Deliverable 5.6

Final report on the evaluation of the tasks of the workpackage 4

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Abstract

This document is a final report on the evaluation of the tasks of the workpackage 4. It gives results of the evaluation of 3 velocity components estimations with optical flow approaches proposed by Alvarez et al. (2007) and Héas & Mémin (2007b).
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Chapter 1

Introduction

In this chapter we describe briefly the approaches developed in WP4 to evaluate and the database considered for this preliminary evaluation.

1.1 Approaches evaluated

Two approaches developed in WP4 were evaluated (cf. Tab 1.1): COROF-3D3C, a combined correlation/variational technique developed by AMI group; 3DWIND, an optical-flow technique developed by INRIA group.

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Approach</th>
<th>Group</th>
<th>Reference</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>COROF-3D3C</td>
<td>correlation/optical-flow</td>
<td>AMI</td>
<td>Alvarez et al. (2007)</td>
<td>§3.1</td>
</tr>
<tr>
<td>OF-3DWIND</td>
<td>optical-flow</td>
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<td>§3.2</td>
</tr>
</tbody>
</table>

Table 1.1: Approaches developed in WP4 and evaluated in the present document.

1.2 Database considered

COROF-3D3C approach was evaluated with 3D synthetic images of particles dispersed in the near wake of a circular cylinder at Re=3900 (case E2a of the FLUID project database).

OF-3DWIND approach was evaluated with the database of the FLUID project (meteorological image sequences).
Chapter 2

Database description

This chapter describes the database used to perform the preliminary evaluation of the workpackage 4. §2.1 presents a set of 3D image data used to evaluate COROF-3D3C approach. §2.2 presents the meteorological image sequences used to evaluate OF-3DWIND technique.

2.1 Synthetic images based on a LES of a circular cylinder wake flow at Re=3900

The numerical code used for this study solved the incompressible Navier-Stokes equations (see Parnaudeau et al. (2007) for details):

\[
\begin{align*}
\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} &= -\frac{1}{\rho_0} \frac{\partial p_m}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j \partial x_j} + f_i, \\
\frac{\partial u_i}{\partial x_i} &= 0,
\end{align*}
\]

where \( \nu \) is the (constant) kinematic viscosity, \( \rho_0 \) the (constant) density, \( p_m \) the modified pressure field. \( f_i \) is a force which mimics the effects of a solid obstacle in the flow. Basically, Large Eddy Simulation method consists in separating, from a spatial filtering operation, the great scales and the small scales of the turbulence. Spatial filtering (denoted by the overbar) of the Navier-Stokes equations is:

\[
\begin{align*}
\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} &= -\frac{1}{\rho_0} \frac{\partial \bar{p}_m}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} + \bar{f}_i + \frac{\partial T_{ij}}{\partial x_j}, \\
\frac{\partial \bar{u}_i}{\partial x_i} &= 0,
\end{align*}
\]

where \( T_{ij} = \bar{u}_i \bar{u}_j - u_i u_j \) are the subgrid-scale stresses. According to the Boussinesq hypothesis, the subgrid-scale stress can be defined as:

\[
T_{ij} = \nu_t \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) + \frac{1}{3} \bar{T}_{kk} \delta_{ij}.
\]

where \( \nu_t \) is evaluated by the Function Structure model. Here, \( \nu_t \sim \Delta \nu \Delta \), where \( \Delta \nu \) is the filter width and \( \nu \Delta \) the subfilter length scale. According to Deardorff \( \Delta_c = (\Delta_x \Delta_y \Delta_z)^{1/3} \), where \( \Delta_x, \Delta_y, \Delta_z \) are the filter widths in each direction.

The incompressible Navier-Stokes equations are solved on a regular Cartesian grid in non-staggered configuration. Sixth-order compact centered difference schemes are used to evaluate all spatial derivatives, except at the outlet and outflow boundaries where single sided schemes were employed for the \( x \)-derivative calculation. Time integration is performed with the second-order Adams-Bashforth scheme. A constant flow is imposed at the entrance of the domain and...
a simple convection equation is applied at the exit. Periodic conditions are used in the two transverse directions $y$ and $z$.

Our computational domain extends over $20D$ in the streamwise and normal directions. The center of the cylinder is located at $x_{cyl} = 5D$ downstream of the inflow. The spanwise extent of the domain was chosen to be $L_z = \pi D$, which corresponds to the size used by most previous authors. For the square which contains the cylinder, we only used $48 \times 48$ points in the streamwise and normal directions. A uniform streamwise flow is imposed in the initial conditions, with no perturbation in the other directions. For the regime considered, the boundary layer is laminar. The simulation was carried out with a constant time step size of $\Delta t = 0.003D/U_c$ which ensured that the Courant number be 0.15. The Reynolds number is $Re_D = 3900$, the domain size is $L_x \times L_y \times L_z = 20D \times 20D \times \pi D$ and the corresponding number of point is $n_x \times n_y \times n_z = 961 \times 960 \times 48$. Fig. 2.1 presents the iso-surface of the vorticity norm near the cylinder.

![Figure 2.1: Iso-surface of the vorticity norm](image)

2.1.1 Set of 3D images considered

200 full 3D velocity fields, separating by $20\Delta t$ time step, are available for the post-processing. Particles are randomly distributed in the 3D domain. For each particle, the Lagrangian equation suitable for non-heavy particle is solved by using Runge-Kutta scheme for the time advancement:

$$\frac{d\mathbf{x}(x,t)}{dt} = \mathbf{u}(x,t)$$ (2.6)

In the package E2a, the time dependency of the velocity field is now considered. Time integration of the Lagrangian equation was performed with the classical 4th order Runge-Kutta scheme. The time step for the time advancement of the particles is $40\Delta t$, requiring the knowledge of the velocity fields every $20\Delta t$. Coordinates of all the particles were recorded every $40\Delta t$ during $1000\Delta t$ giving 25 particle location files.

These files were digitalized as previously giving 3D raw images (case E2a). Fig. 2.2 shows samples of 2D Images extracted from 3D images. The case E2a in (Appendix A) contains all the 3D images.

For the present preliminary evaluation only a couple of images of the whole sequence was treated.

2.2 Meteorological image sequences

See §?? for a description of the meteorological image sequences involved in this evaluation.
Figure 2.2: 2D images extracted from 3D images: left, $t = 0$; right, $t = 40\Delta t$
Chapter 3

Description of the methods

This chapter describes briefly the two approaches evaluated. §3.1 presents a combined correlation/optical-flow estimator for 3D3C motion estimation, named COROF-3D3C in the present document. §3.2 presents a optical-flow technique dedicated to 3D wind estimation, named OF-3DWIND in the present document.

3.1 3D motion estimation of incompressible PIV flows

Lots of work has been carried out using Particle Image Velocimetry to design experiments which capture and measure the flow motion using 2D images. Recent technological advances allow capturing 3D PIV image sequences of moving particles. In this context, a 3D motion estimation technique based on the combination of an iterative cross-correlation technique and a variational (energy-based) technique was proposed by AMI group. A combination of both methods (using the output of the correlation technique as the initial input of the variational method) improves the accuracy of the flow estimation.

3.1.1 Local Cross-Correlation

Cross-correlation is the most common technique for fluid motion estimation in PIV and is described in Raffel et al. (1998). Having the two volumes \( I_1 \) and \( I_2 \), for each voxel \( v = (v_x, v_y, v_z) \) of \( I_1 \), the method takes a rectangular subvolume \( I_{1,v} \) of \( I_1 \) centered on \( v \), and looks for a similar subvolume of \( I_2 \) centered on a neighbor \( v + d \) of \( v \). The similarity measure between two rectangular subvolumes of the same dimensions is based on 2D cross-correlation. The voxel \( v \) is assigned the displacement \( d \) which gives the maximal value of the cross-correlation. Doing this for every voxel in \( I_1 \) we obtain a complete motion vector field \( u \). The method is then extended to allow subvoxel accuracy by means of local interpolation of a Gaussian function close to the discrete maximum.

The implementation takes advantage of the properties of the Fourier transform to improve the processing time and the whole process should be applied iteratively a few times using the current result as an initialization for the next iteration.

3.1.2 Variational Approach

Variational approach to motion estimation are often used for optical flow computation Beau-chemin & Barron (1995). It consists in minimizing an energy as a function of the displacement and that depends on a pair of images \( I_1 \) and \( I_2 \).
The energy to minimize is expressed as:

\[ E(u) = \int_{\Omega} (I_1(x) - I_2(x + u(x)))^2 dx + \alpha \int_{\Omega} \| \nabla u(x) \|^2 dx, \]

where \( \alpha \) is a scalar coefficient that weights the smoothing term.

We use an iterative method to find the vector field \( u \), updating the vector field at each iteration by adding another vector field \( h \) with small displacements. The displacement \( h \) being small, we can use first order Taylor expansions of \( I_2 \) and \( \nabla I_2 \) at \( x + u^n \) to linearize the minimization problem. Furthermore, we use a pyramidal approach to compute the displacement flow at several scales, using the results from a given scale to initialize to the following higher scale.

### 3.1.3 Solenoidal projections

For every method, if we know that the flow we are looking for follows a physical model we can constrain the solution using its solenoidal projection and it will probably improve the results.

In the correlation method we can replace the solution with its solenoidal projection after each iterative call to the method. And in the case of the Horn-Schunck method, we do the same with each partial result of the pyramidal scheme using the solenoidal projection for the next scale.

### 3.2 Optical-flow technique dedicated to 3D wind estimation

The complexity of three-dimensional atmospheric fluid flows associated to incomplete observation of atmospheric layers due to the sparsity of cloud systems makes very difficult the estimation of dense atmospheric motion field from satellite images sequences. The recovery of the vertical component of fluid motion from a monocular sequence of image observations is a very challenging problem for which no solution exists in the literature. The problem of estimating three-dimensional motions of a stratified atmosphere from satellite image sequences is addressed as follow.

Based on a physically sound vertical decomposition of the atmosphere into layers of different altitudes, wind estimation is performed over the complete three-dimensional space using a multi-layer model (3D-ICE model) describing a stack of dynamic horizontal layers of evolving transmittance, interacting at their boundaries via vertical winds. More precisely, the data term relying on the 3D-ICE model, applies on a set of sparse transmittance images related to the different atmospheric layers. A method is proposed to derive such images from satellite infrared images. To overcome the problem of sparse observations, a robust estimator is introduced in the data term. The data term is combined to a regularizers preserving two-dimensional divergent and vorticity structures of the three-dimensional flow and enforcing regions of homogeneous vertical winds. A linearized formulation of the 3D motion estimator is proposed to overcome problems induced by large displacements. For more details see Héas et al. (2007a); Héas & Mémim (2007b).
Chapter 4

Results with fluid mechanics images

This chapter describes the results obtained for the evaluation of COROF-3D3C approach §4.1.

4.1 3D motion estimation for incompressible PIV flows

This section presents the interpretation of 3D3C vector fields estimated with COROF-3D3C, a correlation/optical-flow 3D3C technique developed by AMI group.

Figure 4.1 shows the instantaneous vector fields in 3D turbulent wake flow (case E2a FLUID project database) for the estimation provided with COROF-3D3C and for the corresponding LES ground-truth. Based on these vector fields both vector fields gave comparable informations. The primary vortex structure launched in the very near wake was extracted by COROF-3D3C. However when compared with LES, COROF-3D3C approach provided velocities inside the circular cylinder where there was no particles and luminescence variations in the image sequence. This surprising wrong result could be easily resolved with mask or robust techniques. It also exhibits that COROF-3D3C generated noise. When compared with the LES solution, it is readily observed that the velocities estimated by COROF-3D3C yielded the main pattern of the flow but with the addition of noise. Figures 4.2 and 4.3 indicate that the level of the error was rather high, particularly in regions between the primary vortices. The underlying cause of these discrepancies is mainly due to the resolution of particle image compared to the main scales involved in the flow. The synthetic particle images are based on a LES using 48 grid points (in one direction) to describe the cylinder. This led to images in which the cylinder was described with 48 pixels. In a classical experimental PIV investigation of a cylinder wake flow, the cylinder diameter corresponds to around 200 pixels, i.e. 5 times more than with the present synthetic images. Since the diameter of the particles has been set to 2-3 pixels, the synthetic particle images provided a low pass filtered description of the fluid motion. In this context, the results provided by COROF-3D3C approach are limited by the information contained in the observations.

Comparisons made with LaVision 3D3C PIV technique have shown that COROF-3D3C approach provided comparable results (see Fig. 4.4).

Nevertheless, this method may be improved with higher order regularization technique, which was shown by Corpetti et al. (2006); Yuan et al. (2007) for 2D2C estimations to be better suited for fluid flows, and with dynamic consistent techniques for which the models are better adapted for 3D flows.
Figure 4.1: Instantaneous vector fields in 3D turbulent wake flow (case E2a FLUID project database): Top, $xy$ plane; Bottom, $xz$ plane.

Figure 4.2: Deviation of instantaneous COROF-3D3C velocity field from LES (case E2a FLUID project database) – From top to bottom: error on $u$, error on $v$ and error on $w$ (in voxel).
Figure 4.3: Deviation of instantaneous COROF-3D3C velocity field from LES (case E2a FLUID project database) – From top to bottom: error on $u$, error on $v$ and error on $w$ (in voxel).

Figure 4.4: Comparisons of instantaneous vector fields in 3D turbulent real wake flow (FLUID project database): Red, COROF-3D3C vector field; Green, LaVision vector field.
Chapter 5

Interpretation of 3D atmospheric motion fields

5.1 Data and 3D calculation method

From the meteorological point of view, determining the motion in the 3-dimensional atmosphere from satellite data appeared to be the most difficult task of the FLUID project, because satellite images are 2-dimensional, with pixel data representing some information on the 3rd dimension, at an altitude not necessarily well determined. Thus only one group of methods has been developed by the VISTA group from IRISA.

The IRISA methods have been presented at different conferences and papers (Héas et al., 2007a; Héas & Mémin, 2007b). Practically 2 methods currently exist and produce:

- 3 component, 2 (horizontal) dimension (3C-2D) motion vector fields;
- 3 component, 3 dimension (3C-3D) motion vector fields.

At this stage of the project, the most evolved algorithm enables the determination of 3-D motion on a limited number of levels of the troposphere (i.e. lower part of the atmosphere), on the vertical. Common features of both methods are:

- the segmentation of the troposphere into 3 layers (low, medium and high).
- the use of pressure difference (also called transmittance) images for each layer (derived from pressure images, themselves extracted with a cloud classification).
- the use of a div-curl constraint as part of the regularisation term.
- the use of sparse, correlation-based vectors to constrain further the motion vector calculation, as another part of the regularisation term.

Elements which differentiate both methods are:

- different dynamical models in the data term: shallow-water mass conservation model, including hydrostatic assumption for the 2D method, 3D integrated continuity equation for the 3D method.
- differences in the regularisation term: use of a spatio-temporal regularisation term based on Navier-Stokes equations for the 2D method, use of the gradient of the vertical wind for the 3D method.

- Satellite data:
  From the 3 series of images and related data (AfGG 5 June 2004, NATL 5 June 2004 and
NAtl Vince 2005 cyclone), the method initially developed was tested on the AFGG 5 June
2004 series. The last versions of the motion vector calculation methods were applied on
the NAtl 5 June 2004 image series. As mentioned before, the main satellite data used was
the cloud top pressure images derived from the EUMETSAT cloud classification. These
images have been used to determine the motion vector fields. A complementary dataset
was the LMD AMV fields (derived directly from the original satellite images) ; these were
used as one regularisation constraint.

- Analysed wind data :
  Unlike 2D-2C motion vector fields, which have been compared to 2D-2C satellite vector
  fields (mainly LMD atmospheric motion vectors (AMVs)), we used 3D-2C or 3C analysed
  winds from the ECMWF (European Centre for Medium-Range Forecast) which is part of
  the FLUID meteorological database. Analysed winds are available at 9 discrete heights,
  i.e. at 9 pressure levels between 1000 and 200 hPa. This wind data has been described in
  Deliverable 1.4 on the FLUID database, and in Deliverable 5.5 on 2D fluid motion analysis.

5.2 Verification methodology

5.2.1 Determination of statistical indicators

3D motion vectors calculated on 3 levels are compared to analysed winds at equivalent pressure
levels :

- low-level (i.e. low altitude, or high pressure) vectors with analysed winds at 1000, 925,
  850 and 700 hPa levels.

- medium-level vectors with analysed winds at 500 hPa .

- high-level (i.e. high altitude, or low pressure) vectors with analysed winds at 400, 300, 250
  and 200 hPa.

For each of these 9 comparisons, the same statistical estimators, i.e. the bias, the RMS vector
difference (RMSVD), the normalised RMS vector difference (NRMSVD) and the angular error
(< ∆DIR >), can be calculated. These indicators have been defined in Deliverable 1.4 and
5.5. The closer the two vector fields that are compared, the closer to 0 is the value of these
statistical estimators. Comparisons of 3D motion vectors with analysed winds at the other, non-
corresponding levels (e.g. low-level vectors vs. analysed winds at 500, 400, 300, 250 and 200
hPa, etc) could provide complementary indications on the quality of these vector fields : the
resulting statistical indicators should have higher absolute values than those obtained with the
corresponding levels. But the result is a set of 27 groups of statistical indicators corresponding
to all possible comparisons (3 3D motion vector fields vs. 9 analysed wind fields). 3D motion
vectors represent a motion on a larger slice of atmosphere than analysed winds : low- and high-
level vectors each can correspond to analysed winds at 4 levels (each corresponding to a smaller
slice). If a majority of statistical indicators has the smallest (absolute) value, this may indicate
that the 3D vector fields preferentially correspond to a specific level ; otherwise, there may be
local correspondences with vectors at different levels. An alternative could consist in comparing
3D vector fields at low, respectively high level to averaged analysed winds at corresponding
pressure levels : low analysed winds averaged between 1000, 925, 850 and 700 hPa, resp. high
analysed winds averaged between 400, 300, 250 and 200 hPa.

5.2.2 Local comparisons

Comparisons at local scale, i.e. concerning individual or small groups of vectors potentially can
show if the motion of specific clouds or cloud types is realistic. For this purpose, the same type
of comparisons between 3D motion vectors and analysed winds can be made at a local scale as in 2D motion vector comparisons: the angular difference \( \delta \text{DIR} \), the relative amplitude of the vector difference \( \text{Rvd} \), the relative difference of the vector amplitudes (speeds) \( \text{Rsd} \), and the signed relative amplitude of the vector difference \( \text{Rsvd} \) can be calculated for each vector. These coefficients have been precisely defined in Deliverable 5.5. Analysed winds at a selected level are used as reference data in the definition of the coefficients.

5.2.3 Vertical wind comparisons

In the 3D-3C case, basically the vertical component of motion vectors could also be compared with corresponding (or non-corresponding) vertical analysed winds. Practically the most important comparisons are limited to: low-/medium level vertical motion vs. analysed wind at 700 hPa (highest level of low-level analysed winds, which are close to the limit between low- and medium-levels of the troposphere, generally set to 680 hPa. Medium-/high-level vertical motion vs. analysed wind at 500 hPa (highest level of medium-level analysed winds, which are close to the limit between medium- and high-levels of the troposphere, generally set to 440 hPa. Vertical motion vector or wind data is more difficult to analyse than horizontal winds or vectors for one main reason: vertical motion cannot be measured directly and is generally a product derived from horizontal motion information with the help of physical or mechanical laws (mass conservation...). Thus it is more sensitive to the noise of the original (horizontal) data. For these reasons, and also due to the lack of time, we did not perform comparisons on the vertical wind components.

5.3 Preliminary results on the AfGG sequence

A preliminary version of the 3C-3D motion vector calculation method has been tested on a limited area during a short duration (1 h) of the AfGG sequence. Presented results (fig. 4.7 in Deliverable 5.3) show the evolution with time of horizontal vectors and vertical motion in the upper layer covering an hour. Motion vectors are extracted in an area dominated by large active convective cloud systems, i.e. with rapidly evolving clouds reaching high altitudes. The observed motion is again compatible with the high-level vectors observed on corresponding LMD vector fields and with ECMWF analysed winds at high-levels (400 and 200 hPa). Areas where convective clouds grow are associated to upward motion, as expected from physical cloud formation processes for a large number of cloud systems; similarly decaying clouds are largely superimposed with downward vertical motion. This relation is more flagrant than in the NATl sequence, due also to the stronger physical processes (convection) taking place in this geographical area, close to the equator. Vertical motion in areas without high-level clouds is more difficult to evaluate. They seem to be related to the presence or absence of medium-level (or low-level) clouds (not detectable on the pressure difference image of the highest layer).

5.4 Visual interpretation of results

The most complete and up to date comparison of the 3D vector fields has been obtained with the NATl sequence of 5 June 2004. It is not complete yet, and some verifications have to be fulfilled before giving a complete and reliable interpretation of the results. Nevertheless, we already interpreted partially the results.

In comparison to analysed wind fields (and also LMD AMVs), some meteorological features have been visually identified on the 3D vector fields (See Fig. 5.1):

- the winds from the west on the western (left) side of the image at all levels.
Figure 5.1: 2 layers of 3D-3C motion vectors over the NArl area on 5 June 2004 on IR 10.8 image 48. Low-level winds are in red, high-level winds are green. Differences in amplitude between both levels become visible: low-level vectors are larger in the northwest part of the image and over the eastern part of the image (centre right - red is dominant), high-level vectors are larger in the southwestern part of the image, over the ocean (lower left - green is dominant). Out-of-Earth-disk vectors are not represented (upper left corner).
• A part of the rotation motion around the large extratropical depression in the north-west corner of the image at all levels.

• A part (southern part) of the rotation motion around the low-level depression, located on the centre-left part of the image at low level only, close to the Iberian peninsula.

• The winds from the southwest, then from the west, associated to a jet-stream which runs in the upper part of the images (between the position of the two extratropical depressions).

• The winds from the northwest, in the northeast (upper-right) corner of the images, which are apparently a continuation of the previously mentioned jet-stream.

On the other hand, some difference have been clearly identified:

• Non-zero 3D motion vectors are present in the aout-of-Earth-diskâ part of the images, i.e. in the upper-left corner.

• The rotation motion around the two depression centres is not complete on any of the 3D motion vector fields (it should be present on all three vector fields for the northernmost depression, and on the low-level field for the low-level depression close to the centre of the image).

• Over large areas, 3D vector fields have a smaller intensity than analysed winds at the corresponding pressure levels. This difference is outstanding for the upper (northern) third of the 3D high-level vector field.

At this stage, more comparisons, in particular local ones, have to be undertaken. Statistical indicators have also been calculated at this stage, they do not give clear indications on the quality and representativity of the 3D vector fields and have to be checked. A preliminary qualitative comparison of 3D-3C with 3D-2D motion fields seems to indicate that corresponding fields are close, but this comparison has to be completed with other tests.

5.5 Conclusions and specific questions about 3D motion validation

This first set of comparisons shows that the main motion can be extracted on a limited number of levels or altitudes. But non-negligible differences between have been observed, for which some explanations can be proposed:

• The selected NAtl area represented a difficult challenge for extracting motion vectors : the measurable motion on the images is at different scales and of different nature on different parts of the image. In the upper-left corner of the image, space is visible. In the vicinity of the edge of Earth disk, the motion of atmospheric structures is viewed as a projection and therefore its amplitude and quality is reduced.

• Cloud coverage is very different for the 3 levels. Low clouds have the large coverage of the Earth surface, whereas the coverage by high-level clouds is strongly reduced. Few pixels associated to high-level clouds are present over the eastern half (right) of the images. Thus the high-level vector fields have little dependence to image data and may be more easily corrupted.

• Very few clouds are present over the Sahara, i.e. in the southeast corner of the image (lower-right). Thus the 3D vector fields do not depend much on the image data, nor on the vectors used for initialise the motion (in the regularisation constraint).
• The limited quality of cloud classification images. Cloud top pressure images are a secondary product of the cloud classification. For this study, the extraction of the 3D vector fields has been based on the EUMETSAT cloud classification to segment the cloud top pressure images (also extracted by EUMETSAT) into the 3 different levels. At this time the classification method was not well tuned and some clouds were not correctly extracted. The two other classifications (SAF and LMD), which give very close result, are more reliable and better classify clouds than the EUMETSAT classification. They should have been used preferentially, but unfortunately no related products (in particular cloud top pressure) were derived at that time. (For the Vince sequence (9-10 October 2005) added later to the database, the SAF cloud classification is available with all derived products, and the EUMETSAT classification method has been optimised and tuned. Unfortunately EUMETSAT classification images and derived products are calculated and used operationally in real-time, are normally not stored and were not available for us. Thus a complete comparison of motion vectors based on each classification is not possible with the current database.)

Although the verification and validation of these 3D results are not finished, this attempt to extract 3D motion vectors is promising: the main motions are extracted. It should also be tested on other cases and other geographic areas. One final remark, also valid for 2D motion fields: the original data used to extract motion vectors is a pair (or a series) of images in a single channel. (In the case of 3D vectors, it is a pseudo-channel, the cloud top pressure). We suggest to use also the images in other channels: in some areas the motion (and height) information will be the same, but in other cases this added information could lead to a more realistic determination of the motion.
Appendix A

Evaluation database and procedure

The aim of the evaluation is to present, discuss and analyze the results from the different algorithms on the image database. Detailed and quantitative comparisons will be undertaken in order to provide a feedback to improve the different methods. The comparison of the results obtained by the different approaches will be performed and presented at the next meetings and in the deliverables D5.1 to D5.6. Statistical quantities and spectra will be looked at in order to evaluate the capability of the methods to analyse 2D and 3D turbulent flows. The database is composed of simple analytical flows, 2D and 3D turbulent flows, couple of images and time resolved image sequences, particle and scalar images.

A.1 Fluid mechanics database for the evaluation

A database of particle and scalar images was designed for analysis. All images in this database are suitable for variational approaches. Correlation analysis can also be done except maybe for scalar images. The database is organized in three packages. Details on the characteristics of flows and images are given in the documents, delivered by Johan Carlier (.FLUID-website./WP01/package_02_readme_Cemagref.pdf).

The first group is composed of simple analytical solutions. Seven subcases have been provided:

<table>
<thead>
<tr>
<th>Case n°</th>
<th>Description</th>
<th>Provider</th>
<th>Image type</th>
<th>Seeding</th>
<th>Number of sets</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Viscous and potential flows</td>
<td>Cemagref</td>
<td>synthetic</td>
<td>particle</td>
<td>A1(41)</td>
</tr>
<tr>
<td>A1</td>
<td>Poiseuille</td>
<td>Cemagref</td>
<td>synthetic</td>
<td>particle</td>
<td>A1(41)</td>
</tr>
<tr>
<td>A2</td>
<td>Lamb-Oseen vortex</td>
<td>Cemagref</td>
<td>synthetic</td>
<td>particle</td>
<td>A2(41)</td>
</tr>
<tr>
<td>A3</td>
<td>Uniform flow</td>
<td>Cemagref</td>
<td>synthetic</td>
<td>particle</td>
<td>A3(41)</td>
</tr>
<tr>
<td>A4</td>
<td>Sink flow</td>
<td>Cemagref</td>
<td>synthetic</td>
<td>particle</td>
<td>A4(41)</td>
</tr>
<tr>
<td>A5</td>
<td>Vortex flow</td>
<td>Cemagref</td>
<td>synthetic</td>
<td>particle</td>
<td>A5(41)</td>
</tr>
<tr>
<td>A6</td>
<td>Cylinder with circulation</td>
<td>Cemagref</td>
<td>synthetic</td>
<td>particle</td>
<td>A6(41)</td>
</tr>
<tr>
<td>A7</td>
<td>PIV-Challenge 2005</td>
<td>LaVision</td>
<td>synthetic</td>
<td>particle</td>
<td>A7(2)</td>
</tr>
</tbody>
</table>

The second group is composed of two dimensional turbulent flows obtained by experimental and numerical approaches. Two subcases have been provided for the numerical approach:
<table>
<thead>
<tr>
<th>Case no</th>
<th>Description</th>
<th>Provider</th>
<th>Image type</th>
<th>Seeding</th>
<th>Number of sets</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Exp. of 2D turbulent flow</td>
<td>LPS-ENS</td>
<td>real</td>
<td>fluorescein</td>
<td>B(96)</td>
</tr>
<tr>
<td>C</td>
<td>DNS of 2D turbulent flow(^a)</td>
<td>Cemagref</td>
<td>synthetic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C1a</td>
<td>Time resolved (\Delta T = 10\delta t)  (^b)</td>
<td>Cemagref</td>
<td>synthetic</td>
<td>particle</td>
<td>C1a(1000)</td>
</tr>
<tr>
<td>C1b</td>
<td>Time resolved (\Delta T = 10\delta t)</td>
<td>Cemagref</td>
<td>synthetic</td>
<td>temperature</td>
<td>C1b(1000)</td>
</tr>
<tr>
<td>C2</td>
<td>Time resolved (\Delta T = \delta t)</td>
<td>Cemagref</td>
<td>synthetic</td>
<td>particle</td>
<td>C2(200)</td>
</tr>
</tbody>
</table>

\(^a\)Direct Numerical Simulation (DNS).

\(^b\)\(\Delta T\) is the time step between two images and \(\delta t\) is the time step for the Direct Numerical Simulation.

The third group is composed of three dimensional turbulent flows obtained by experimental and numerical approaches. Ten subcases have been provided:

<table>
<thead>
<tr>
<th>Case no</th>
<th>Description</th>
<th>Provider</th>
<th>Image type</th>
<th>Seeding</th>
<th>Number of sets</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>Exp. of turbulent wake</td>
<td>Cemagref</td>
<td>real</td>
<td>particle</td>
<td></td>
</tr>
<tr>
<td>D1</td>
<td>Far wake ((x/D = 30))</td>
<td>Cemagref</td>
<td>real</td>
<td>particle</td>
<td>D1(5000)</td>
</tr>
<tr>
<td>D2</td>
<td>Near wake ((x/D = 0))</td>
<td>Cemagref</td>
<td>real</td>
<td>particle</td>
<td>D2(5000)</td>
</tr>
<tr>
<td>D3</td>
<td>Near wake - Time resolved</td>
<td>Cemagref</td>
<td>real</td>
<td>particle</td>
<td>D3(\text{xxx})</td>
</tr>
<tr>
<td>E</td>
<td>LES of turbulent wake(^a)</td>
<td>Cemagref</td>
<td>synthetic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E1</td>
<td>Volume</td>
<td>Cemagref</td>
<td>synthetic</td>
<td>particle</td>
<td>E1(10)</td>
</tr>
<tr>
<td>E2a</td>
<td>3D image - Time resolved</td>
<td>Cemagref</td>
<td>synthetic</td>
<td>particle</td>
<td>E2(200)</td>
</tr>
<tr>
<td>E2b</td>
<td>2D image - Time resolved</td>
<td>Cemagref</td>
<td>synthetic</td>
<td>particle</td>
<td>E2(200)</td>
</tr>
<tr>
<td>F</td>
<td>Time-Resolved 2D2C PIV</td>
<td>LaVision</td>
<td>real</td>
<td>particle</td>
<td>F(\text{xx})</td>
</tr>
<tr>
<td>G</td>
<td>3D synthetic data</td>
<td>LaVision</td>
<td>synthetic</td>
<td>particle</td>
<td></td>
</tr>
<tr>
<td>G1</td>
<td>constant velocity</td>
<td>LaVision</td>
<td>synthetic</td>
<td>particle</td>
<td>G1(\text{xx})</td>
</tr>
<tr>
<td>G2</td>
<td>compression wave</td>
<td>LaVision</td>
<td>synthetic</td>
<td>particle</td>
<td>G2(\text{xx})</td>
</tr>
<tr>
<td>G3</td>
<td>compression wave + gradient</td>
<td>LaVision</td>
<td>synthetic</td>
<td>particle</td>
<td>G3(\text{xx})</td>
</tr>
<tr>
<td>G4</td>
<td>shear flow</td>
<td>LaVision</td>
<td>synthetic</td>
<td>particle</td>
<td>G4(\text{xx})</td>
</tr>
<tr>
<td>G5</td>
<td>shear flow + gradient</td>
<td>LaVision</td>
<td>synthetic</td>
<td>particle</td>
<td>G5(\text{xx})</td>
</tr>
</tbody>
</table>

\(^a\)Large Eddy Simulation (LES) of the wake of a circular cylinder at \(Re = 3900\).

According to the recommendations of the first review of the FLUID project, a new case (case D2) will be provided. This case will include a reference flow solution obtained using the result of an optimized experiment (zoom in the flow, high image quality). Then the data set containing images for the analysis will be acquired in more realistic situations (non-optimal conditions: limited spatial resolution, contrast etc.).

Lines in italic correspond to cases not yet available.

### A.1.1 Database location

The data of the different cases have been provided either on the FLUID website or on portable hard-disks (USB-HDD) sent to each group involved in the project.
A.2 Evaluation procedure

A.2.1 Generalities

Tasks of workpackages 2, 3 and 4 will be evaluated with the database presented above. The first group can be used by developers to provide simple validations of their methods. These images include divergence and rotational free flows (potential flows), which can show immediately the capability of the algorithms to estimate correctly these quantities. The case A7 provided by LaVision, including different degrees of local flow gradients without and with varying degrees of image noise, can show immediately in a visual as quantitative way the strengths and weaknesses of the algorithms.

According to the recommendations of the first FLUID project review, mainly groups 2 and 3 will be considered for the evaluation procedure. Indeed, the validation will be focused on the cases considering turbulent flows, obtained with experiments or numerical simulations. The case G including 3D-synthetic data will also be considered since it contributes to innovative aspects in the project (evaluation of 3D3C methods).

Depending on the different cases the ground truth will be provided by analytical expressions, DNS/LES solutions, controlled PIV measurements or hot-wire anemometry measurements.
A.2.2 Format of results

The results of the analysis have to be provided by contributors in ASCII format compatible with gnuplot and tecplot: \((x, y, u, v, w, \text{flag})\) with a tab character to separate each column and a blank line (carriage return) to separate each block of \(y\) fixed coordinates. The results have to be given in pixel units with the origin on the bottom left border of the image. \(x, y\) and \(\text{flag}\) (optional) have to be in integer format. \(u, v\) and \(w\) have to be in float format (simple precision). If your method provides vectors with subpixel location, \(x\) and \(y\) can be given in float format (simple precision). The optional \(\text{flag}\) can be provided if you want to give information on each individual vector. The \(\text{flag}\) definition should be provided in a separate file. An example of file structure is presented below.

```plaintext
# If you want to add a comment.
x1   y1   u   v   w   f
x2   y1   u   v   w   f
    .
    .
xn   y1   u   v   w   f

x1   y2   u   v   w   f
x2   y2   u   v   w   f
    .
    .
xn   y2   u   v   w   f

...

x1   ym   u   v   w   f
x2   ym   u   v   w   f
    .
    .
xn   ym   u   v   w   f
```

An acronym and a number must appear in the name of all the files you will provide. For instance a00001_cvgpr_01.txt contains the vector map of the computation 01 obtained by CVGPR-group from the set of images a00001a.tif and a00001b.tif. If you have different methods or if you use different parameters, use the number after the acronym to distinguish them. Define this number in a separate file.

A.2.3 Evaluation of 2D2C methods

Compute cases A7, B, C1, C2, C3, D1, E2 and F.

A.2.4 Evaluation of time resolved methods

Compute cases C1, C2, C3, E2 and F.

A.2.5 Evaluation of 3D3C methods

Compute cases E1, G1, G2, G3, G4, G5.
A.2.6 Computation of cases C3 and D1

Case C3: Compute image 0 and image 9, image 0 and image 19, ... up to image 0 and image 199, with the same set of parameters for the 19 couples of images. Compute the same set of images as many time you change the set of parameters (see §A.2.2 for the name of the files).

Case D1: In order to reduce the computational time and the size of the results you can crop the images before computation. With the origin of the image coordinate system on the bottom left, crop the image from (275, 0) (bottom-left) to (787, 1024) (top-right).
Bibliography


Parnaudeau, P., Carlier, C., Heitz, D. & Lamballais, E. 2007 Experimental and numerical studies of the flow over a circular cylinder at reynolds number 3900. In revision for Physics of Fluids . 7
