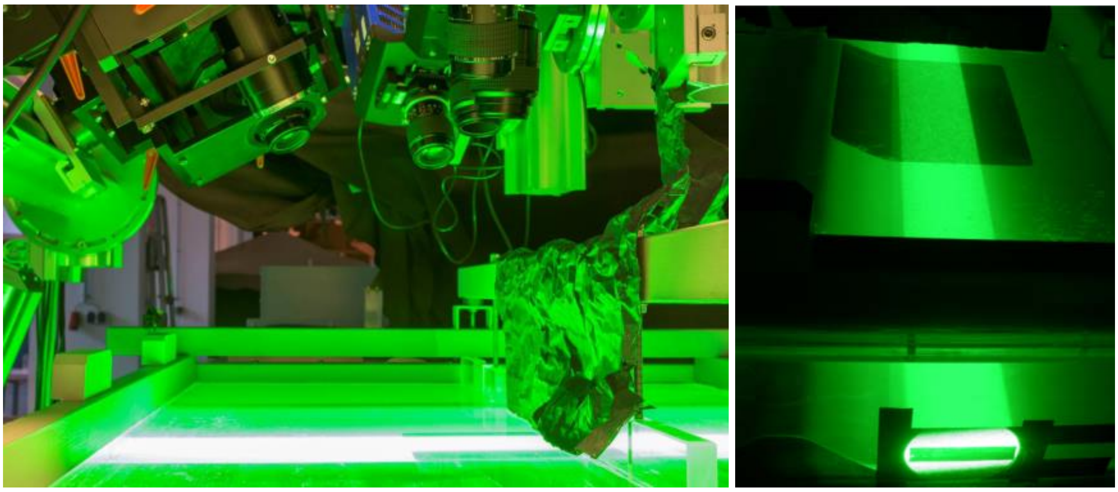


Figure 8 *(Left) Six Imager pro HS 4M / PCO Dimax cameras looking through 5 x f = 105 mm Nikon lenses and one f = 100 mm Zeiss Distagon Macro lens, all at* $f_{\#} = 22$ *(four cameras in Scheimpflug mounts), onto the light volume within the water flow. (Right) Collimated light volume with ~ 90 x 20 mm cross-section entering through a passe-partout from a side wall and being back-reflected in itself via a mirror from behind the opposite side wall.*

The large variance of the turbulent structures and events on different time scales can be clearly seen in the instantaneous flow fields for the lower Reynolds number. Especially the v-component shows regions of different sign and magnitude which gives an impression of the turbulent nature of the flow. It is obvious, that the shear layer is not stable at all. Due to the confinement of the channel and continuity, the flow speeds up over the hill.

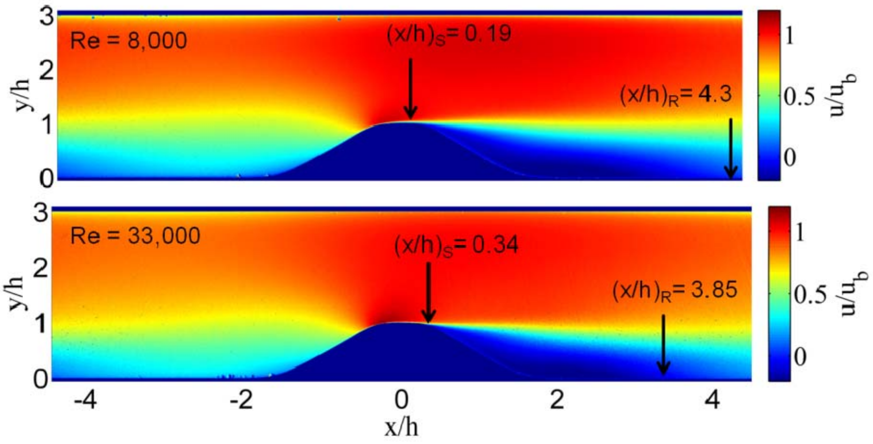


Figure 9 *Mean stream-wise velocity distributions Re = 8,000 (top) and Re = 33,000 (bottom).*

Time-series, visualizing the flow for both Reynolds numbers were created using the processing steps as described in paragraph 3.2. The close temporal sampling enables an accurate examination of the development of turbulent structures within the interrogation volume. On average, the particles move around 8.5 pixels between frames for Re = 33.000 and around 6 pixels for Re = 8.000. Occurring structures can be tracked for several hundred of images before leaving the measurement domain. ***Figure 10*** shows a single snapshot from such a time-series for Re = 33.000. Shown are isosurfaces of swirl strength (λ2), overlayed by vector planes, color coded with wall normal velocity (v). Vast regions of negative v (sweeps) as well as positive v, accompanied by regions of decelerated flow (ejections), can be seen. A multitude of different-sized flow-structures are visualized, documenting the highly turbulent state of the flow at this stage of the experiment.

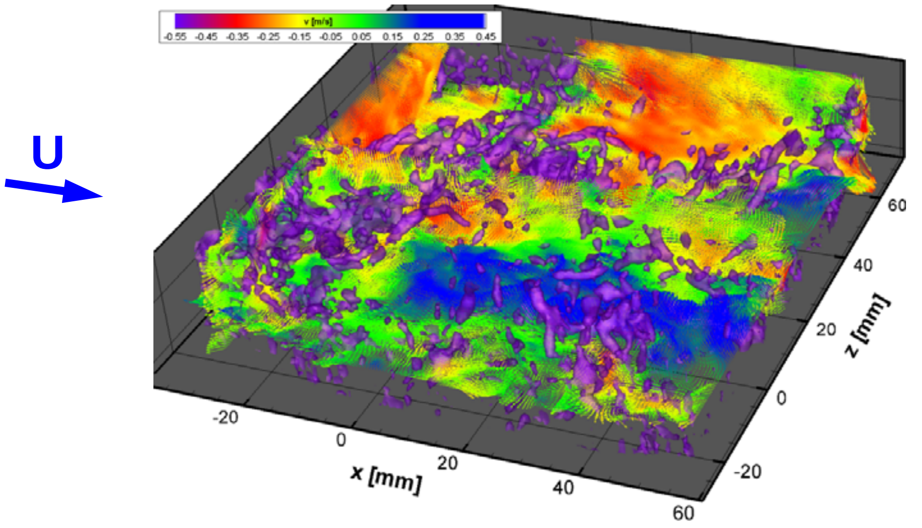


Figure 10 *Instantaneous snapshot the flow field at Re = 33.000. Isosurfaces of swirl strength (λ2), overlayed by vector planes color coded with wall normal velocity.*

T.5.3. Volumetric PIV and long-range microscopic PIV application in a transonic cascade

In the second part of the project Tomographic PIV (tomo-PIV), conventional stereo PIV (SPIV) and astigmatism particle tracking (APTV) are utilized in order to characterize the complex transonic flow within a highly loaded compressor cascade at M1 = 0.60 in T5.3 (see also D5.4). The application of volume resolving thick-sheet PIV (or tomo-PIV) near the trailing edge of the cascade's blades is intended to demonstrate the technique's potential of instantaneously resolving secondary flow structures within the separation region of the cascade and its ability to derive three dimensional statistical data of fluctuations of velocity in the turbulent flow region.

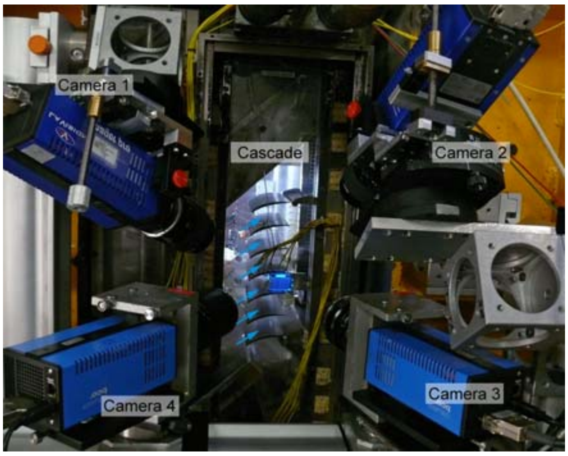


Figure 11 *Tomo PIV setup and back-illuminated calibration target on a micro traverse*

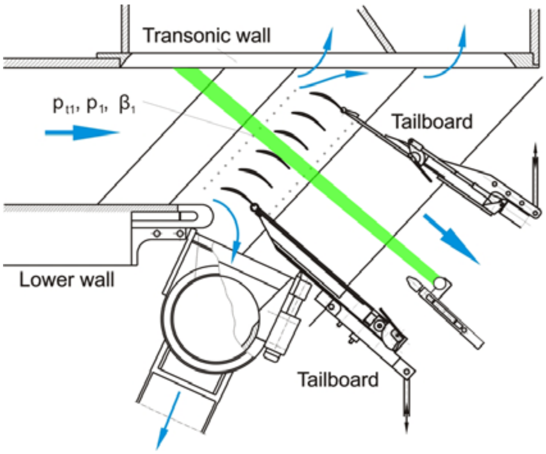


Figure 12 *The TGK test section and light-sheet orientation*

The investigation presented in D5.4 demonstrates the applicability of volumetric PIV and high resolution PIV in a highly loaded compressor cascade at M_1=0.60. The report describes various aspects of the adaption of the tomographic PIV setup to the restricted access on the cascade wind tunnel. Aside from details of implementation the report also contains investigations regarding the accuracy of in-situ camera calibrations and an analysis of global camera pixel shifts due to wind tunnel vibrations during operation.

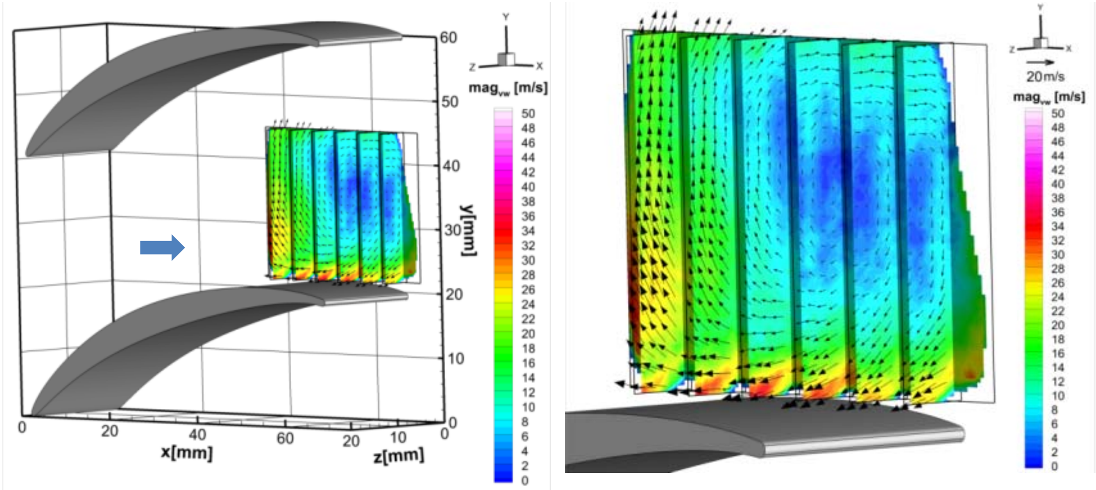


Figure 13 *Average of N=100 tomographic measurements for a volume of 36×24×4 mm³ at z=8 mm distance to the end wall, overview (left) and detailed flow field with boundaries of reconstructed domain (right). Only every third vector along each dimension is plotted*

Task 5.4. Volumetric PIV Aerodynamic Investigation of AVIO Innovative Injection System Prototype of an Ultra-Low Emissions Combustor

An investigation of the three-dimensional flow field of a turbulent swirling jet at $Re = 50 \cdot 10^3$ generated by a non-reactive model aero engine lean burn injector is carried out in a water facility with tomographic particle image velocimetry. This work is focused on the organization of the coherent structures arising within the near field of the swirling jet both in free and confined configurations. The confinement causes an increase of the swirl number: the measured values are equal to 0.90 and 1.27, respectively for free and confined swirling jets. The effects of the confinement induce a larger spreading of the swirling jet promoting the enhancement of turbulence at the nozzle exit, but the expected upstream displacement of the reverse flow region is not observed. The instantaneous flow field is characterized by the presence of the Precessing Vortex Core (PVC), of the outer helical vortex and of smaller turbulent structures perturbing the structure of the PVC.

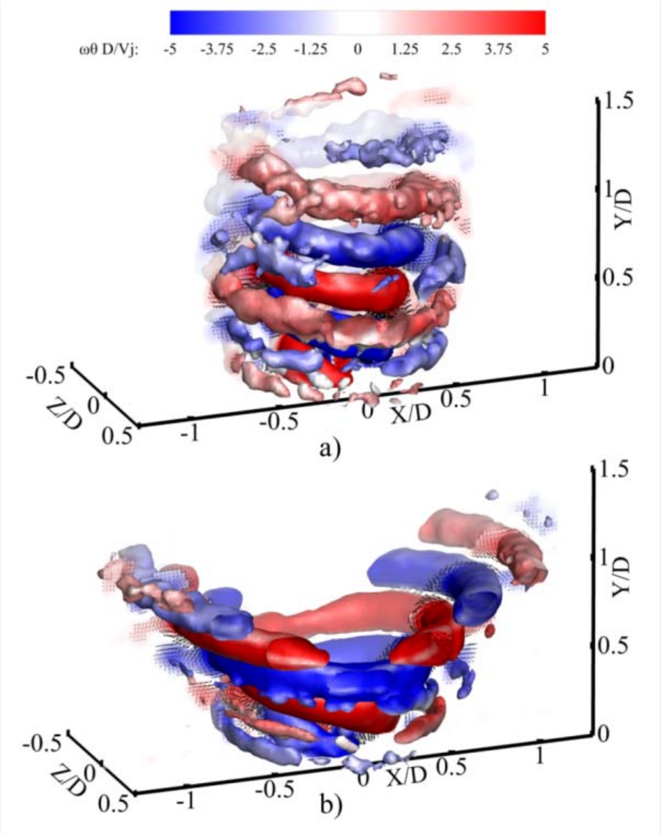


Figure 14 *First POD mode describing the coherent streamwise development of PVC helix for the free (a) and confined (b) swirling jet. Iso-surface of positive* $QD^2/V_j^2=0.7$ *color-coded with* $\omega_\theta D/V_j$ *. Contour of* $\omega_\theta D/V_j$ *with velocity vectors at plane* $Z/D = 0$ *blanked by imposing the* $-1.2 < \omega_\theta D/V_j < 1.2$ *constraint.*

Task 5.5. **High-speed PIV, tomo BOS technique and blade deformation measurements on a large scale helicopter rotor**

Recently, the initial roll up of blade vortices of a model-scale rotor was investigated by time-resolved and simultaneously recorded PIV, blade deformation and background oriented schlieren (BOS) measurements. The combination of these measurement techniques allows for a complete characterization of the blade tip vortices and their spatial and temporal development. This information is essential for understanding the evolution of the local blade loading. To characterize the blade tip vortices of the rotor and the influence of the active twist actuators thereon, two optical measurement techniques are applied simultaneously: the Particle Image Velocimetry (PIV) to determine the flow velocities around the blade tip vortices and the Background Oriented Schlieren (BOS) method to evaluate the density distribution within the vortex cores. Blade deformation measurements have been made shortly after the combined PIV-BOS test at partly the same settings of the rotor.

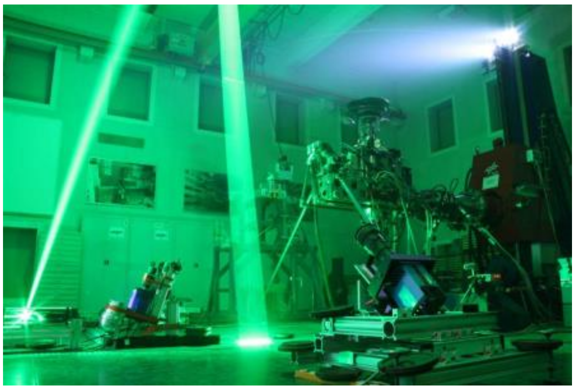


Figure 15 *Set up for PIV and BOS measurements*

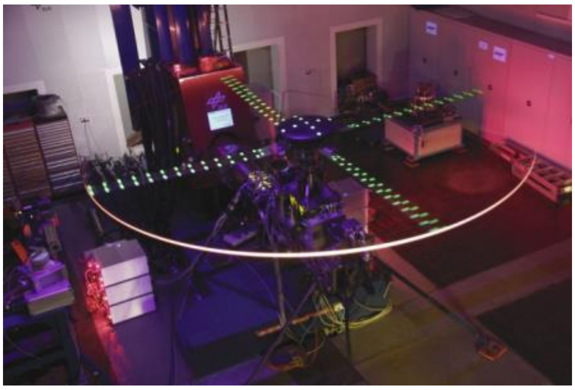


Figure 16 *Set up for SPR measurements*

1.4. Potential impact

The impact for AFDAR has been aimed at two activities of the work programme: 7.1.1 The greening of air transport; 7.1.4 Improving cost efficiency. In particular, the activities are pertinent to the sub areas “flight physics” (AAT.2010.1.1.1) and “propulsion” (AAT.2010.1.1.3). With the objective of reducing emissions addressed directly with the research on ultra-low NOx emission combustor and on the aeroacoustic analysis of wing profiles and flaps in high-lift configuration. Furthermore a potential impact is also achieved in the area of emission reduction considering the experimental means delivered that can study and optimize aerodynamic performances in off-design conditions and in high-lift configuration. Three main activities have focused on the development of advanced experimental analysis of engine subsystems: combustion diagnostics, three-dimensional aerodynamic analysis of combustor flows and a transonic turbine cascade.

The impact in flight physics is potentially achieved with the study of external aerodynamics of complex wing configurations (three-elements airfoil in high-lift). Such systems cannot yet be reliably predicted by CFD simulations especially in relation to the unsteady flow behaviour dominated by trailing vortices responsible of acoustic noise generation and unsteady aerodynamic loads. The experiments executed on this system can be used for reference when improving CFD software for the simulation of high lift systems.

Impact on “Improving Cost Efficiency” is achieved, considering the reduction of development costs achieved with the new experimental tools developed, in particular high-speed PIV supports the improvement of numerical tools for system design (AAT.2010.4.1.1. Design Systems and Tools).

More complete measurements of boundary layers, especially in adverse pressure gradient, wakes, tip and trailing vortices, improve the reliability of computer simulations by reducing the uncertainty for instance on turbulence closure models. The same considerations apply for the development of aero-engines where the experimental approaches demonstrated in AFDAR combine flow analysis and thermal and chemical species mapping, fundamental to the understanding and optimization of the combustion process.

The AFDAR project also aims at improving aircraft efficiency, by providing unprecedented details and insight in the 3D flow structure around wings and jet engine components. These results will evidently help designers to understand more deeply the flow around their prototypes and drive them to potential improvements. By a better quantitative assessment of flows such as vortices, wakes and boundary layers, both on the mean and instantaneous point of view, with a good spatial resolution and accuracy, the designer of wings, tails, bodies and engine nacelles of aircraft has now at hand an extensive experimental tool to push one step further the quality and safety of the aerodynamics of their products, for drag and noise reduction.

The activities performed in WP4 on the combination of advanced PIV techniques for the aeroacoustic analysis of wings and turbomachines have delivered experimental data bases of use for designers to improve the efficiency and reduce the aerodynamic noise sources.

The activities of AFDAR have brought an ideal cross link with the European Wind tunnels Association EWA in support of the generic activities on Measurement and Testing by providing new measurement technologies and supporting standardization and improvement of quality (WP5). By advertising the use of reference data bases in the form of high quality PIV recordings of standard flow conditions within an international framework of cooperation Europe and its industry potentially benefit from the AFDAR research and development.

The work conducted in AFDAR has much potential for aeronautics and wind tunnel operators (EWA). The European experts in the field have delivered through AFDAR the development of measurement techniques key for future aircraft development and wind tunnel characterization. Moreover, the AFDAR activities have been a unique opportunity not only to enable new types of measurements of higher quality and productivity, but they have also stimulated research teams from large research organizations such as DLR and CNRS to test and demonstrate their ability jointly, performing such complex measurement campaigns. Beside this operational aspect, the collaborative research effort has been of high scientific and technical level and can only be completed by the joint effort of most of the best research teams working in the field of PIV in Europe.

The formation of the consortium with the given partners organizations demonstrate the complementary and trans-national structure of the AFDAR consortium. A further impact of the project has been that of reinforcing the European competitiveness by leading edge joint research in the specific area of measurement technologies involving industry, ROR's and universities around new promising experimental tools applied to targeted industrial objectives. The PIV research is oriented towards industrial applications and has been of precompetitive nature. The proposed project has provided synergies between different types of partners in three different directions:

developers ⇔ end users
aircraft aerodynamic technologies ⇔ propulsion technologies
developers and end users ⇔ manufacturers of PIV equipment.

Although the main contribution of the programme to the European Union policy has been of course in the transport field, by contributing to enhance the EU competitiveness in the field of air transport, considerable benefits can be translated to the sectors of ground transport, naval engineering and to some extent in all industrial fields that involve fluid dynamics.

AFDAR partners have actively cooperated in international organizations (Bi-annual Laser Symposium for Application of Laser Techniques to Fluid Mechanics in Lisbon and the International PIV Symposium, AIVELA, EREA partnership among few others).

Another added value of the AFDAR activities is that no individual company or university, nor any given European nation can afford to follow the different possible tracks to develop innovative PIV methods due to the costs it represents and the risks involved. The AFDAR activities thus are prototype of the kind of subject where cooperation at a European level offers benefits to all participants. Without the AFDAR project, it would have been unlikely for multilateral cooperation be continued. However, after having successfully performed cooperation during the work of AFDAR, the individual teams maintain research exchange and are placed in a good position to apply for international industrial projects, employing the newly developed PIV techniques.

Contribution to Community Social Objectives, Environment, health and safety

Being a research project with substantial upstream character AFDAR did not produce a direct impact on employment. Instead, its direct contribution was in improving the tools, skills and efficiency of European aeronautics industry, and indirectly AFDAR contributes to preserve employment in Europe. As far as the development of this method is concerned, the situation in Europe is unique. Similar initiatives have just started in Japan and do not exist in the US, which places Europe in at the forefront of this field.

Moreover, AFDAR achieved the unique goal of enhancing the general skill and knowledge available in Europe on this method. A large transfer of know how was done between the different countries and research organizations, making the method available at its best level for industry in more and more sites. This has been exchanged within AFDAR the use of advanced PIV systems in more complex flow fields was disseminated beyond the consortium. Participation of different European teams in joint presentations of the PIV technique, workshops, and working groups have stimulated transnational mobility.

The impact of AFDAR on employment as seen by the SMEs may be described by an example: LaVision, as manufacturer of PIV equipment, has four two persons for PIV during this project.

Also, nine teams from universities, research establishments from five European countries have contributed to the project. This is a direct mean to develop the knowledge of the research/teaching staff and to allow them to improve the education of their graduate students ‘on the job’ by providing first hand information about work in large industrial facilities and international projects.

Finally, several young scientists have grown to become responsible for some part of the research activities. This is also a unique opportunity to bring these young scientists at a high level of knowledge and skill, in a European environment. These will be available afterwards to strengthen industry and research organizations in their competition at international level.

In the field of environment, the contribution of the research activities of AFDAR may also be considered as indirect. It is by the contribution of the PIV method to the improvement of the performances of aircraft and the clear demonstration of such capabilities that AFDAR can contribute to the reduction of noise and pollution. Improvement of aerodynamic noise and reduction of fuel consumption will have a direct impact on the environment and preservation of natural resources and energy, as clearly stated in the fifth frame work program. Workshops and presentations dealing with multi-phase flows have also shown how their better understanding through application of PIV can optimise energy processes.

It is also by its help in making more efficient, less noisy and more safe aircraft, trains and cars that the newly developed PIV methods can be considered as contributing to the quality of life, comfort, health, mobility and safety of European citizens.

Economic Development

State-of-the-art PIV systems can be characterized as PIV systems which automate the data acquisition process by providing automatic system synchronisation and control hardware and software for all components for the system (lasers, CCD cameras, frame grabbers, computers, experiment). This makes the use of the PIV systems more straightforward. This is of practical significance particularly in industrial areas where there are high cost facilities, such as wind tunnels and engine test beds, and experimental time is constrained by tight development/production time schedules.

It is becoming a reality that more and more laboratories are making use of 3D PIV capabilities and in the next 10 years, it is most likely that the 3D-time resolved capabilities of the PIV technique will be used as an everyday measurement tool in almost all university, governmental and industrial research and development laboratories. AFDAR has played a primary role in fostering this development. Thus, the AFDAR project can be considered responsible for the further growth of market for advanced PIV systems, for the understanding of the basic principles, advantages and limitations of the method, and for training in the application of PIV to measure flow fields. This directly impacts the market prospects as seen by those SMEs manufacturing PIV equipment.

1.5. Project public website

1.5.1 AFDAR public website

The address of the project public website is: http://afdar.eu/.

1.5.2 Contact details

The contact information can be found on the AFDAR website: http://www.afdar.eu/contact/.

For information on the AFDAR project, please contact:

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1.5.3 Project logo

For project logo can be seen on the top-left corner of the AFDAR website: http://afdar.eu/.

1.5.4 List of beneficiaries

The list of beneficiaries can be found on the AFDAR website: http://www.afdar.eu/consortium-description/.

The corresponding contact names of the beneficiaries can be found at: http://www.afdar.eu/people/.

The main scientific contacts of each beneficiary are listed below:

1. **Delft University of Technology (TU Delft) – The Netherlands**

   Prof. Fulvio Scarano (Coordinator)

2. **Centre National de la Recherche Scientifique (CNRS) – France**

   Laurent David

3. **Deutsches Zentrum Fuer Luft - und Raumfahrt EV (DLR) – Germany**

   Andreas Schröder

4. **Lavision GMBH (LAVIS) – Germany**

   Bernhard Wieneke

5. **Universitaet Der Bundeswehr Muenchen (UNIBW) – Germany**

   Christian Kähler

6. **Universita Degli Studi Di Napoli Federico II. (UNINA) – Italy**

   Tommaso Astarita

7. **Stichting Nationaal Lucht- en Ruimtevaartlaboratorium (NLR) – The Netherlands**

   Martijn Tuinstra

8. **Von Karman Institute for Fluid Dynamics (VKI) – Belgium**

   Christophe Schram

9. **Monash University (UNIMO) – Australia**

   Julio Soria

10. **Kutateladze Institute of Thermophysics (IOT) – Russia**

    Dimitriy Markowich

2 Use and dissemination of foreground

As clear from the description of individual consortium partners, the existing knowledge, expertise and skills in the field of particle image velocimetry techniques were excellently represented by AFDAR participants. This condition has enabled performing activities at the edge of current state-of-the-art for spreading of excellence.

The first mean to spread excellence has been mobilizing researchers among the consortium participants, which enabled further strengthening of the competences and multi-disciplinary skills within the consortium. This is the result of the large number of collaboration activities involved with the AFDAR tasks mostly performed jointly by two to three partners.

The second step has been to organize specific workshops where personnel not belonging to the consortium has been able to follow introductory lectures and practical laboratory activities familiarizing with the peculiar aspects of tomographic PIV, high-speed measurements and combined optical measurement techniques.

The dissemination at broadest level has been performed by specific actions:

i) a VKI Lecture Series coordinated by AFDAR partners on the post-processing of experimental and numerical data

ii) The DLR PIV course has served as a yearly event to revise the state of the art of the techniques under development in AFDAR. It should be known that this course has now achieved a large impact in the scientific and industrial community and the number of people attending it has steadily grown over the years

iii) All the consortium participants have a rather conspicuous scientific productivity and most results have been disseminated directly by peer-reviewed publications on international journals. The close relation between some of the consortium members and editorial boards of experimental fluid mechanics and measurement techniques journals resulted in a special issue on the developments from a number of AFDAR partners

Progress meetings have been connected with major events (Lisbon Conference on the Applications of Laser Techniques to Fluid Mechanics, Biannual International Symposium on Particle Image Velocimetry) and when possible open to non AFDAR participants to maximize the dissemination of results. This formula has been already adopted for other European projects like PIVNET and turned out to be successful to the point that the workshops had an impact comparable to that of the major conference.

2.1. Section A (see online full list of A1 and A2)

Dissemination measures have been described in the bulleted list at section 2. The detailed list of dissemination through publications in international peer reviewed journals as well as at international conferences is included in templates A1 and A2 respectively. The data has been input directly through the ECAS website.

The complete list of A1 (publications) and A2 (dissemination activities) can be found online.

- A1: List of all scientific (peer reviewed) publications relating to the foreground of the project.
- A2: List of all dissemination activities (publications, conferences, workshops, web sites/applications, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters).

2.2. Section B

The research conducted within AFDAR can be brought to public domain to most of its extent. Exceptions are the specific data about geometries used in some experiments where industry plays the role of subcontractor or with contributions in kind.

Apart from the above cases, the consortium activities have been distributed among consortium partners and disseminated worldwide by means of publications.

Because of the above, no exploitable foreground has been left for patents, which was the specific strategy chosen within AFDAR as a project that should provide upstream technology developments for further exploitation by research centres and industry.

3 Report on societal implications (see online version)