Preliminary Study of Single Particle Lidar for Wing Wake Survey

M.Valla, B. Augère, D. Bailly, A. Dolfi-Bouteyre, E. Garnier, M. Méheut

ONERA

THE FRENCH AEROSPACE LAB

return on innovation

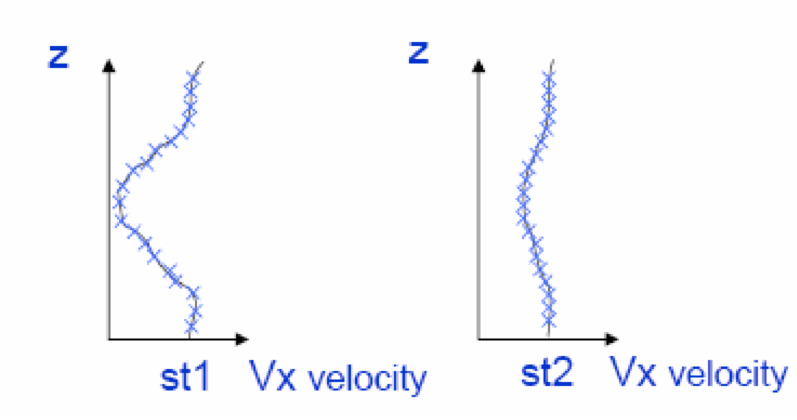
Context of research

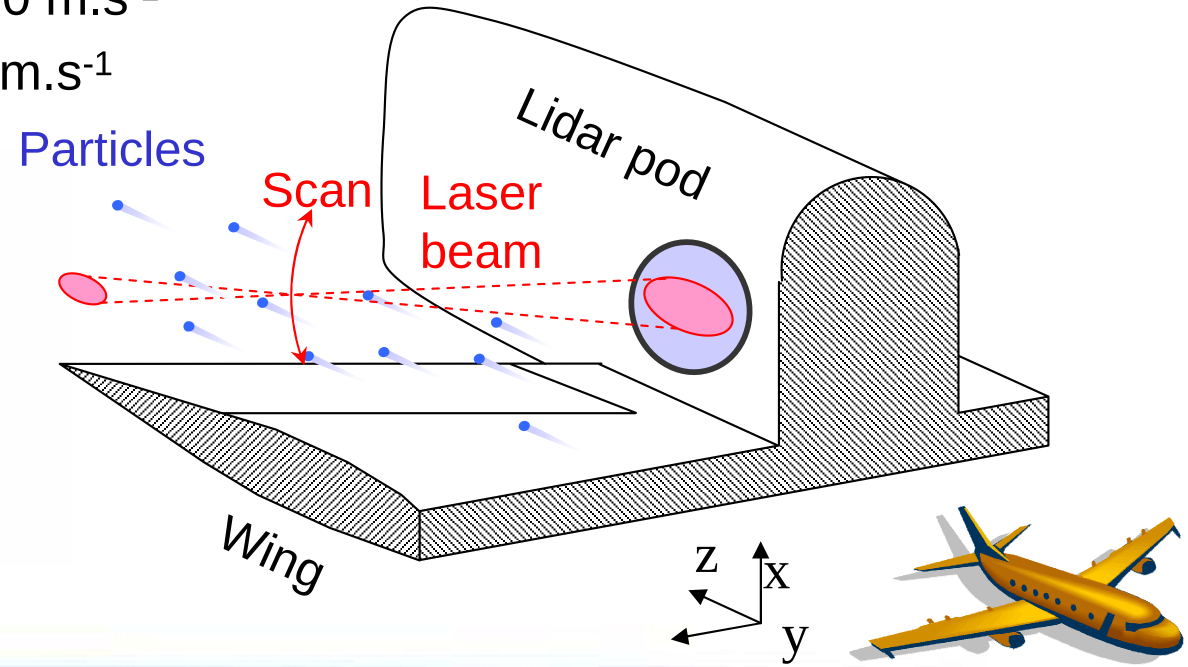
- Clean Sky Joint Technology Initiative :
  - Aims at reducing the environmental footprint of civilian aircraft & rotorcraft
  - Smart Fixed Wing Aircraft (SFWA) objectives:
    - 10 % reduction of aircraft drag (25 % reduction of wing drag)
    - 20 % reduction of fuel burn
    - 10 dB reduction of aircraft noise
  - Part of ONERA work is to evaluate the feasibility of coherent lidar for non intrusive in flight wing drag measurements
  - The following ONERA results have received funding from the European Community's Seventh Framework Program for the Clean Sky Joint Technology Initiative under grant agreement no SFWA-2008-001.

CLEANSKY
Joint Technology Initiative
for Aeronautics & Air Transport
www.cleansky.eu

Single Particle Lidar for Wing Wake Survey

- Lidar environment:
  - Atmosphere: high altitude, clear sky aerosols → Single particle coherent lidar
  - Wing wind field: steady flight parameters, highly turbulent flow in the wing wake (standard deviation of wake turbulence: 10 to 15% of mean speed)
- Measurements characteristics objectives:
  - Wing wake velocity profile: x component of flow velocity scanned along z axis
  - Measurement location: approx. 1 chord down stream of the wing trailing edge
  - Air velocity dynamic range: 200-250 $m.s^{-1}$
  - Air velocity accuracy objective ≈ 1 $m.s^{-1}$

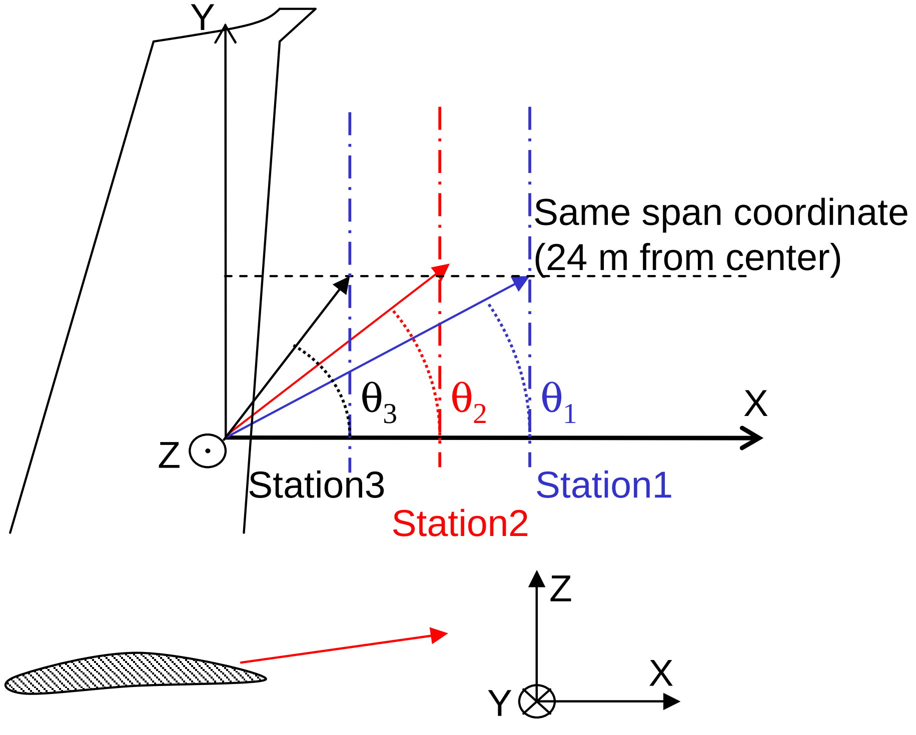




Lidar geometrical setup

- 3 stations with respect to the wing trailing edge
- Laser beam focused at range F_T and orientated with θ angle compared to aircraft tail to nose direction in the XY plane

Station 1 (1.5 chord); θ_1=29.2°; F_T=5.6m
Station 2 (1 chord); θ_2=41.2°; F_T=4.1m
Station 3 (0.5 chord); θ_3=63.4°; F_T=3.04m

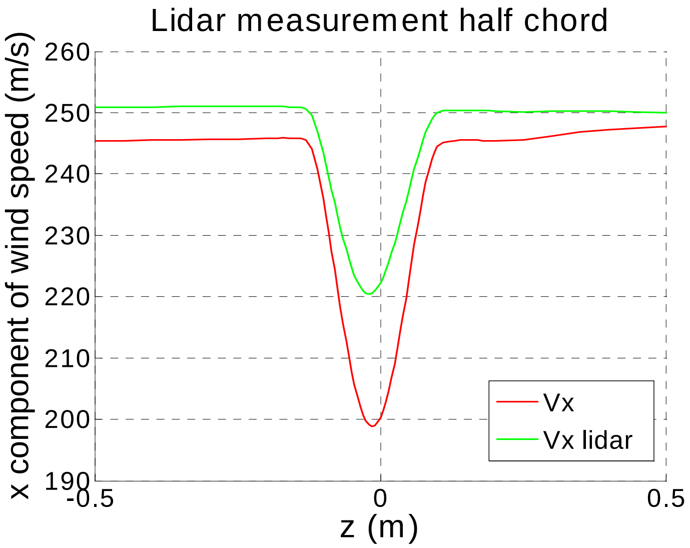


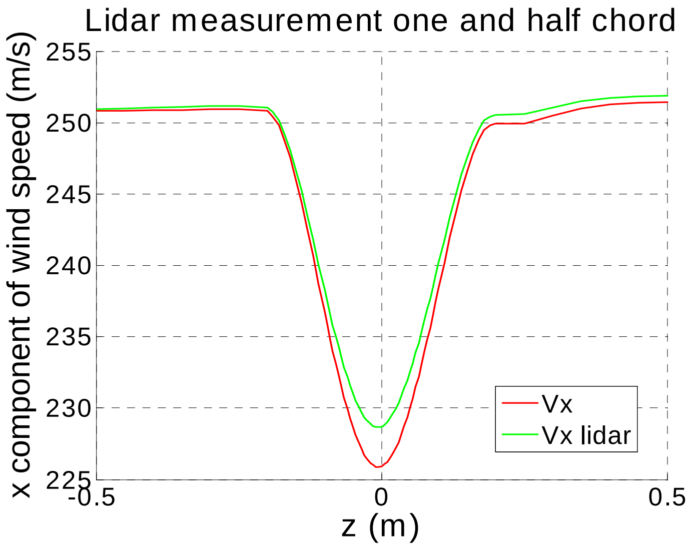
For each station, the laser probe carries out a scan in the vertical Z axis to describe the Wind field Vx :

γ_{scan}=±8°(±0.5m @ station 2)

Impact of lidar geometry

- Lidar velocity bias assessment:
  - Lidar measurement = radial velocity, not x component of air velocity
  - Non zero y and z component of air velocity → Lidar measurement bias
  - Higher bias at 0.5 chord, lower bias at 1.5 chord
- Simulations of lidar bias from 2.5D Elsa RANS (Reynolds-Averaged Navier Stokes) computed data



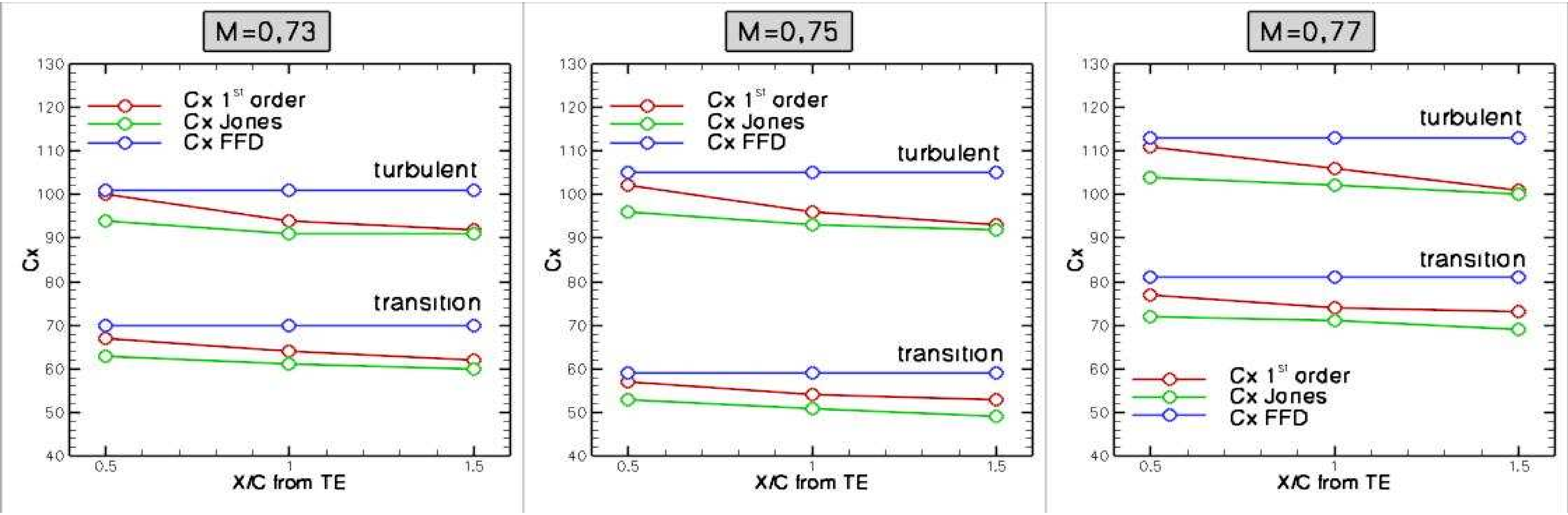


- Drag extraction assessment
  - Fast Fluids Dynamics Code for RANS computed data
  - 1st order and Jones formulations for Lidar data

Drag extraction : FFD / LIDAR comparison

	Mach	***Fast Fluids Dynamics Code***	***LIDAR*** ***Cx 1st order*** ***Cx Jones*** ***x/c = 0,5 / 1,0 / 1,5***
Transition	0,73	70	67 / 64 / 62 63 / 61 / 60
	0,75	59	57 / 54 / 53 53 / 51 / 49
	0,77	81	77 / 74 / 73 72 / 71 / 69
Turbulent	0,73	101	100 / 94 / 91 94 / 91 / 91
	0,75	105	102 / 96 / 93 96 / 93 / 92
	0,77	113	111 / 106 / 101 104 / 102 / 100
Turbulent - Transition	0,73	31 (31%)	33 (33%) / 30 (32%) / 29 (32%) 31 (33%) / 30 (33%) / 31 (34%)
	0,75	46 (44%)	45 (44%) / 42 (44%) / 40 (44%) 43 (45%) / 42 (45%) / 43 (47%)
	0,77	32 (28%)	34 (31%) / 32 (30%) / 28 (28%) 32 (31%) / 31 (30%) / 31 (31%)

FFD / LIDAR : Results



- Convergence of both experimental methods in the wake (1.5 chords)
- Maximum difference between CFD and experimental methods : 3%

Lidar efficiency

Flow turbulence:

- Standard deviation of 40 $m.s^{-1}$ in turbulent area (15% of mean flow speed inside the wake)
- Standard deviation of 5 $m.s^{-1}$ in less turbulent area (out of wake)

Single particle lidar measurement accuracy bounded by the flow turbulence:

→ Lidar accuracy ≈ standard deviation of flow / square root of particles detected

Lidar detection efficiency = Number of detection per second

Aerosol density ranging from 1 to 5 $part.cm^{-3}$

A priori fixed parameters:

- Laser power P_L = 5W: available "on the shelf", compact and its consumption is compatible with onboard operation
- Lidar footprint → Beam radius ≤ 35 mm

Lidar efficiency without aero-optic effects

Beam radius choice:

- Lidar detection efficiency = Number of detection per second
- Tradeoff between measurements at different chords : 0.5chord, 1chord, 1.5chord

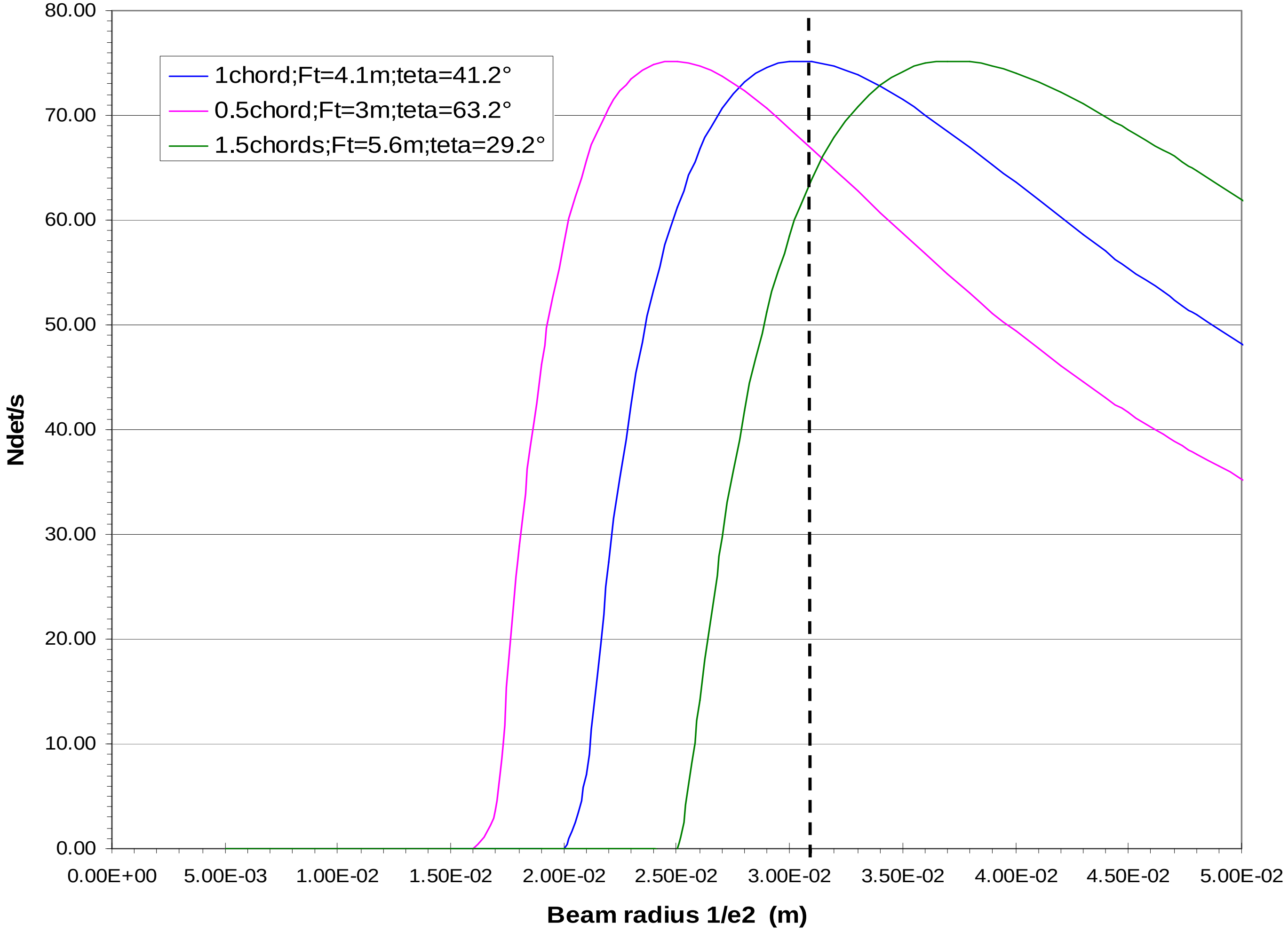
Optimal beam radius on pupil: 31mm

- 67 part/s at 0.5chord
- 75 part/s at 1 chord
- 64 part/s at 1.5 chords

@ 1 particle per cm³

- 335 part/s at 0.5chord
- 375 part/s at 1 chord
- 320 part/s at 1.5 chords

@ 5 particle per cm³



Preliminary evaluation of the aero-optic effects

- Air density fluctuations lead to refractive index fluctuations (Gladstone Dale law)

  $n_1 = K\rho$

- Expected effects: beam propagation in turbulent medium
  - focused spot larger
  - loss of lidar performance in terms of detection per second

  → Preliminary assessment of aero optical effects required

- Two regions of interest
  - Boundary layer on the pod
  - Wake

- Flow conditions: altitude=40000 ft, Ma=0.77, turbulent case

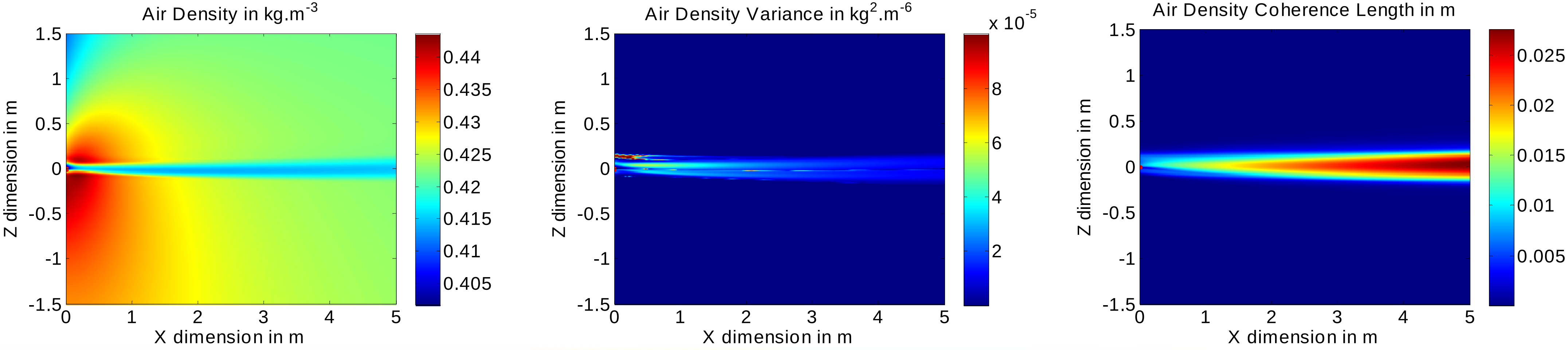
- On the pod (boundary layer): a simple model
  - Variance of the density: $\sigma_\rho^2 = [A(\rho_{wall} - \rho_{ext})]^2$ with A=0.2
  - Correlation length of the density fluctuation: $L_\rho = 0.1 \times \text{layer thickness} = 5\text{ mm}$

Preliminary evaluation of the aero-optic effects

- On the wake: a k-Ω stationary computation on a infinite wing
  - Air density (direct output)
  - Air density variance (from Aupoix formulae, only valided in boundary layer)

$$\sigma_\rho = \frac{k}{\mathrm{Pr}_t{}^2}\left(\frac{\left(\frac{d\rho}{dz}\right)}{\left(\frac{du}{dz}\right)}\right)^2$$

  - Air density coherence length (assumed to be equal to wind coherence length reconstructed from a turbulence integral length scale with k and Ω)



Preliminary evaluation of the aero-optic effects

- Objective: Finding an equivalent refractive index structure parameter C_n^2 (optical propagation of laser beam is well described with the knowledge of C_n^2)

- Assumptions:
  - Air density is an isotropic random filed described with a spatial spectrum model
  - Air density has a Von Kármán like spatial spectrum without inner scale

$$\Phi_{n_1}(k) = \frac{K^2 \sigma_\rho^2 \Gamma(11/6)}{\left(2\pi L_0^2\right)^{1/3} \Gamma(3/2)\Gamma(2/6)} \left(k^2 + 4\pi^2 L_0^{-2}\right)^{-11/6}$$

  - Value of the Gladstone Dale constant K of 0.22 10^{-3} $m^3.kg^{-1}$, given at sea level pressure and temperature (no data given at flight level 400)

- Identification with Von Kármán spectrum yields:

$$\hat{C}_n^2 = \frac{(2\pi)^{5/3} K^2 \sigma_\rho^2 \Gamma(11/6)}{\sin(\pi/3)\Gamma(8/3)\Gamma(3/2)\Gamma(2/6) L_0^{2/3}}$$

Preliminary evaluation of the aero-optic effects

- From RANS computed data:
  - Air density coherence length → Outer scale of turbulence retrieved from 3D Fourier transform of spectrum
  - Outer scale of turbulence & Air density variance → value of refractive index structure parameter C_n^2

- Turbulent wing wake flow → $C_n^2 = 3.4\ 10^{-12}\ m^{-2/3}$ highly turbulent medium

- Impact of refractive index turbulence on laser propagation proportional to lidar range:
  → Higher aero optical penalty expected at 1.5 chord

Power budget modeling with aero-optic effects

Aero optical effects:

- Worst case: entire optical path inside the wing wake
- Measurements at different chords : 0.5, 1 & 1.5 chord, impact of turbulence higher with distance

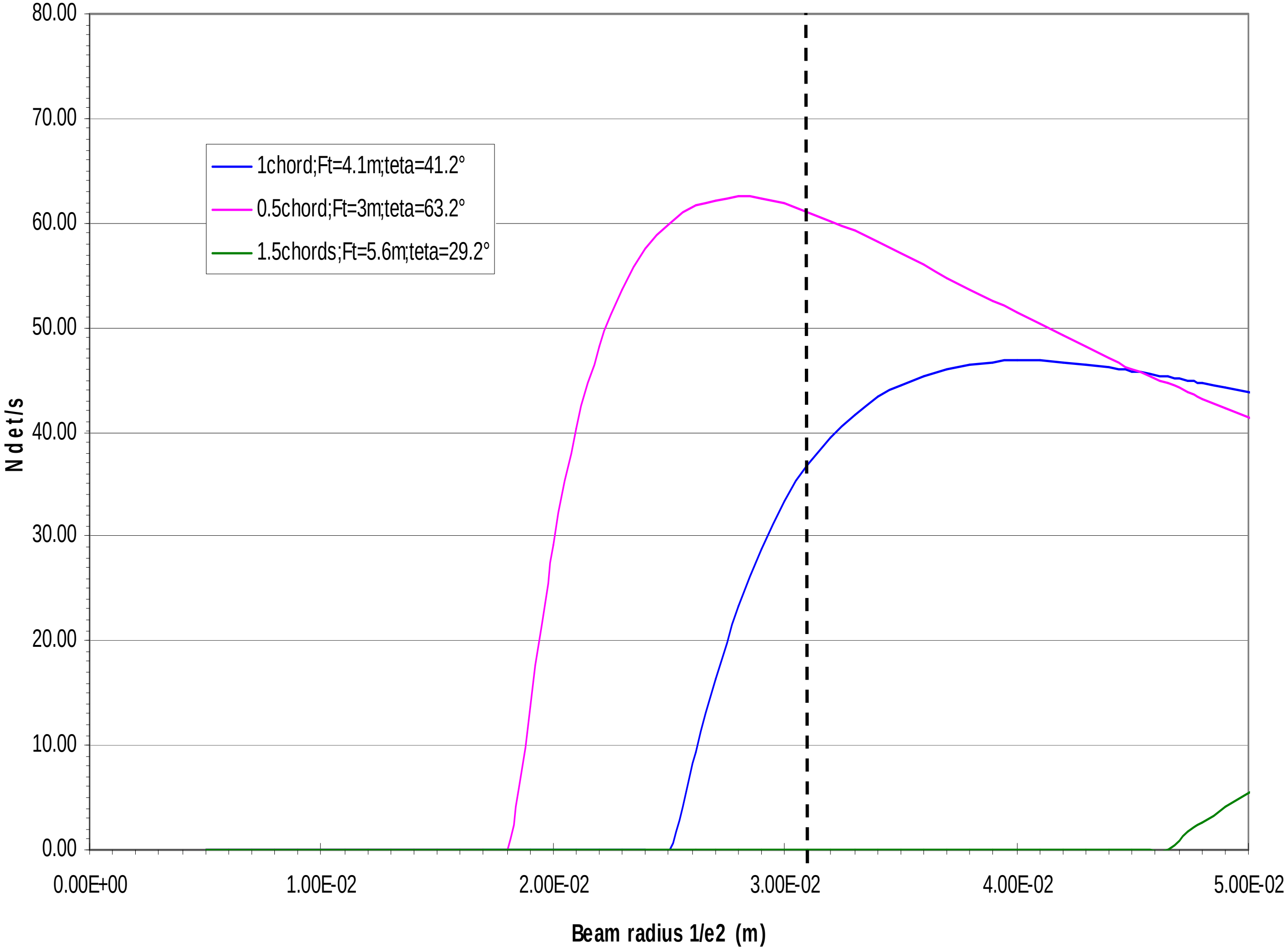
At previous beam radius on pupil: 31mm

- 62 part/s at 0.5chord
- 37 part/s at 1 chord
- 0 part/s at 1.5 chords

@ 1 particle per cm^3

- 310 part/s at 0.5chord
- 185 part/s at 1 chord
- 0 part/s at 1.5 chords

@ 5 particle per cm^3



Conclusion

A preliminary study of a single particle lidar for wing wake survey has shown two main issues:

- Biased x component of flow velocity due to geometrical constrains
- Presence of aero-optic effects due to the nature of the flow to be analyzed

Bias assessment shown that lidar data are relevant for drag extraction

Aero-optic effects estimated impact for measurements in the wing wake:

- Reasonable risk for measurements at 0.5 chord
- High risk for measurements at 1 chord
- No measurement possible at 1.5 chord
- Presence of uncertainties in the model (ex.: Gladstone Dale constant value)

Single particle lidar for wing wake survey still has to go through a proof of concept phase