Flow Visualization

Part 1 (out of 3)

Overview: Flow Visualization, Part 1

- Introduction, overview
  - Flow data
  - Simulation vs. measurement vs. modelling
  - 2D vs. surfaces vs. 3D
  - Steady vs time-dependent flow
  - Direct vs. indirect flow visualization
- Experimental flow visualization
  - Basic possibilities
  - PIV + Example

Flow Visualization

Introduction, Overview

Flow Visualization

- Introduction:
  - FlowVis = visualization of flows
    - Visualization of change information
    - Typically: more than 3 data dimensions
    - General overview: even more difficult
  - Flow data:
    - nD×nD data, $1D^2$ / $2D^2$ / nD^2 (models), $2D^2$ / $3D^2$ (simulations, measurements)
    - Vector data (nD) in nD data space
  - User goals:
    - Overview vs. details (with context)

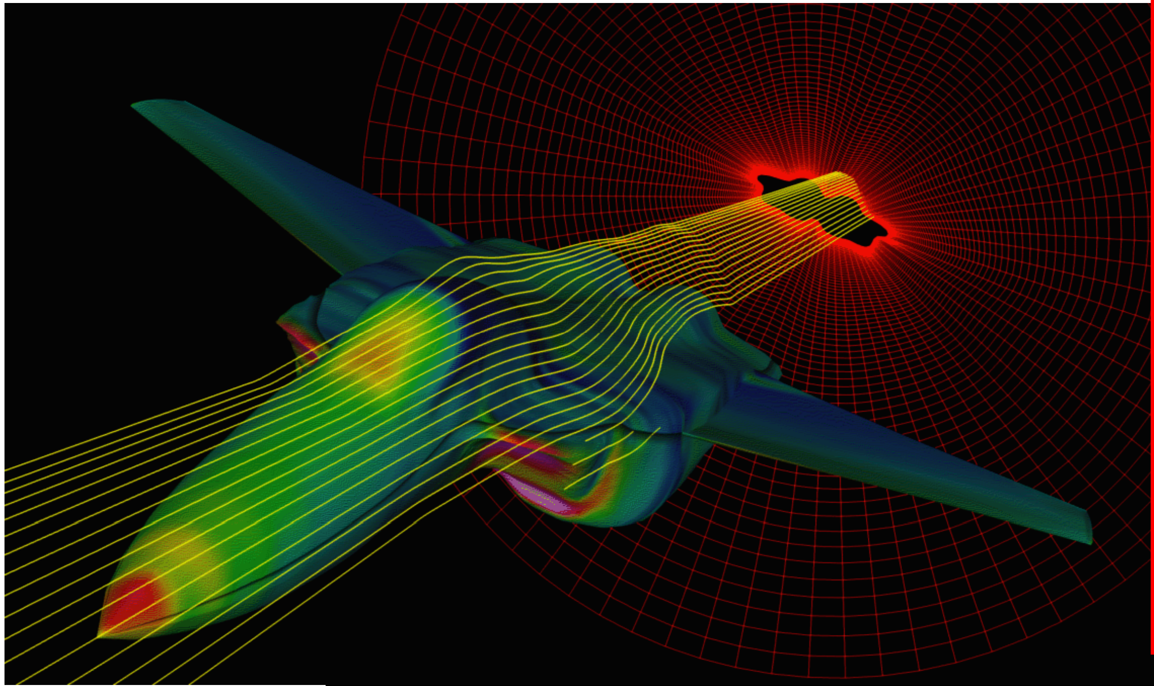
Flow Data

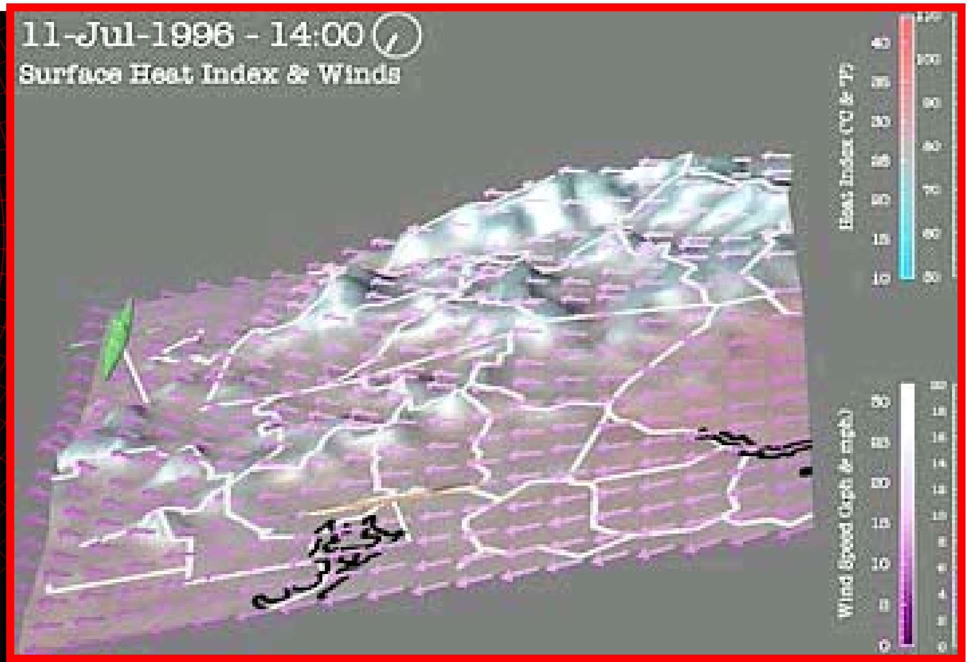
- Where do the data come from:
  - Flow simulation:
    - Airplane- / ship- / car-design
    - Weather simulation (air-, sea-flows)
    - Medicine (blood flows, etc.)
  - Flow measurements:
    - Wind tunnel, fluid tunnel
    - Schlieren-, shadow-technique
  - Flow models:
    - Differential equation systems (ODE) (dynamical systems)

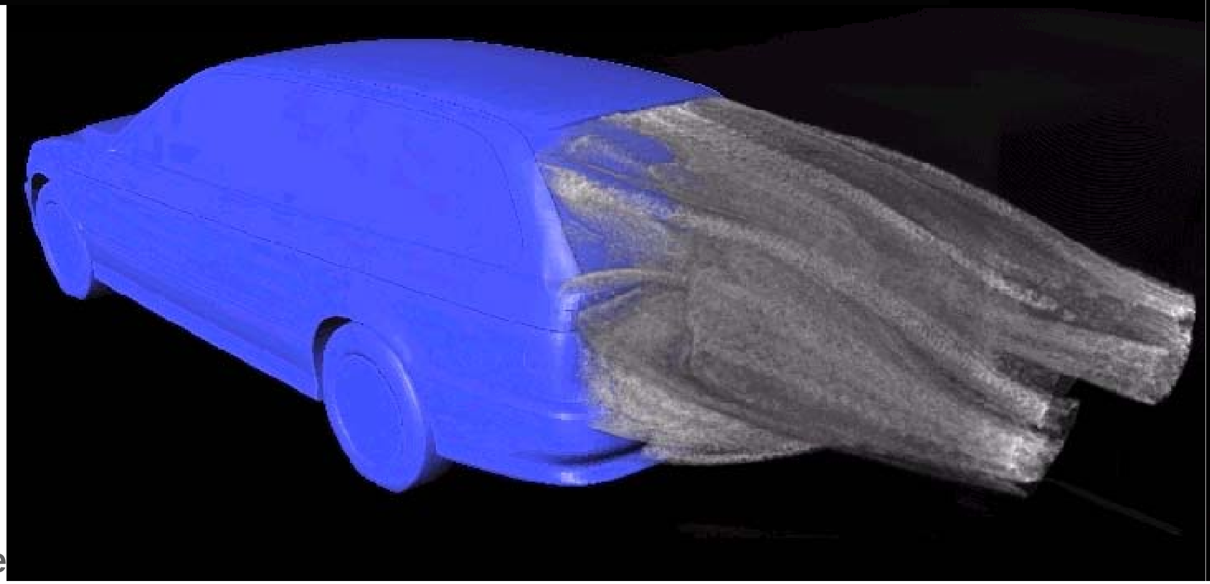
Flow Data Specification

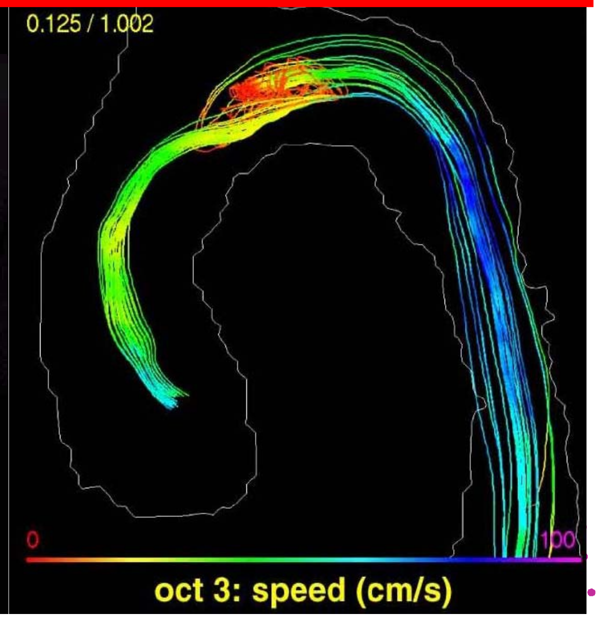
- Simulation:
  - Flow: set of samples (n dimensions of data), e.g. given on curvilinear grid
  - Most important primitive: tetrahedron (cell)
- Measurement:
  - Flow-vectors: reconstruction out of correlations, often calculated on regular grids
- Modelling:
  - Flow: analytic formula, can be evaluated “everywhere”

Data Source – Examples 1/2

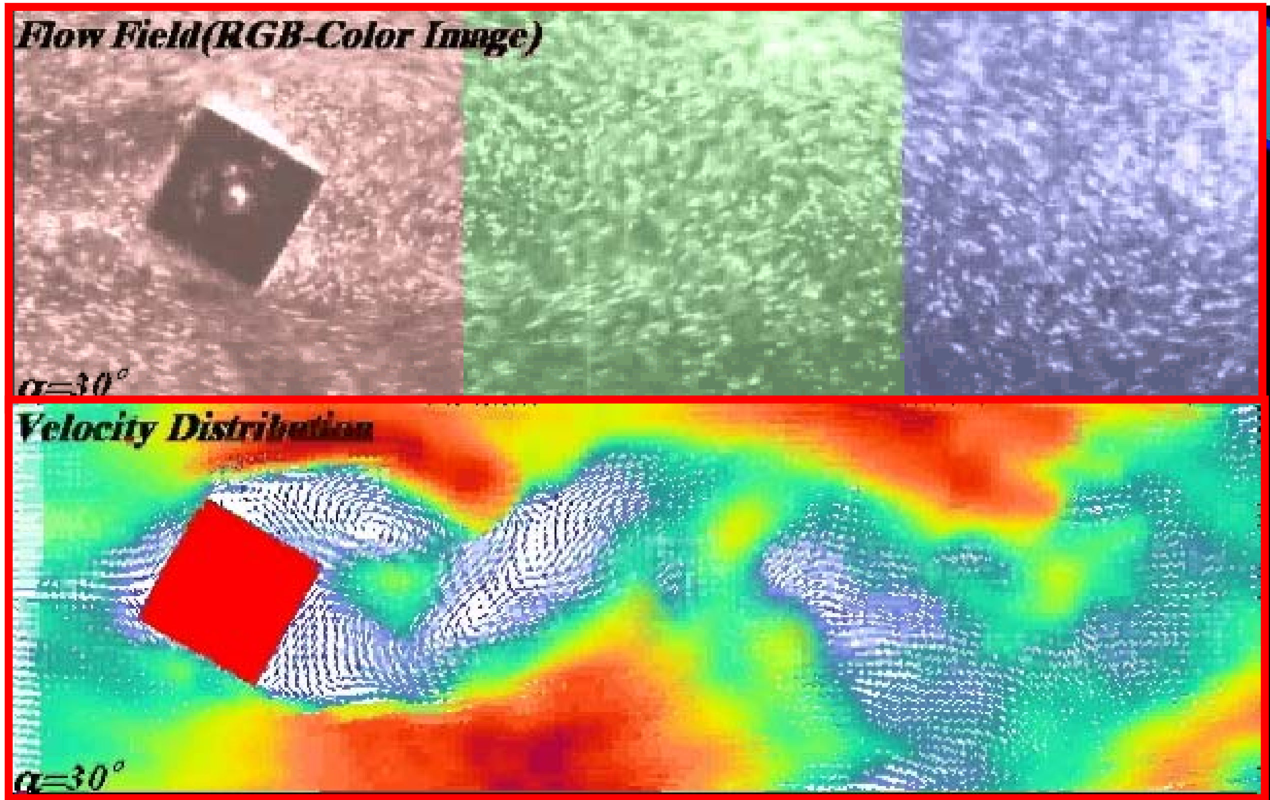


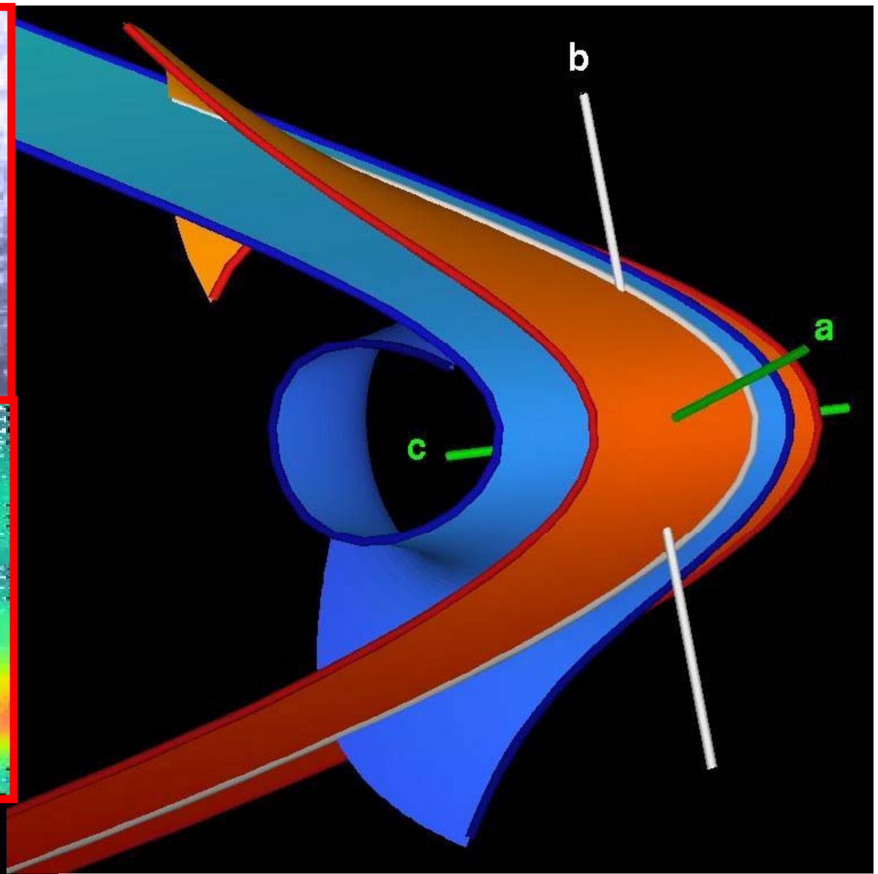


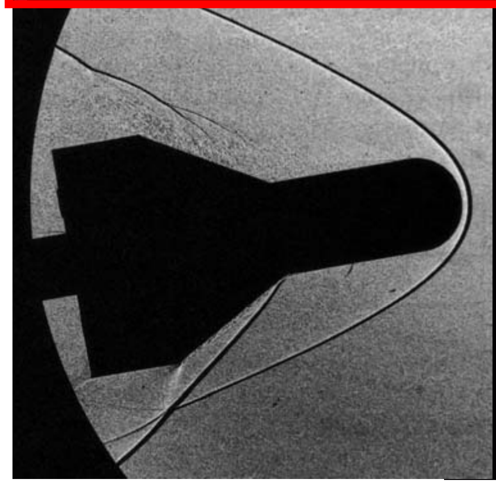


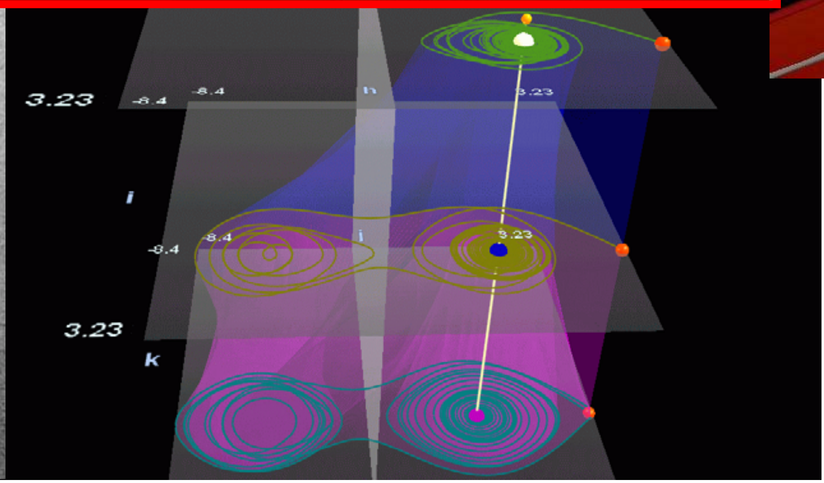


Data Source – Examples 2/2







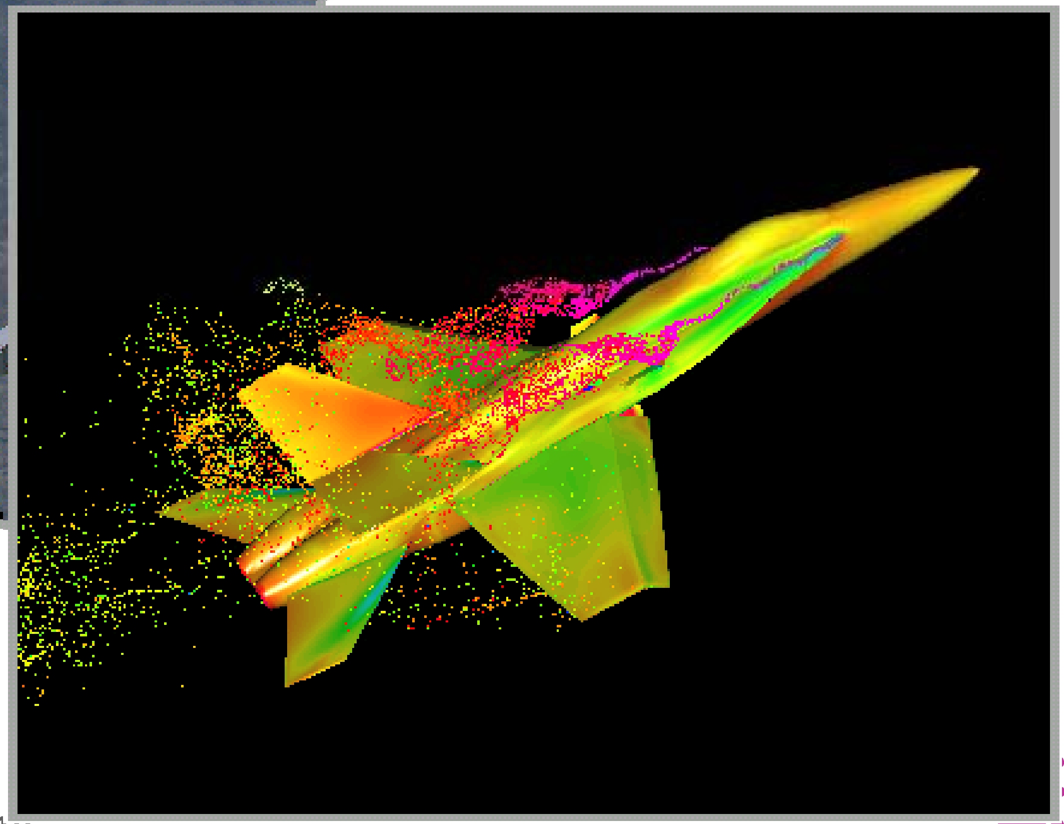


Simulation vs. Measurement vs. Modelling

- Simulation:
  - Flow space modelled with grid
  - FEM (finite elements method),
    CfD (computational fluid dynamics)
- Measurements:
  - Optical methods + pattern recognition,
    e.g.: PIV (particle image velocimetry)
- Models:
  - Differential equation systems d**x**/dt

Comparison with Reality

Experiment



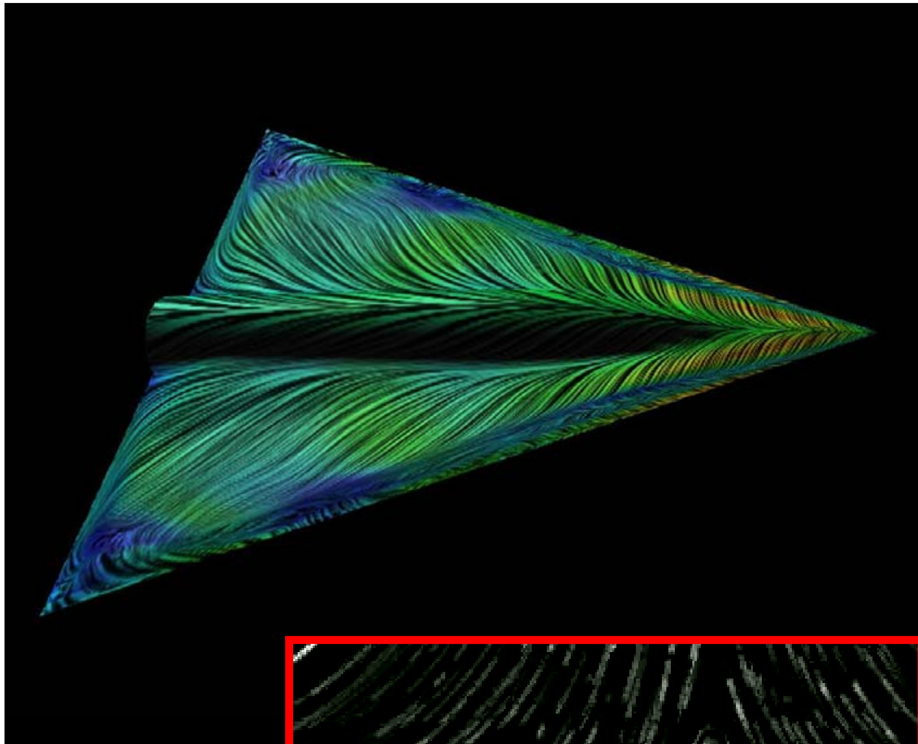
Simulation

2D vs. Surfaces vs. 3D

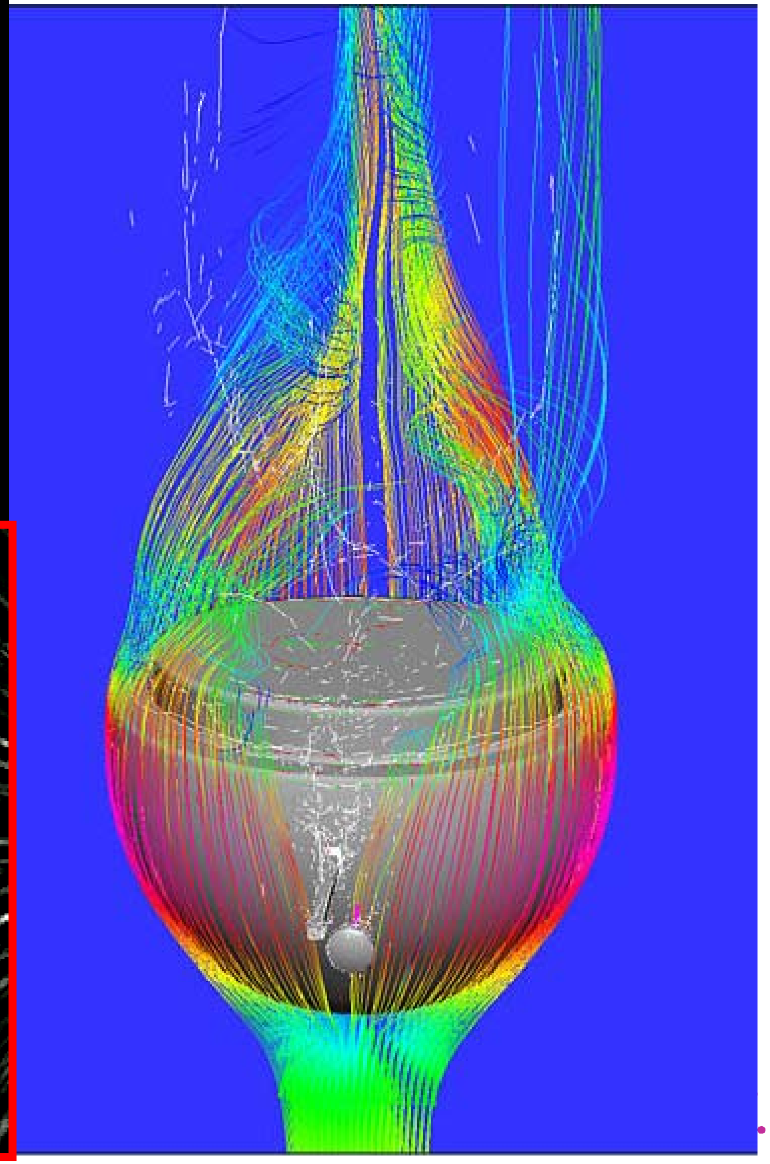
- 2D-Flow visualization
  - 2D×2D-Flows
  - Models, slice flows (2D out of 3D)
- Visualization of surface flows
  - 3D-flows around “obstacles”
  - Boundary flows on surfaces (2D)
- 3D-Flow visualization
  - 3D×3D-flows
  - Simulations, 3D-models

2D/Surfaces/3D – Examples

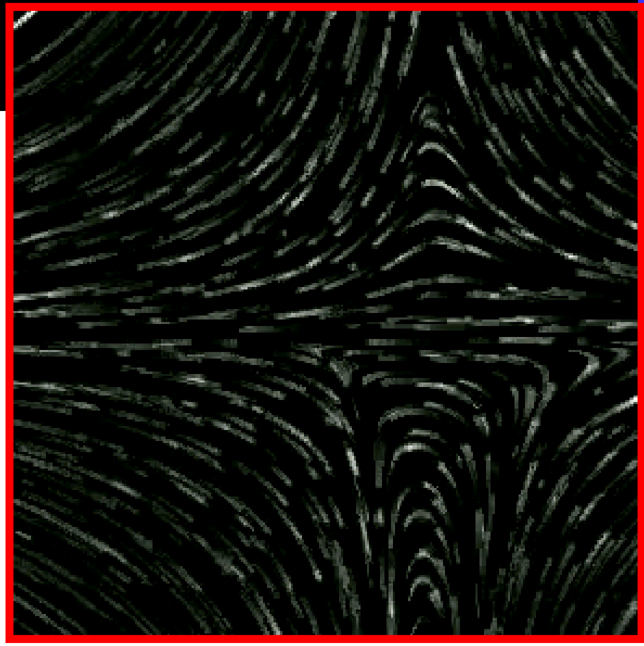
Surface



3D



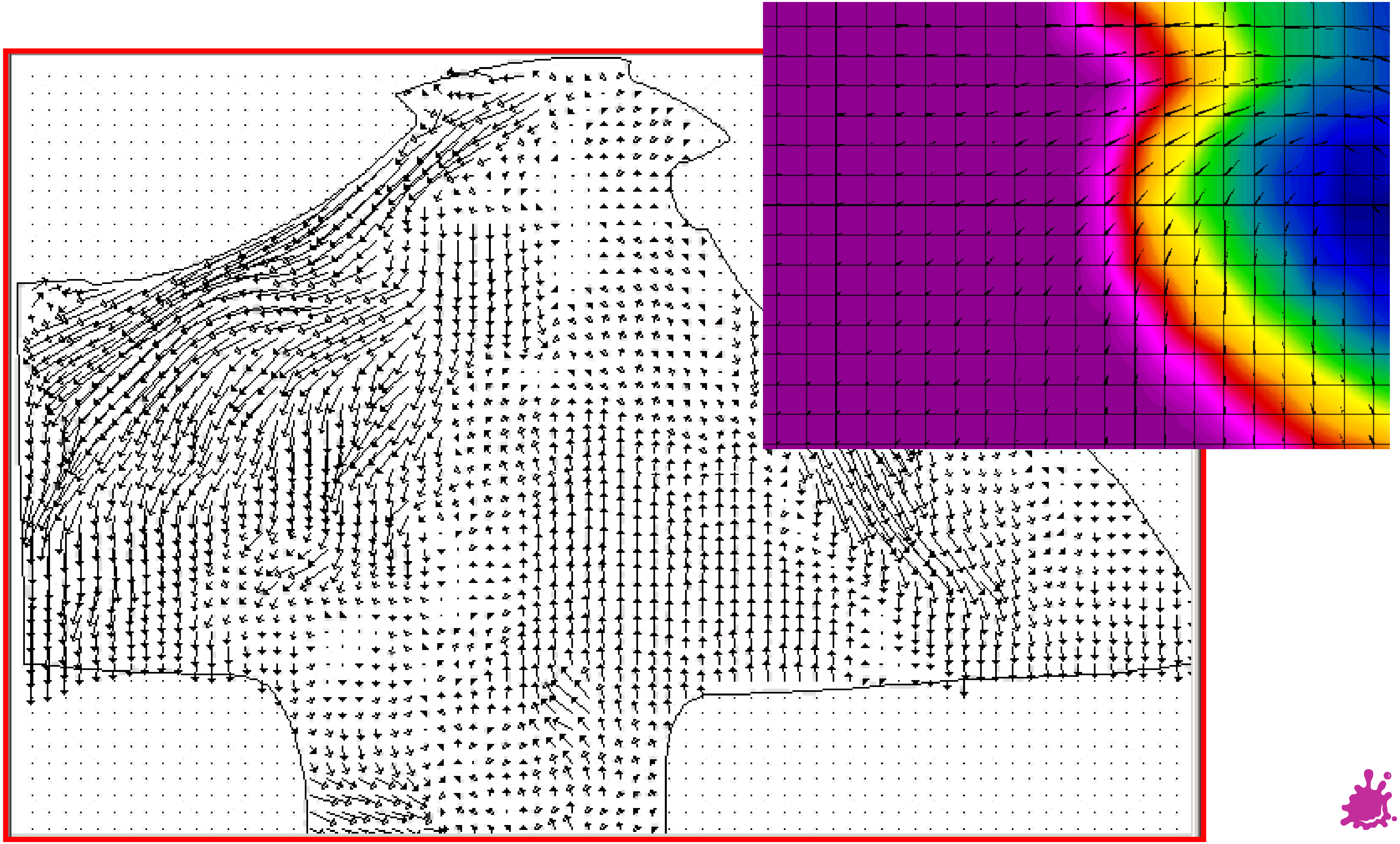
2D



Steady vs. Time-Dependent Flows

- Steady (time-independent) flows:
  - Flow static over time
  - **v**(**x**): $R^n \rightarrow R^n$, e.g., laminar flows
  - Simpler interrelationship
- Time-dependent (unsteady) flows:
  - Flow itself changes over time
  - **v**(**x**,t): $R^n \times R^1 \rightarrow R^n$, e.g., turbulent flows
  - More complex interrelationship

Time-Dependent vs. Steady Flow

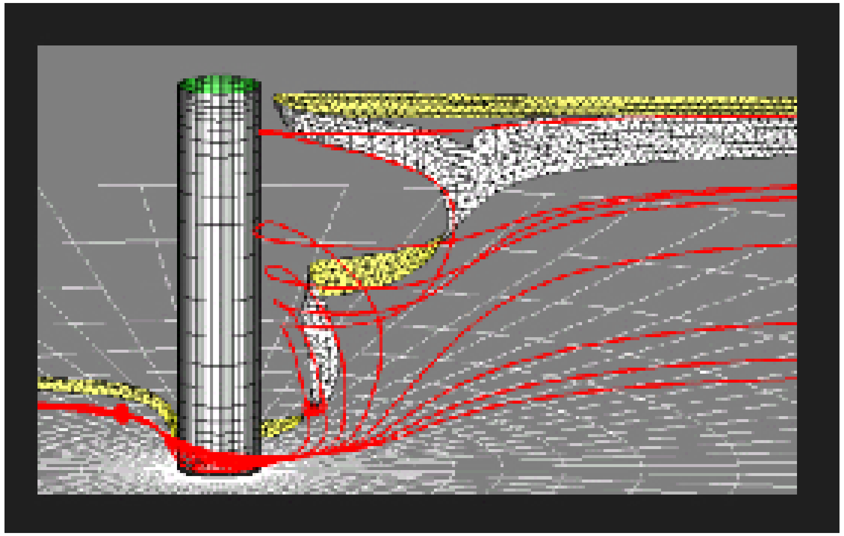


Time-Independent (Steady) Flow Data

- Data size in the course of time:

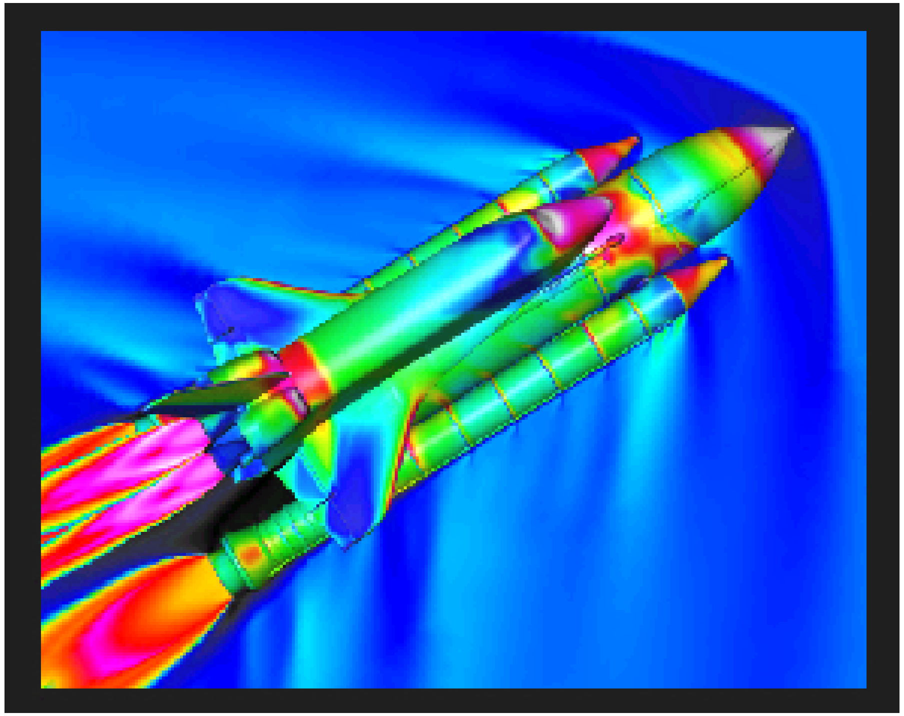
Data set name and year	Number of vertices	Size (MB)
McDonnell Douglas MD–80 ’89	230,000	13
McDonnell Douglas F/A–18 ’91	900,000	32
Space shuttle launch vehicle ’90	1,000,000	34
Space shuttle launch vehicle ’93	6,000,000	216
Space shuttle launch vehicle ’96	30,000,000	1,080
Advanced subsonic transport ’98	60,000,000	2,160
Army UH–60 Blackhawk ’99	100,000,000	~4,000

Time-Independent (Steady) Data



Single Zone
100K Nodes
4 MB

(1985)



128 Zones
30M Nodes
1080 MB

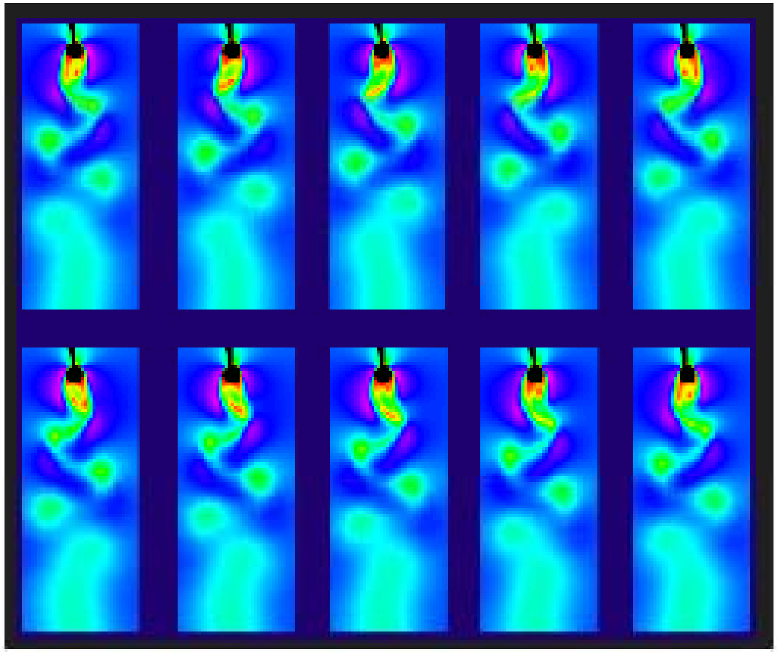
(1996)

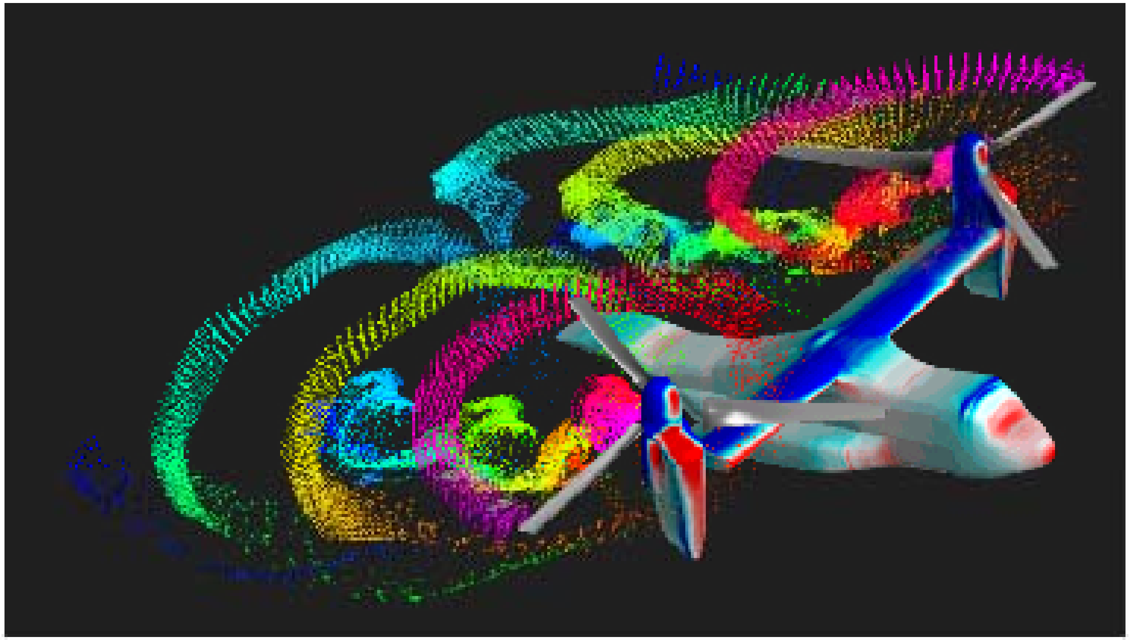
Time-Dependent (Unsteady) Data

- Historical development:

Data set name and year	# vertices	# time steps	size (MB)
Tapered Cylinder '90	131,000	400	1,050
McDonnell Douglas F/A–18 '92	1,200,000	400	12,800
Descending Delta Wing '93	900,000	1,800	64,800
Bell–Boeing V–22 tiltrotor '93	1,300,000	1,450	140,000
Bell–Boeing V–22 tiltrotor '98	10,000,000	1,450	600,000

Time-dependent (unsteady) Data



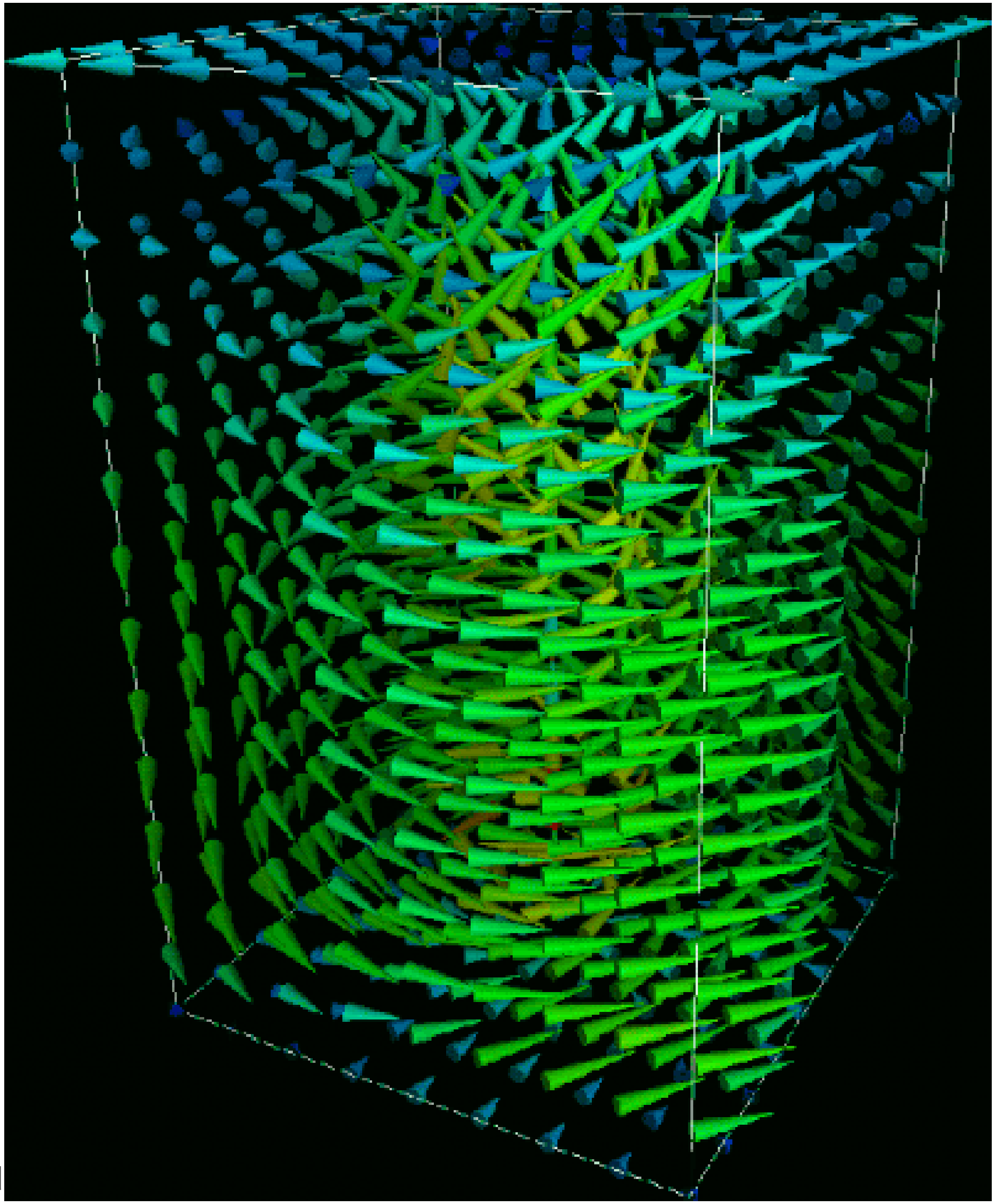


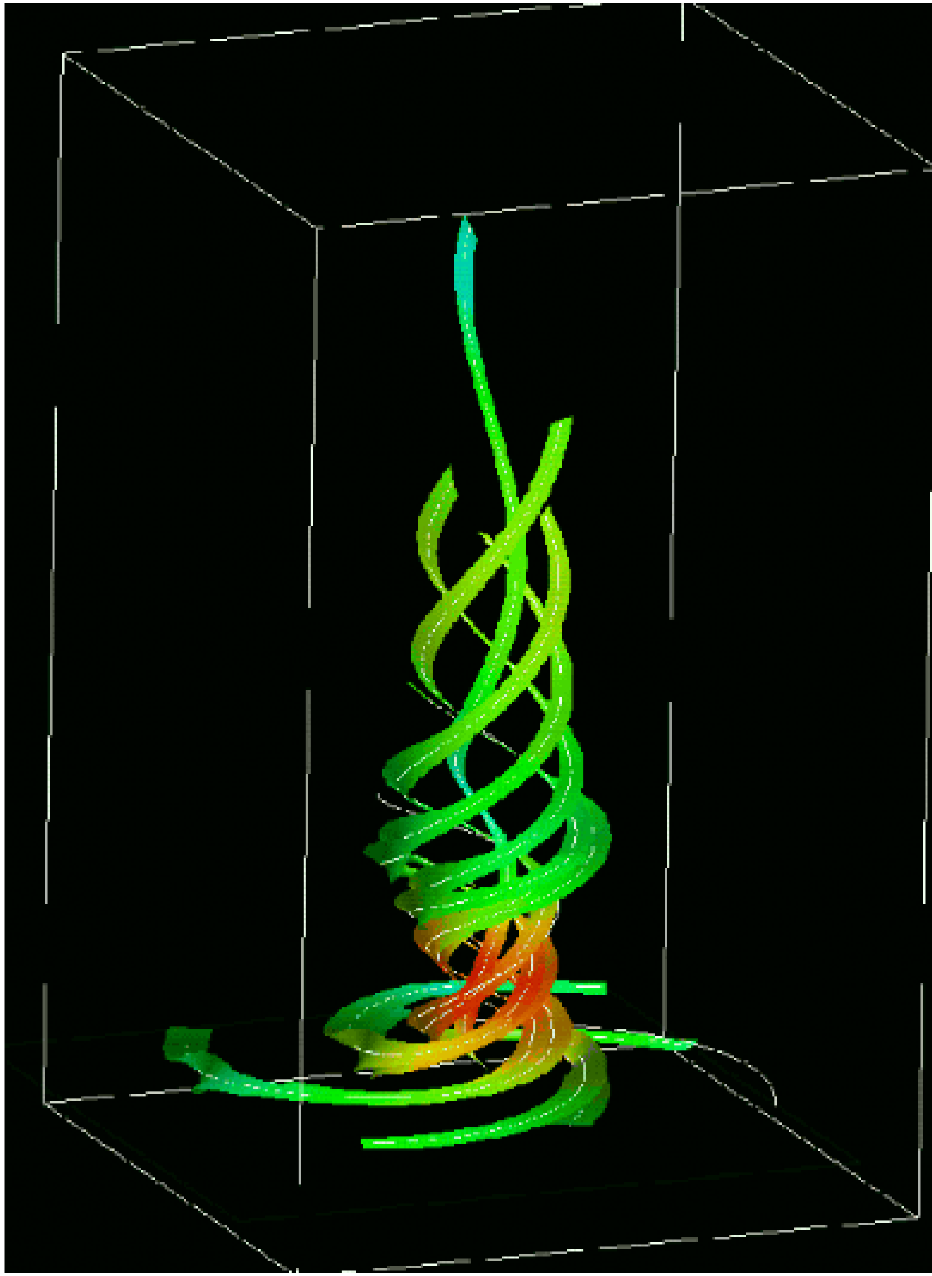
Single Zone 128K Nodes 1 GB	25 Zones (9 Moving) 2.8M Nodes 300 GB
(1990)	(1996)

Direct vs. Indirect Flow Visualization

- Direct flow visualization:
  - Overview on current flow state
  - Visualization of vectors
  - Arrow plots, smearing techniques
- Indirect flow visualization:
  - Usage of intermediate representation: vector-field integration over time
  - Visualization of temporal evolution
  - Streamlines, streamsurfaces

Direct vs. Indirect Flow Vis. – Example



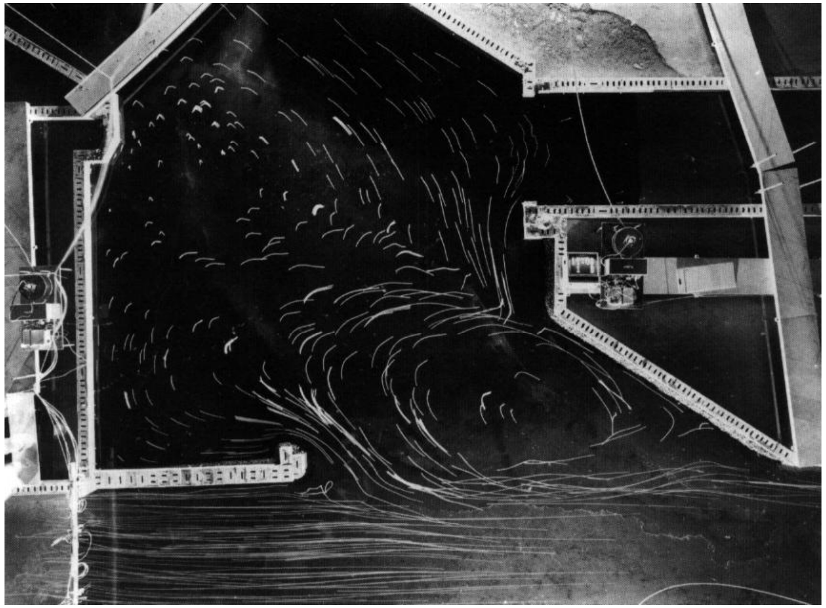


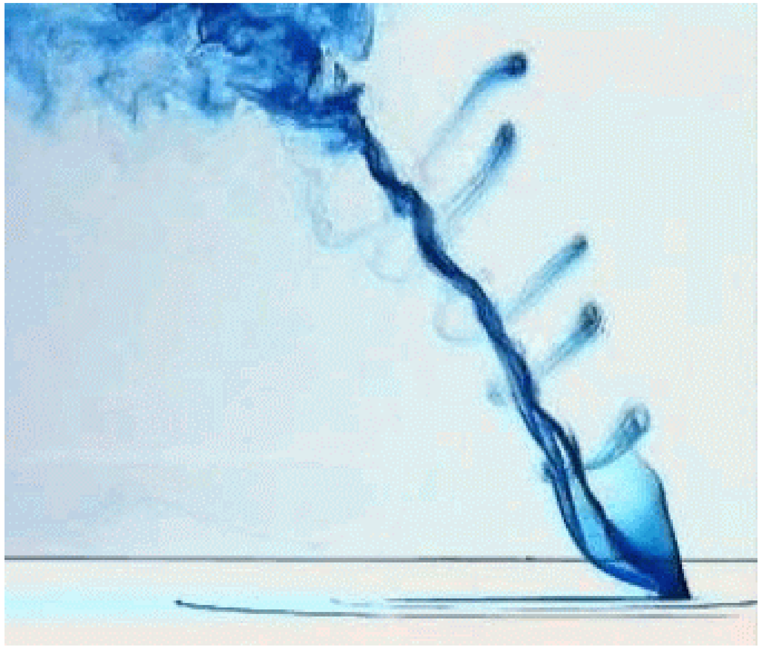
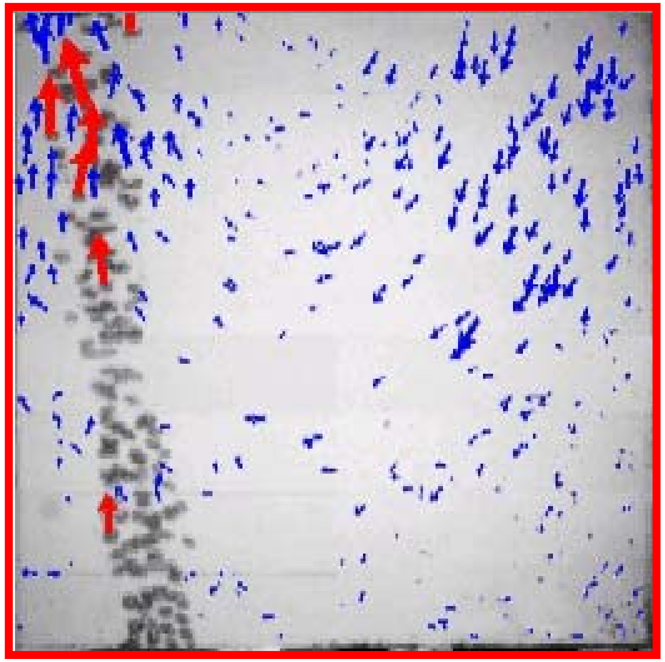
Experimental Flow Visualization

Optical Methods, etc.

With Smoke rsp. Color Injection

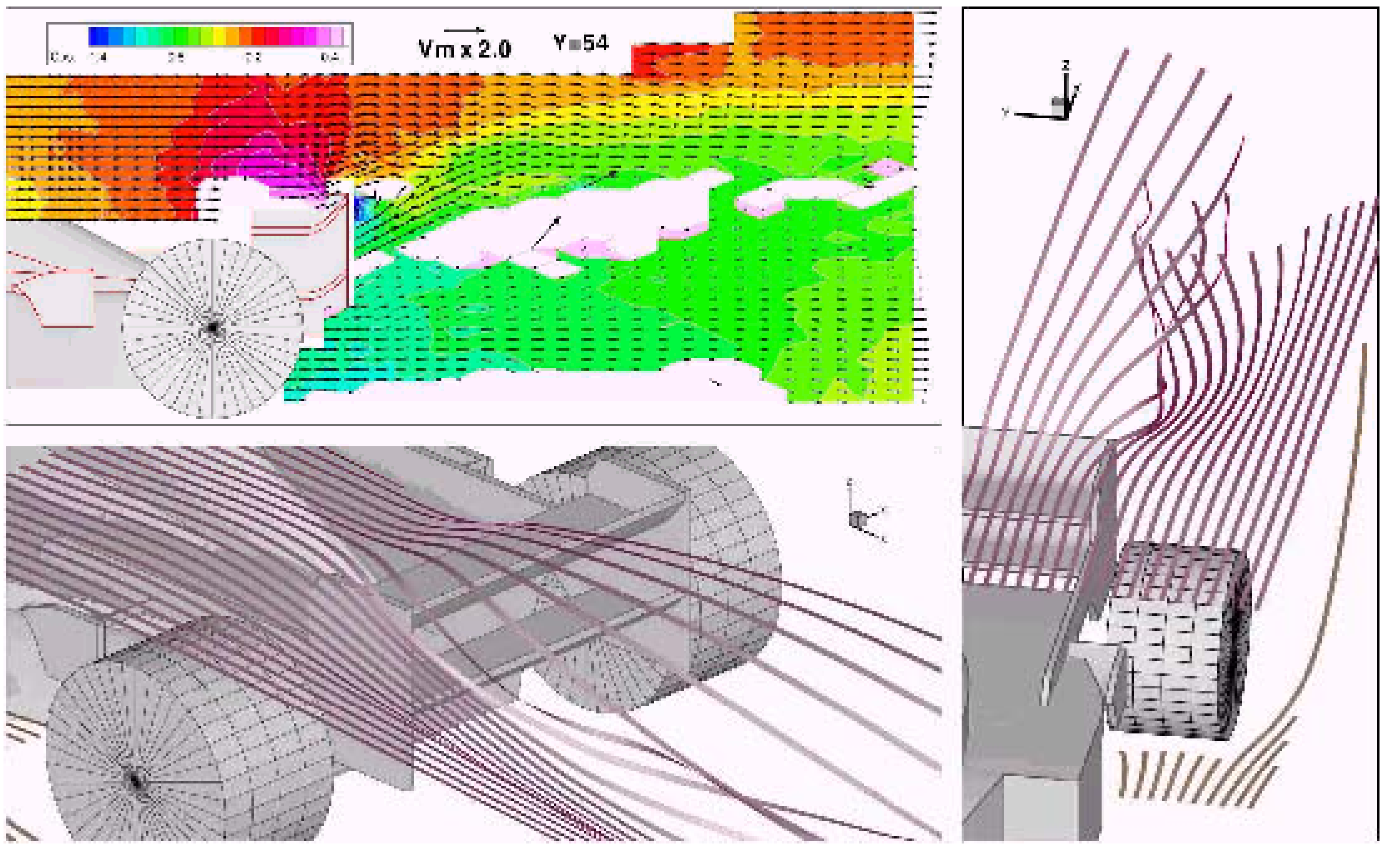
- Injection of color, smoke, particles
- Optical methods:
  - Schlieren, shadows



Example: Car-Design

- Ferrari-model, so-called five-hole probe (no back flows)

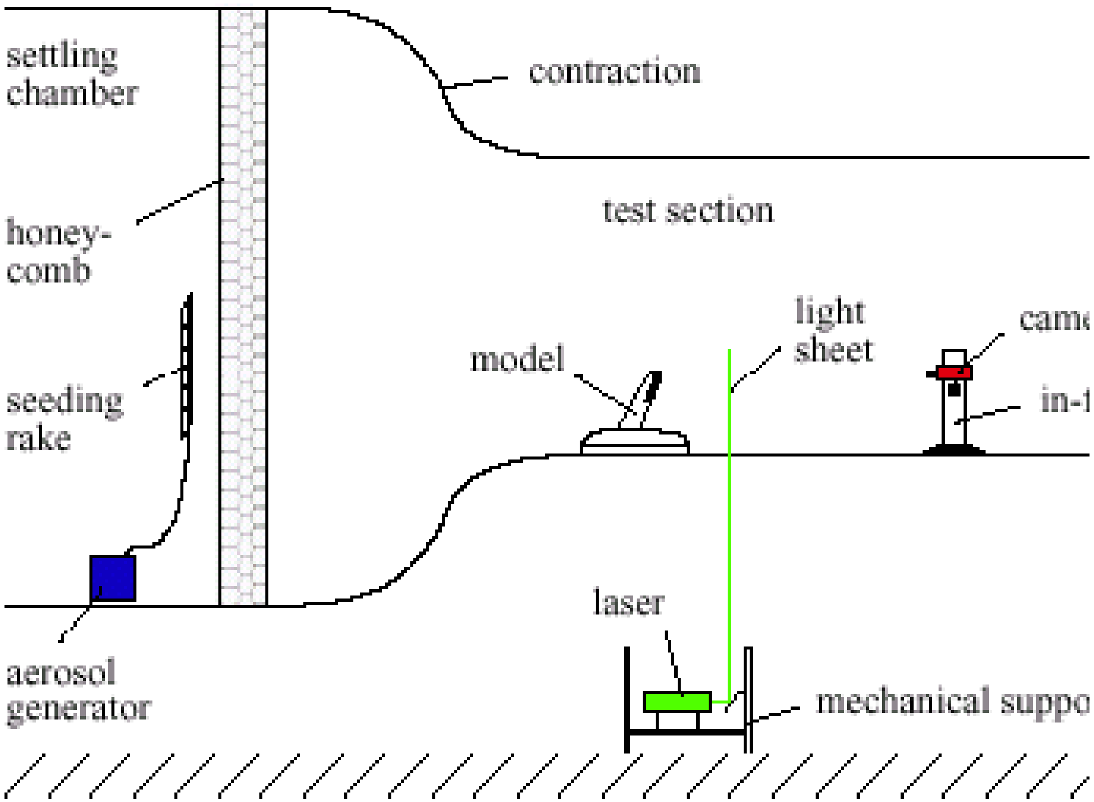


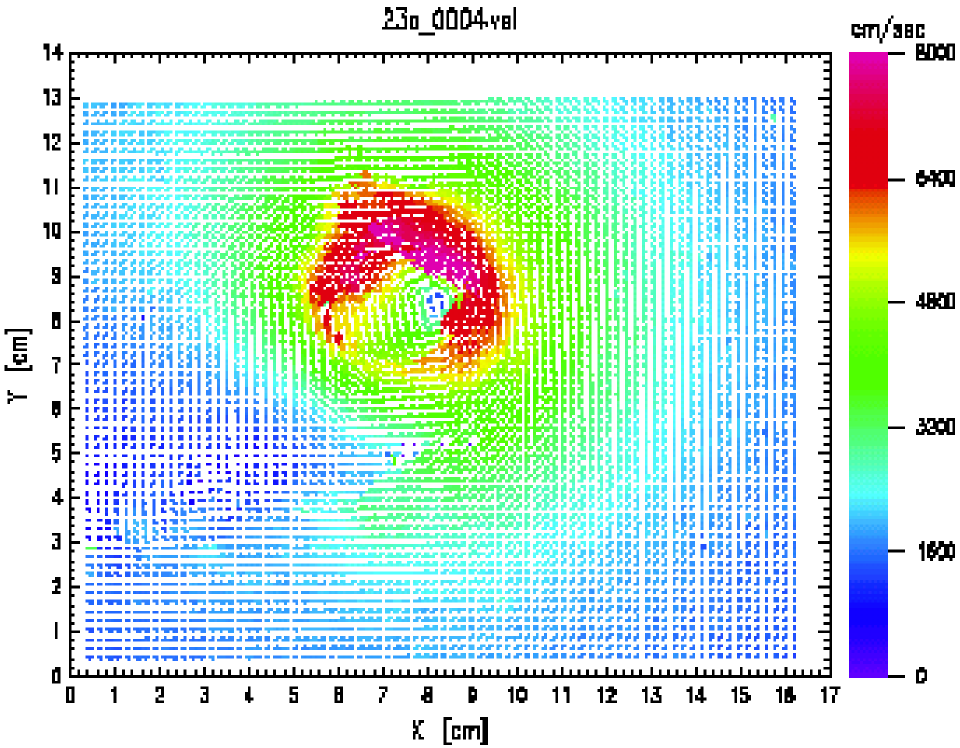
PIV: Particle Image Velocimetry

- Laser + correlation analysis:
  - Real flow, e.g., in wind tunnel
  - Injection of particles (as uniform as possible)
  - At interesting locations:
    2-times fast illumination with laser-slice
  - Image capture (high-speed camera),
    then correlation analysis of particles
  - Vector calculation / reconstruction,
    typically only 2D-vectors

PIV - Measurements

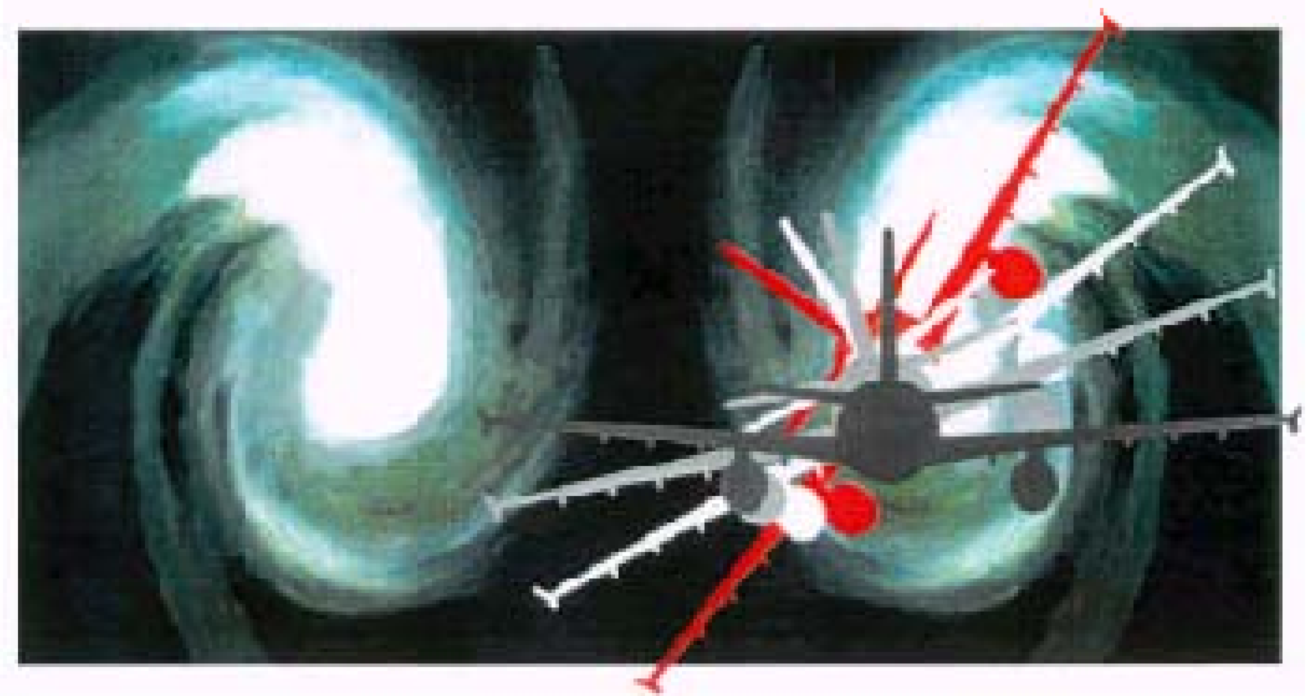
- Setup and typical result:

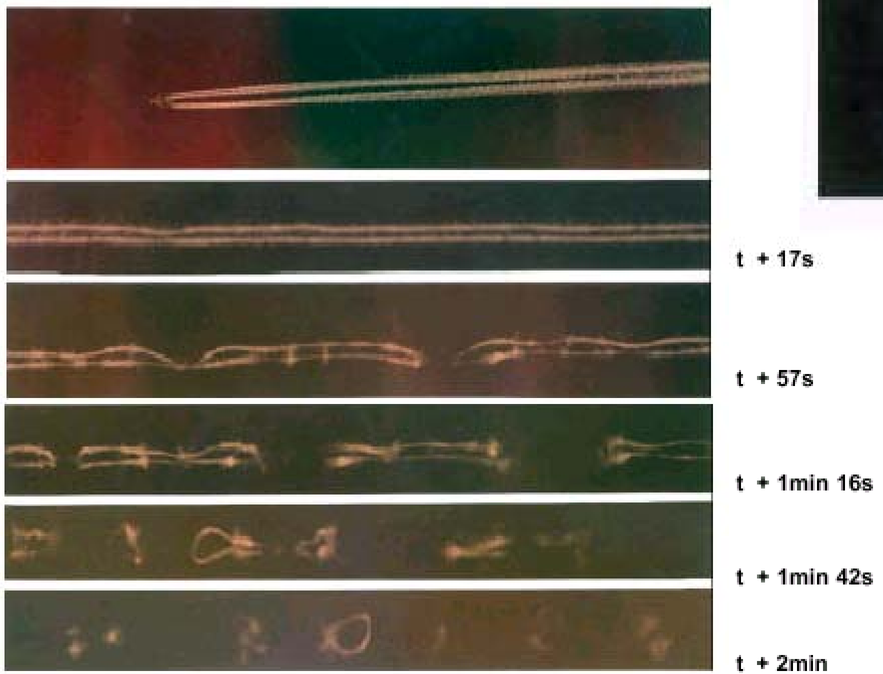




Example: Wing-Tip Vortex 1/7

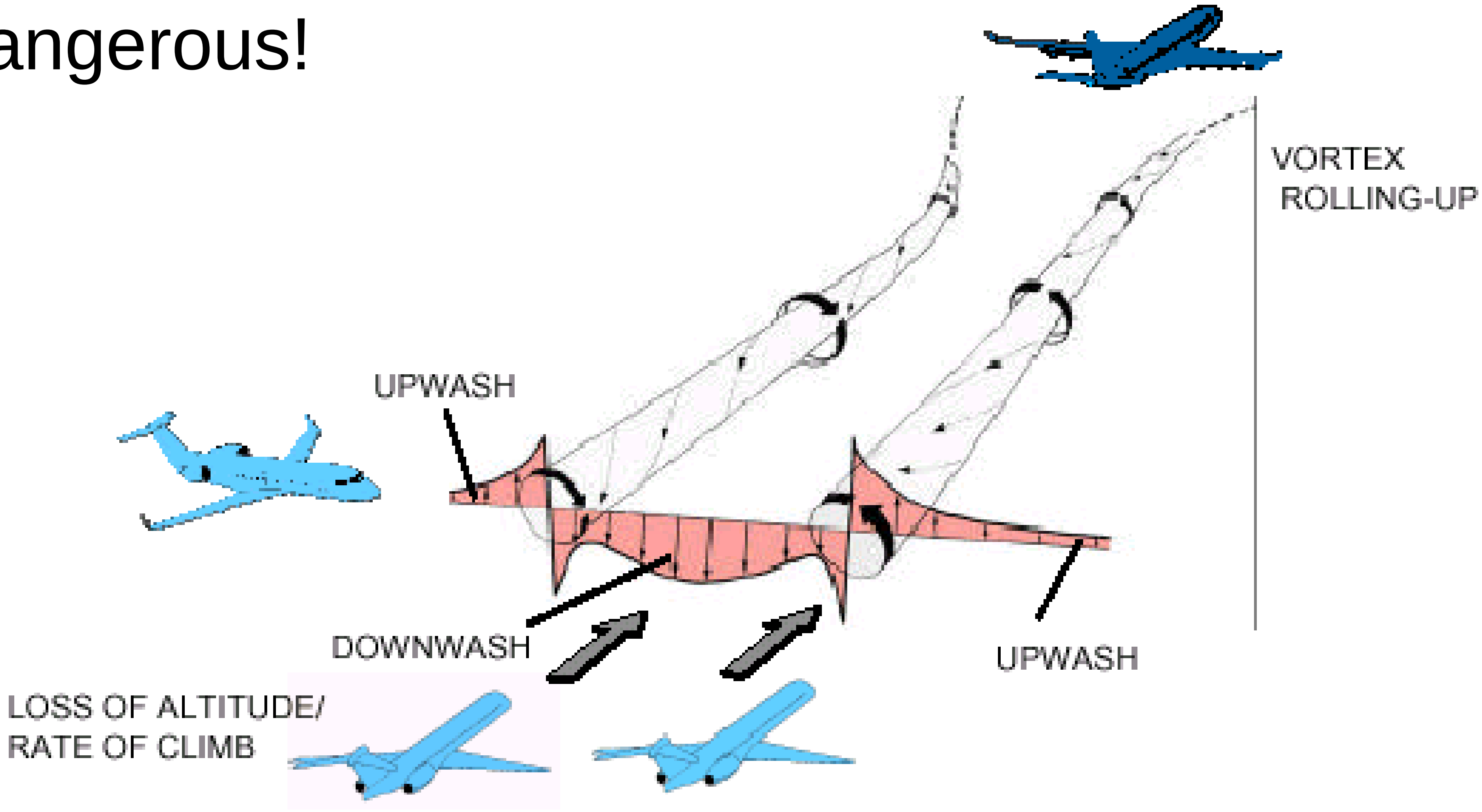
- Problem: Air behind airplanes is turbulent





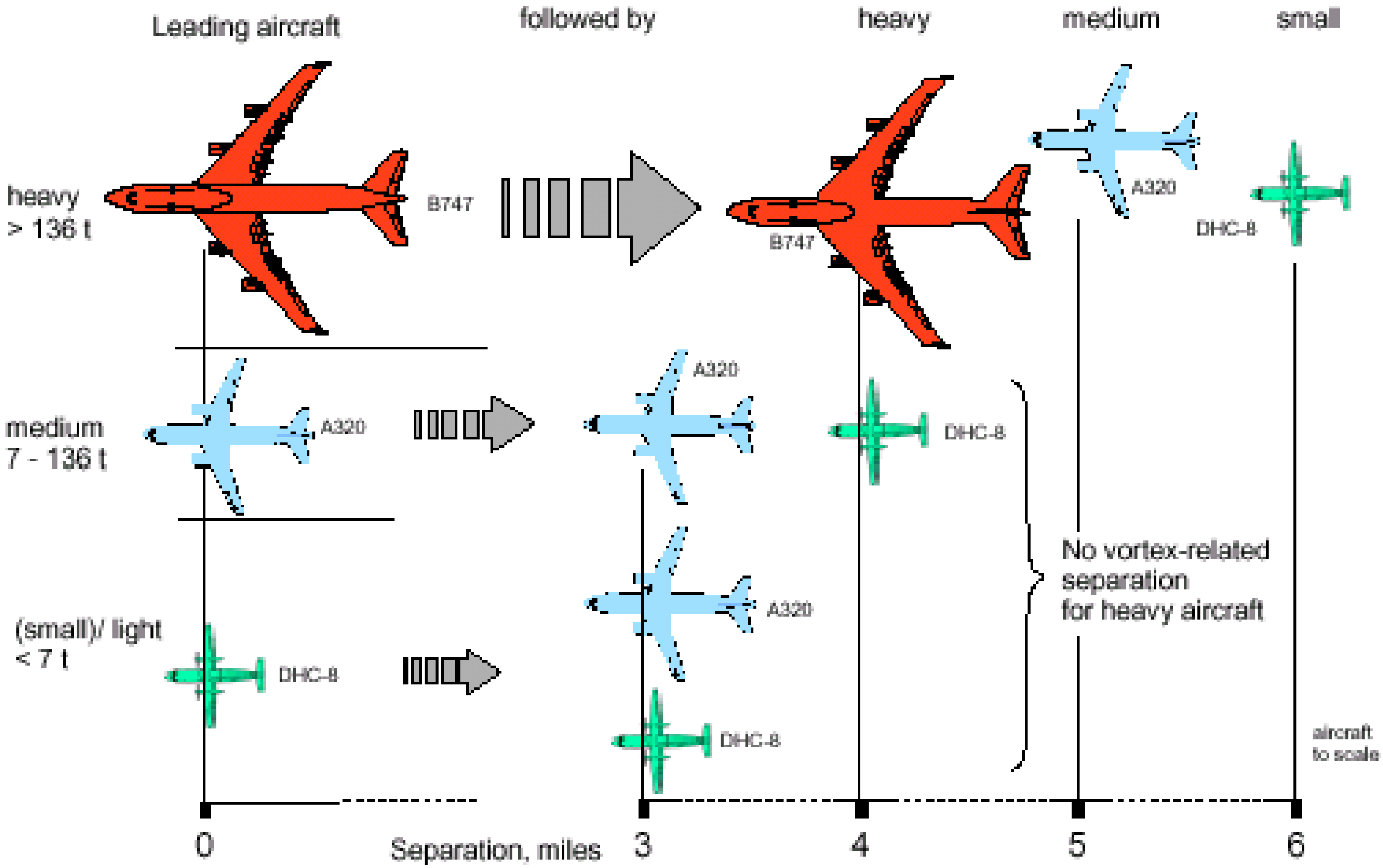
Example: Wing-Tip Vortex 2/7

- Vortex: dangerous!



Example: Wing-Tip Vortex 3/7

- Therefore: keep distance!



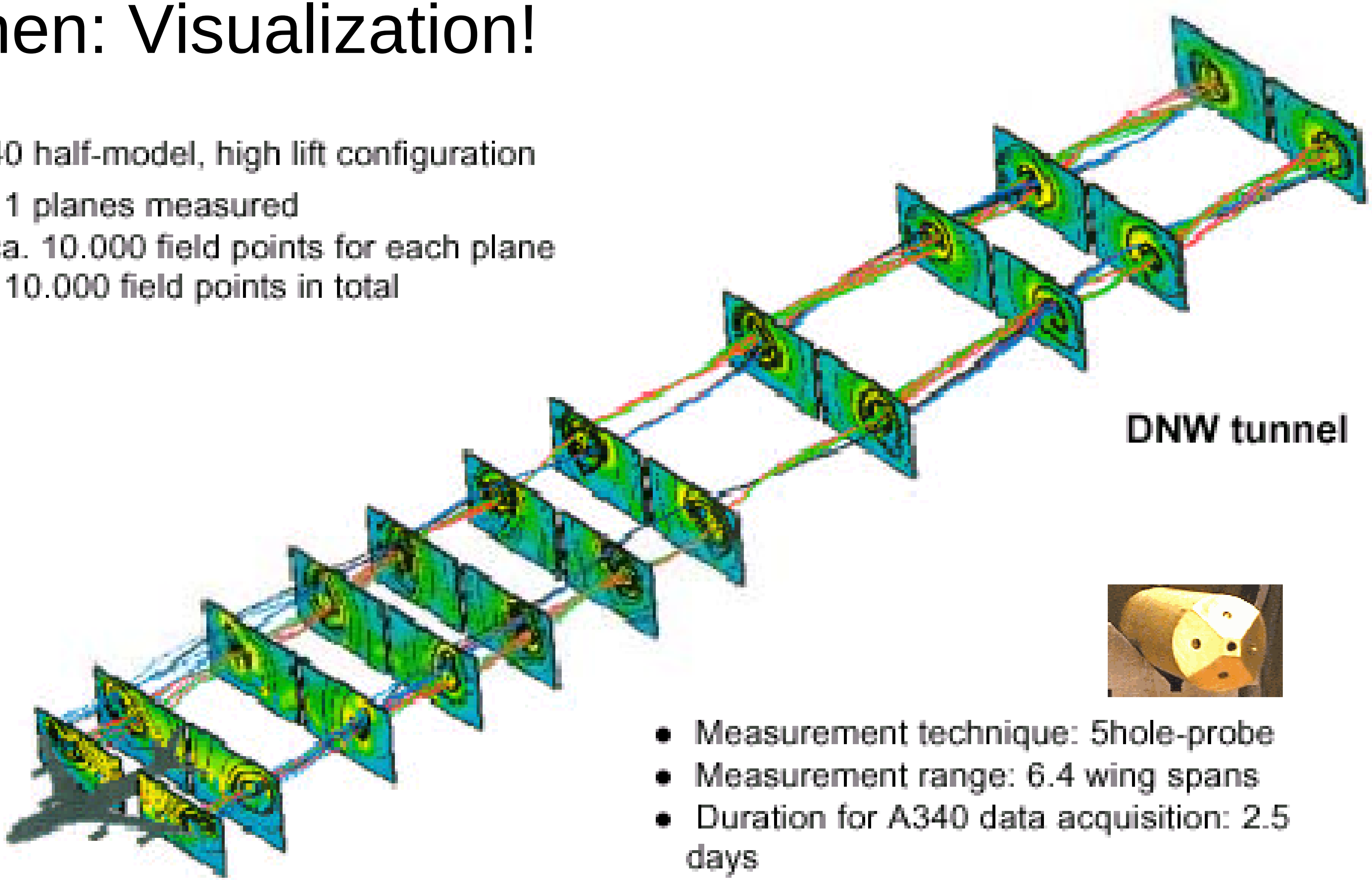
Example: Wing-Tip Vortex 4/7

- Tests in wind tunnel:

Then: Visualization!

A340 half-model, high lift configuration

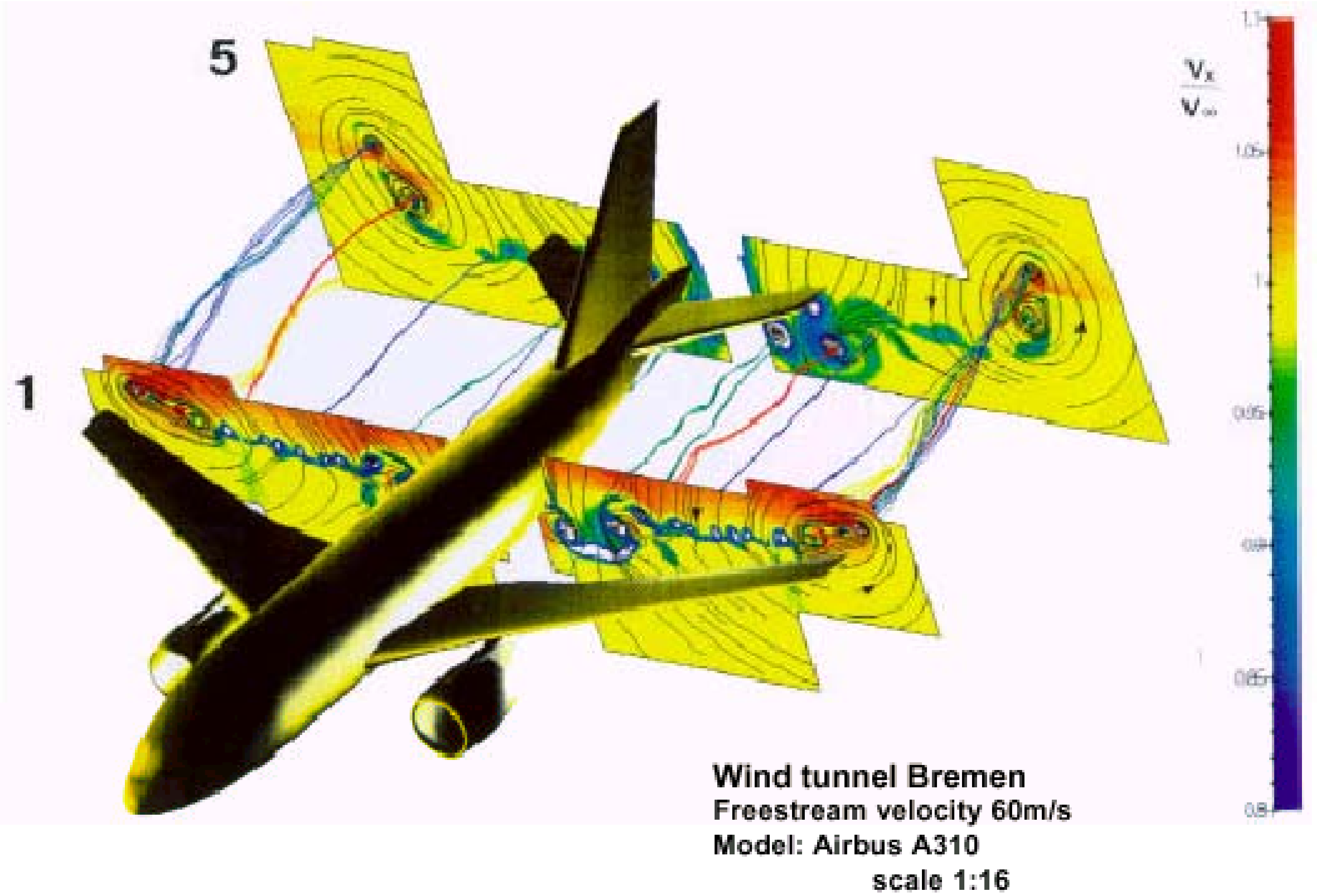
- 11 planes measured
- ca. 10.000 field points for each plane
- 110.000 field points in total



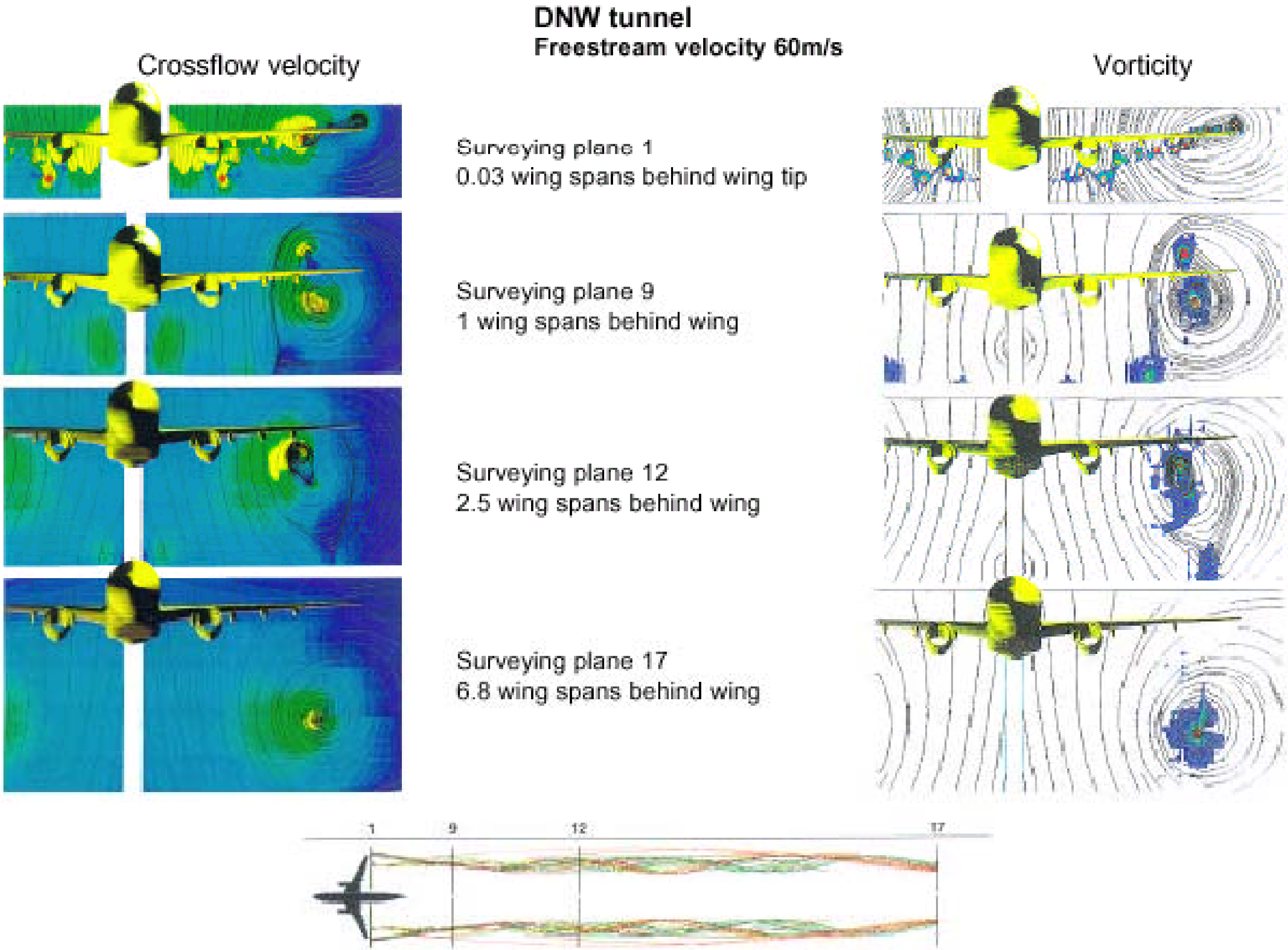
DNW tunnel

- Measurement technique: 5hole-probe
- Measurement range: 6.4 wing spans
- Duration for A340 data acquisition: 2.5 days

Example: Wing-Tip Vortex 6/7



Example: Wing-Tip Vortex 7/7

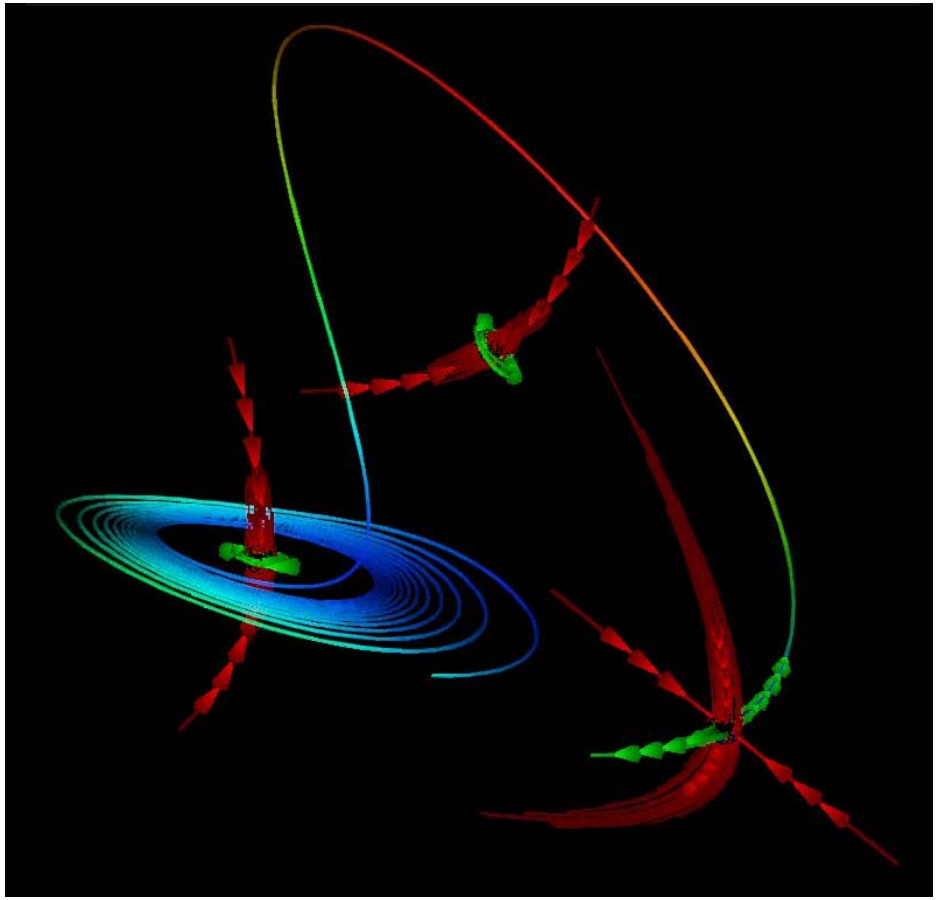


Visualization of Models

Dynamical Systems

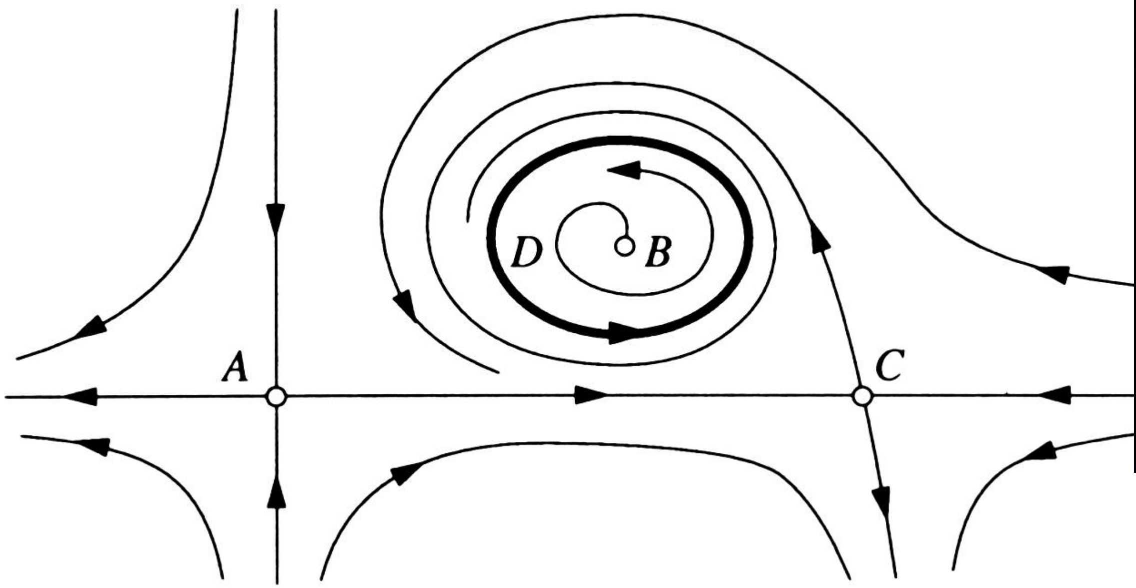
Dynamical Systems Visualization

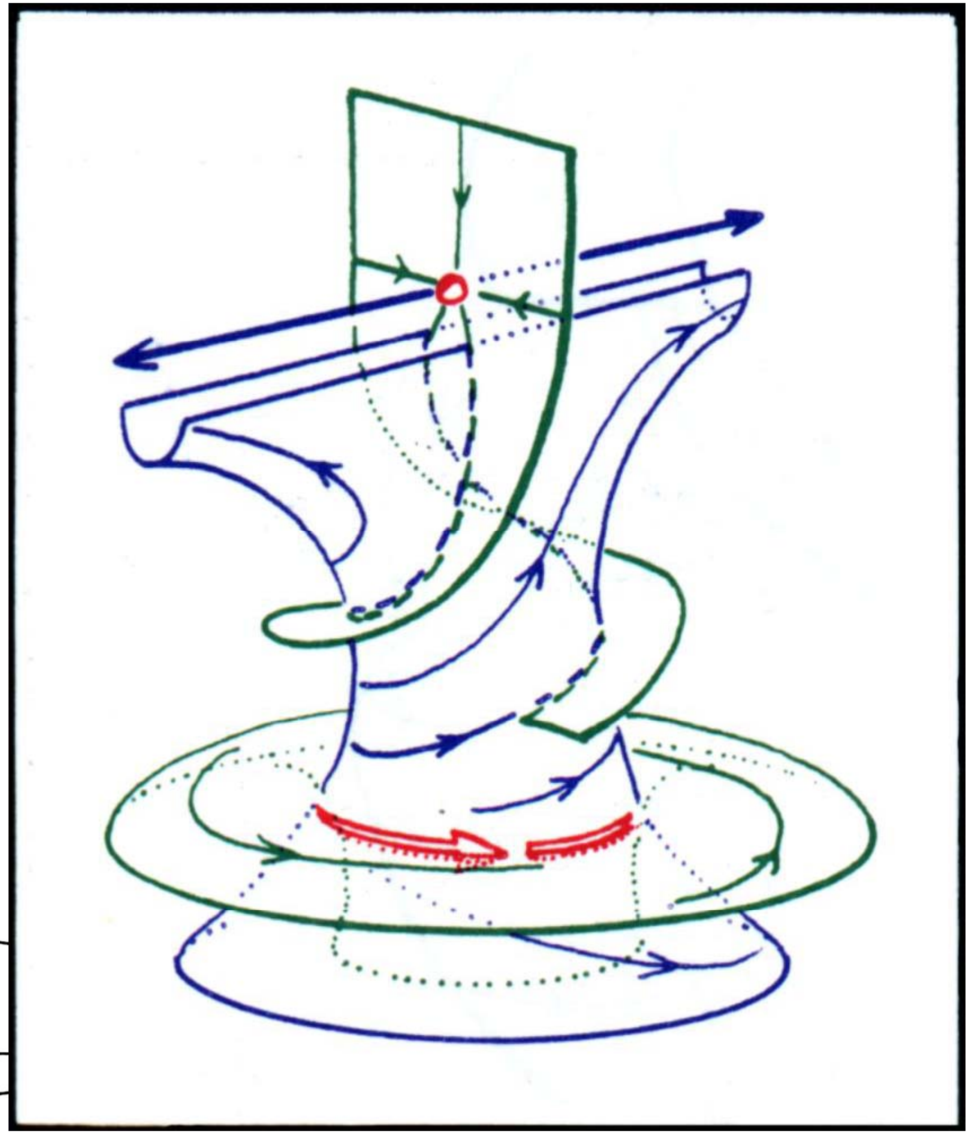
- Differences:
  - Flow analytically def.: $d\mathbf{x}/dt = \mathbf{v}(\mathbf{x})$
  - Navier-Stokes equations
  - E.G.: Lorenz-system:
    $dx/dt = \sigma(y-x)$
    $dy/dt = rx-y-xz$
    $dz/dt = xy-bz$
  - Larger variety in data:
    - 2D, 3D, nD
    - Sometimes no natural constraints like non-compressibility or similar



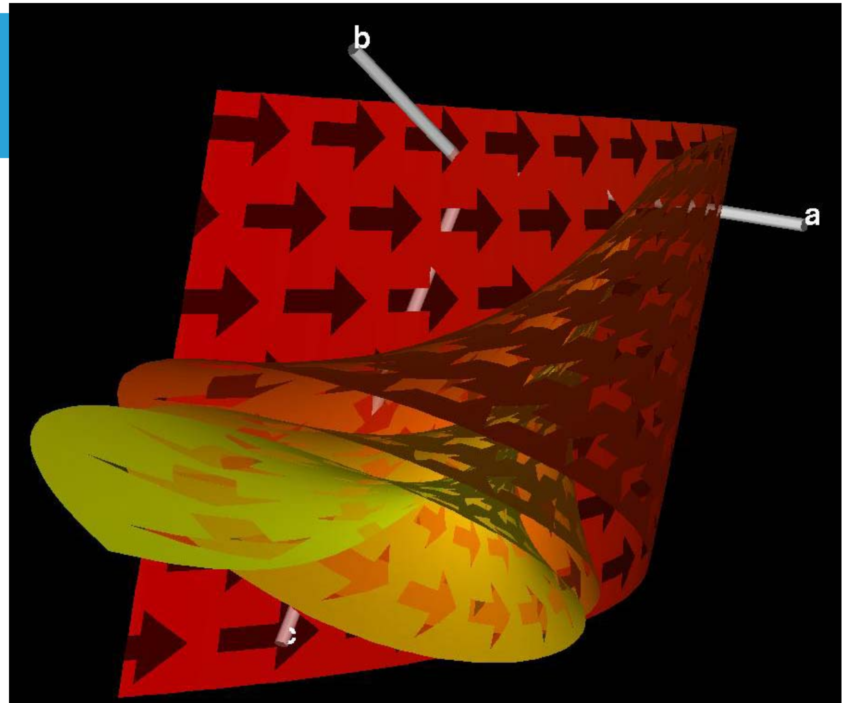
Visualization of Models

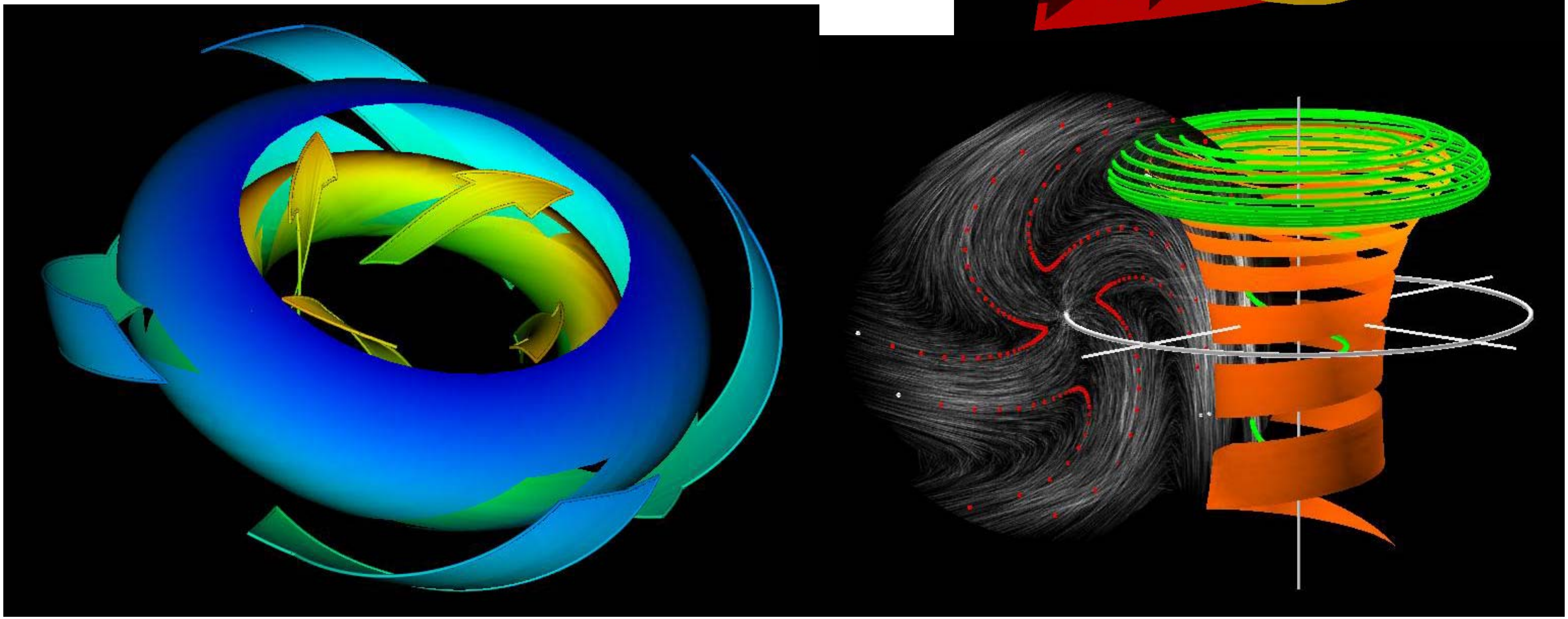
- Sketchy,
  “hand drawn”





Visualization of 3D Models



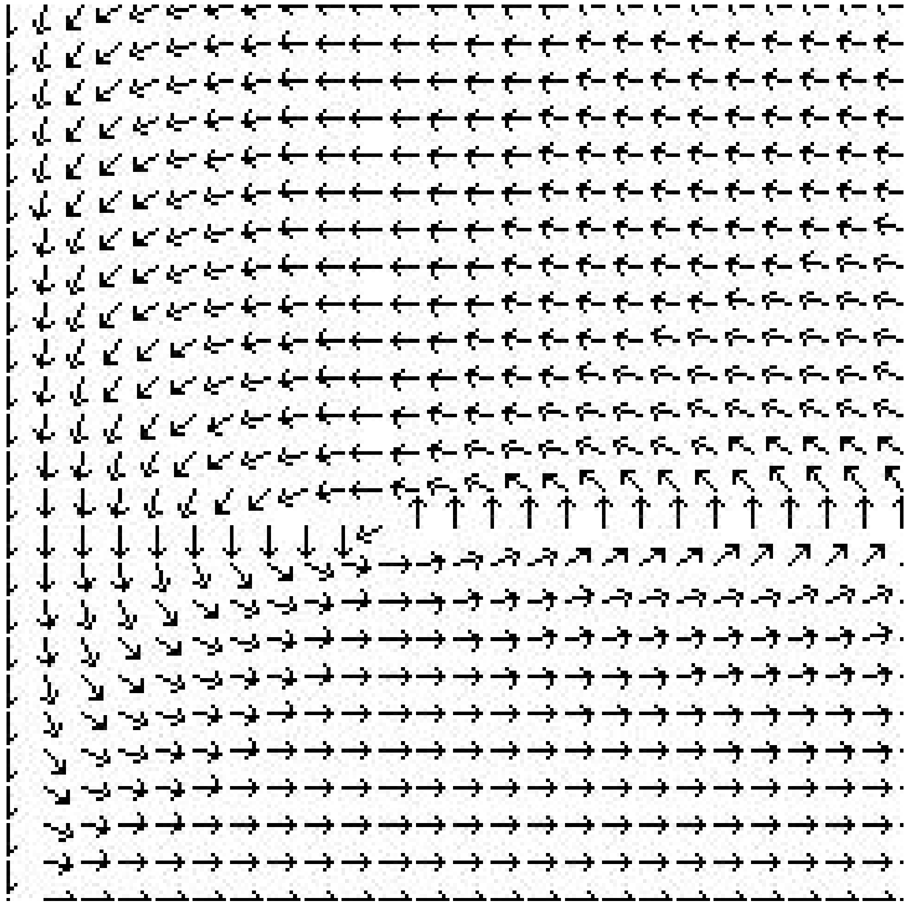


Flow Visualization with Arrows

Hedgehog plots, etc.

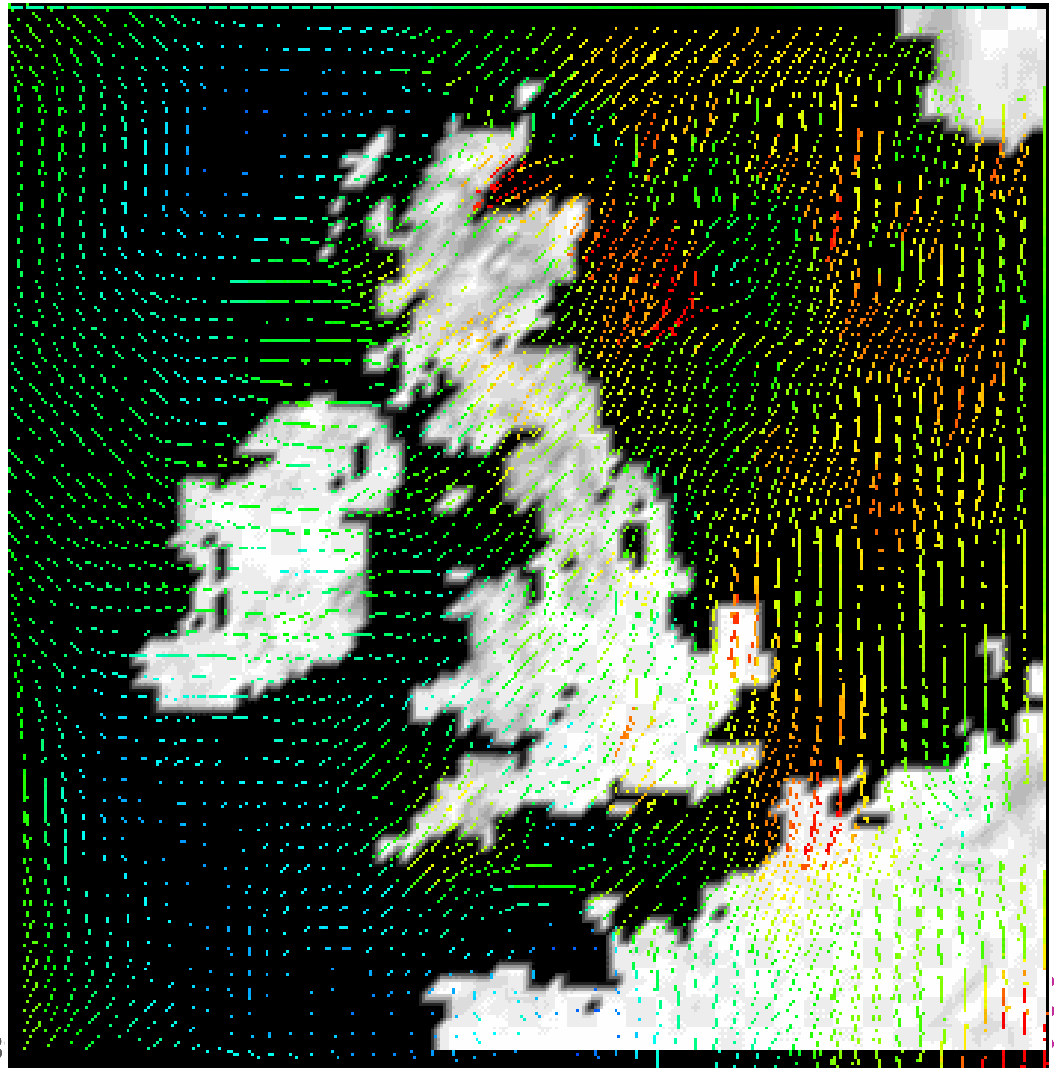
Flow Visualization with Arrows

- Aspects:
  - Direct Flow Visualization
  - Normalized arrows vs. scaling with velocity
  - 2D: quite usable, 3D: often problematic
  - Sometimes limited expressivity (temporal component missing)
  - Often used!



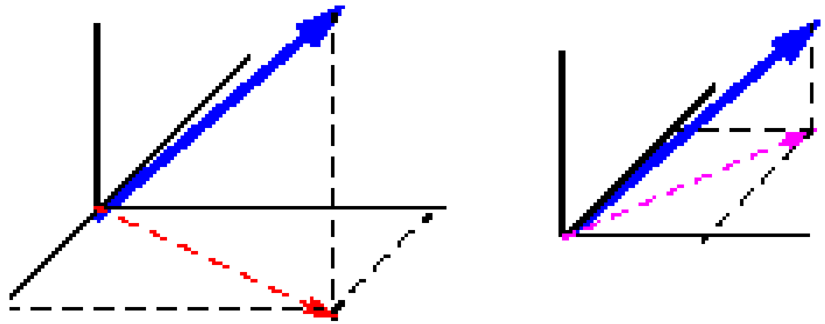
Arrows in 2D

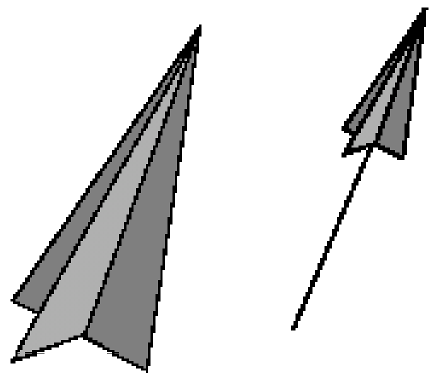
- Scaled arrows vs. color-coded arrows



Arrows in 3D

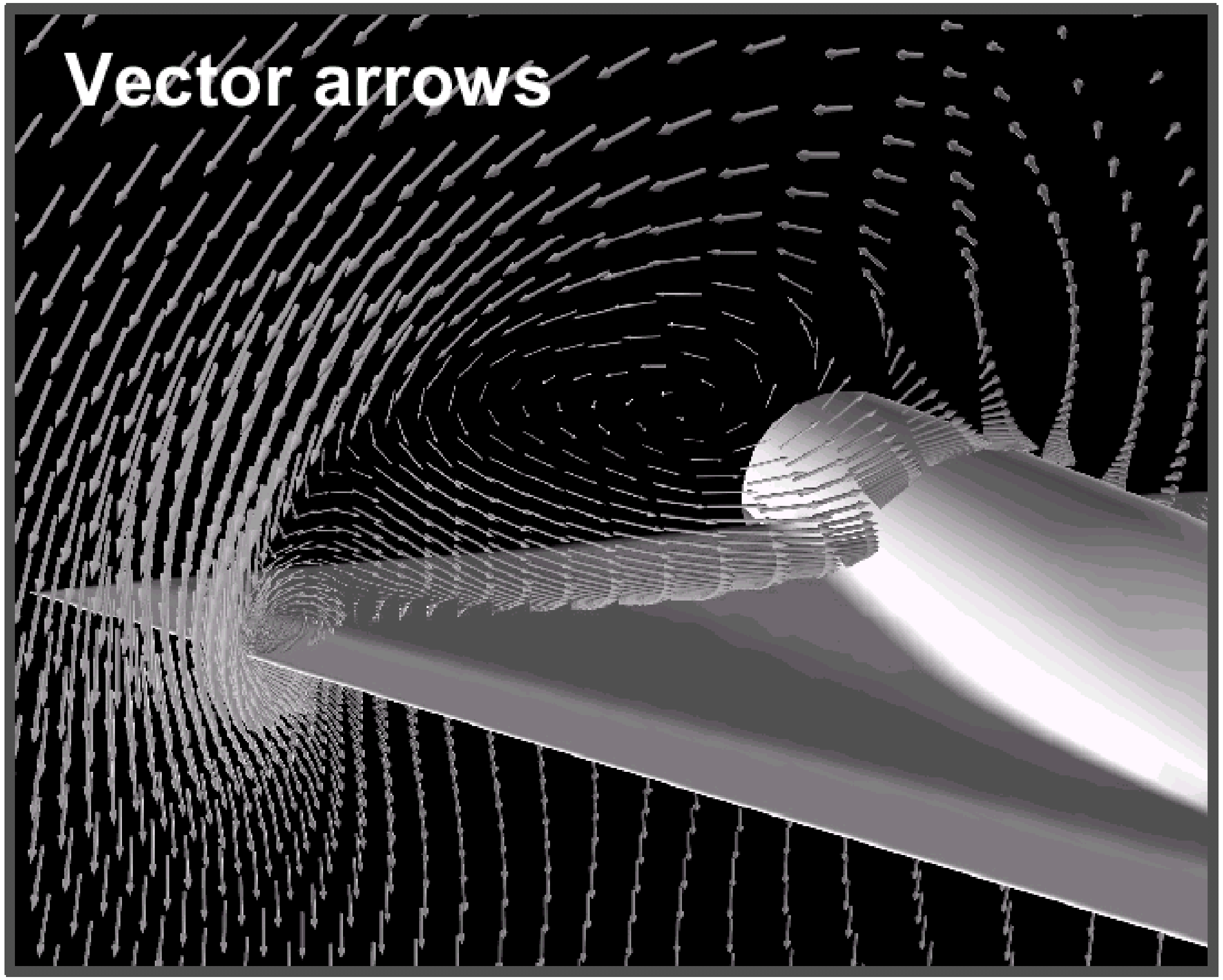
- Following problems:
  - Ambiguity
  - Perspective Shortening
  - 1D-objects in 3D: difficult spatial perception
  - Visual clutter
- Improvement:
  - 3D-arrows (help to a certain extent)

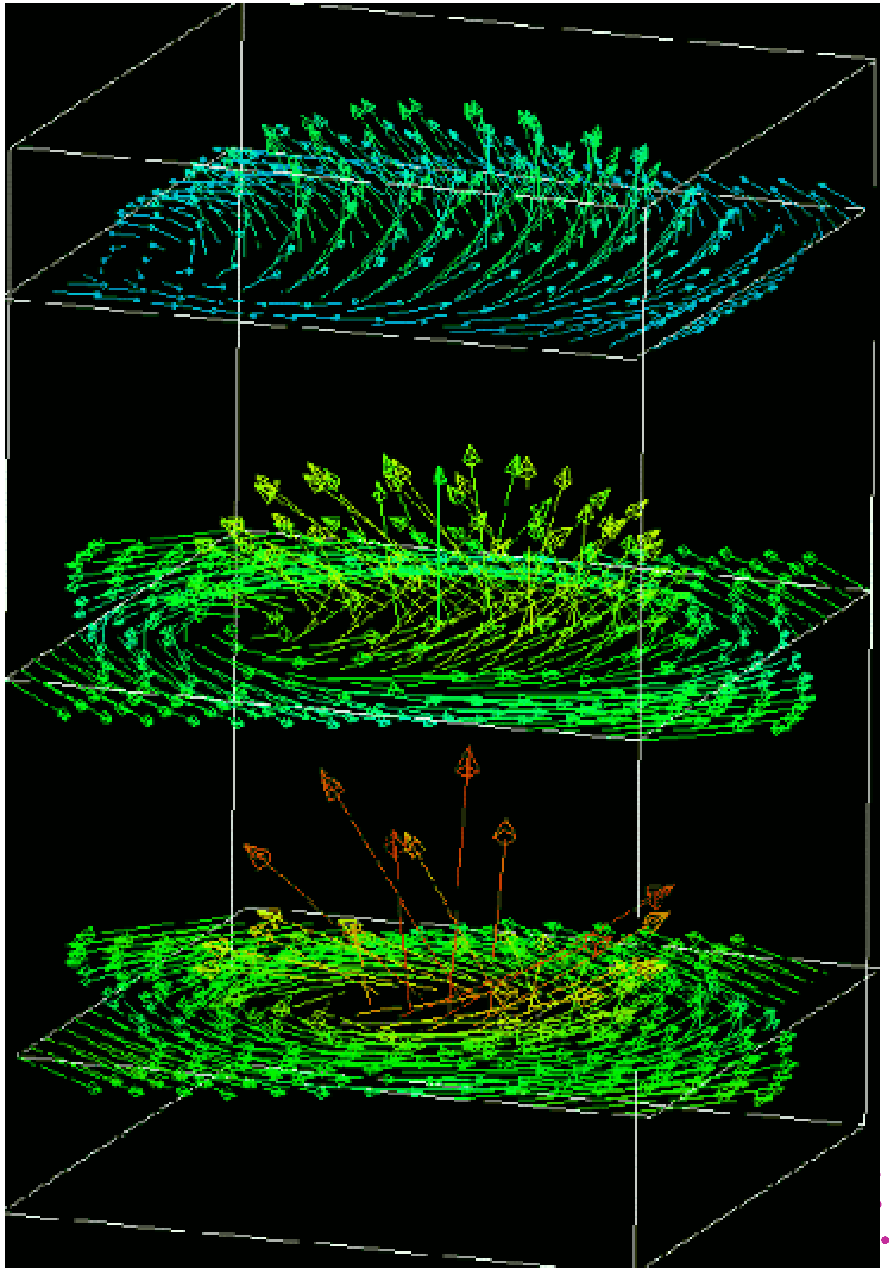




Arrows in 3D

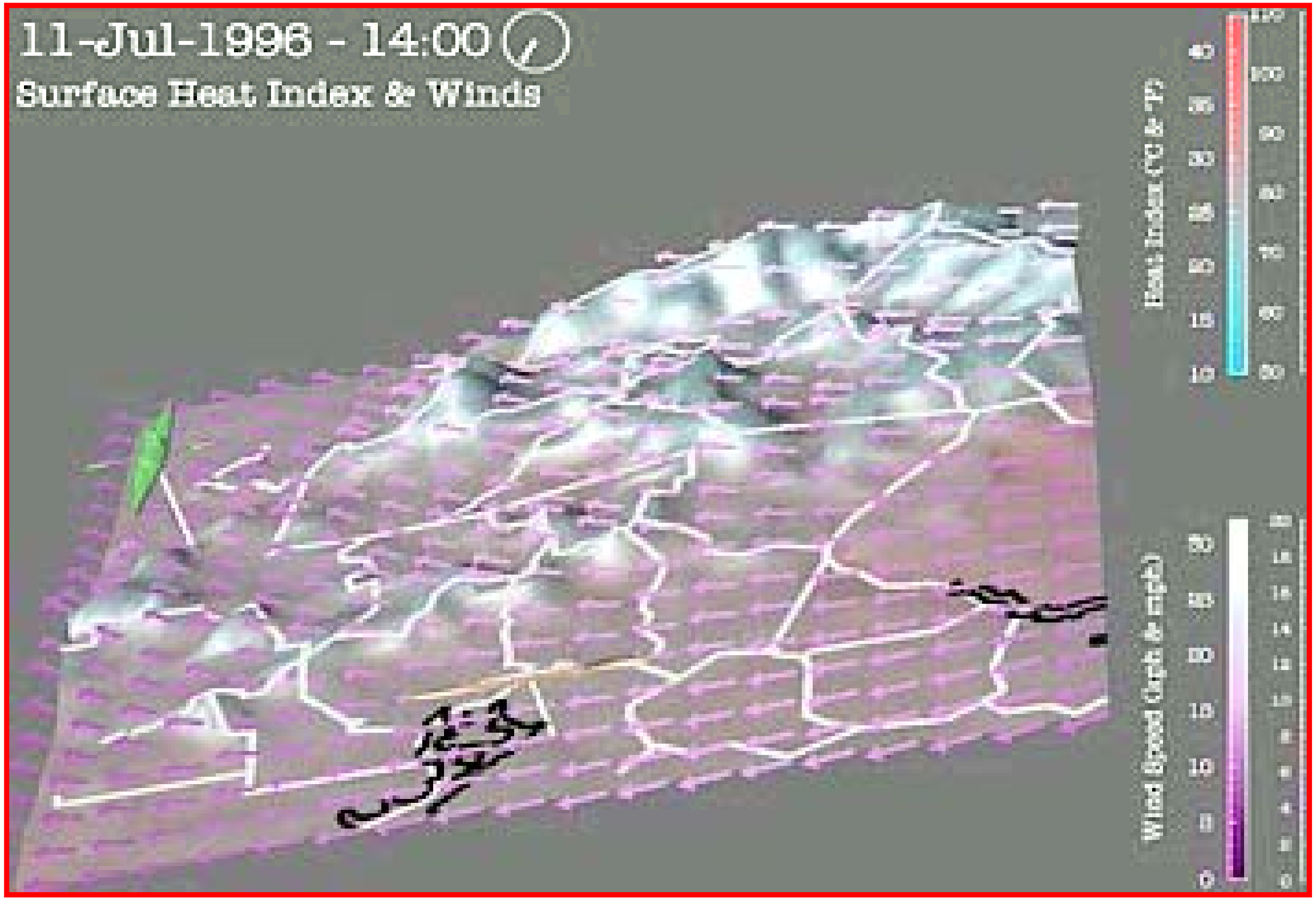
- Compromise:
  Arrows only in slices





Arrows in 3D

- Well integrable within “real” 3D:



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