

## Applications aéronautiques des lidars vent

**A. Dolfi-Bouteyre , C. Besson, B. Augère, M. Valla**



retour sur innovation

# Applications aéronautiques des lidars vent

## Senseurs de navigation

- **mesure de vitesse air 1 point, 3 composantes**
  - ④ **Mie multiparticules**
  - ④ **Mie monoparticules**
  - ④ **Rayleigh**

## Senseurs d'alertes

- **Au sol**
  - ④ **Turbulence de sillage / wake vortex**
  - ④ **Cisaillements / rafale ( « wind hazard » )**
- **Embarqués**
  - ④ **Turbulence de sillage /wake vortex**
  - ④ **Cisaillements / rafale / Turbulence en air clair**

# Applications aéronautiques des lidars vent

## Applications aéronautiques des lidars vent

### Senseurs de navigation

- **mesure de vitesse air 1 point 3 composantes**
  - Mie multiparticules
  - Mie monoparticules
  - Rayleigh

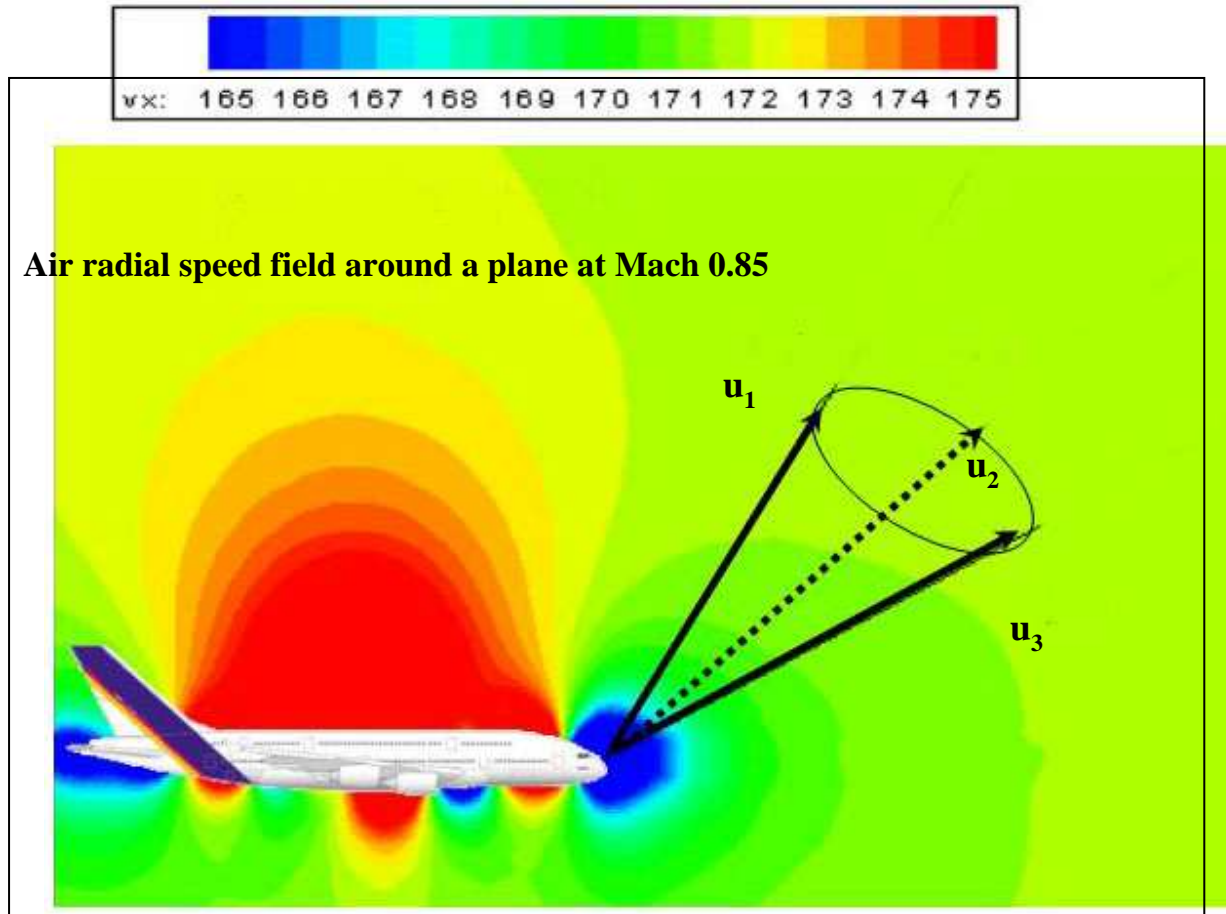
### Senseurs d'alertes

- **Au sol**
  - Turbulence de sillage / wake vortex
  - Cisaillements / rafales
- **Embarqués**
  - Turbulence de sillage /wake vortex
  - Cisaillements / Turbulence en air clair

### Applications éoliens des lidars vent

- **Caracterisation de site**
- **Optimisation des turbines**

# Principe de l'anémométrie laser

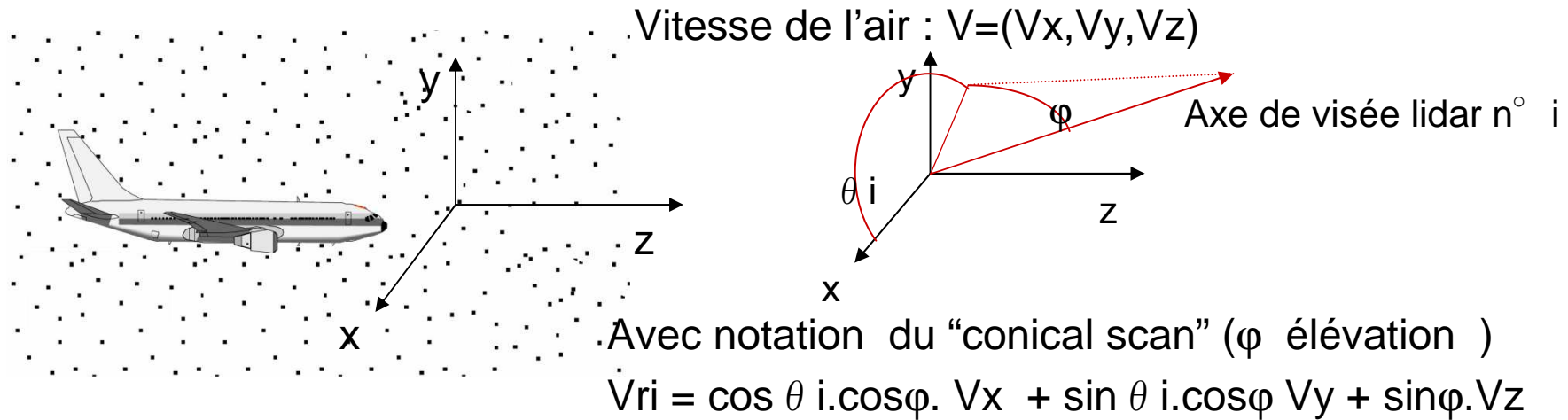


Source : J-L Hantrais-Gervois, Aerodynamics Department, ONERA

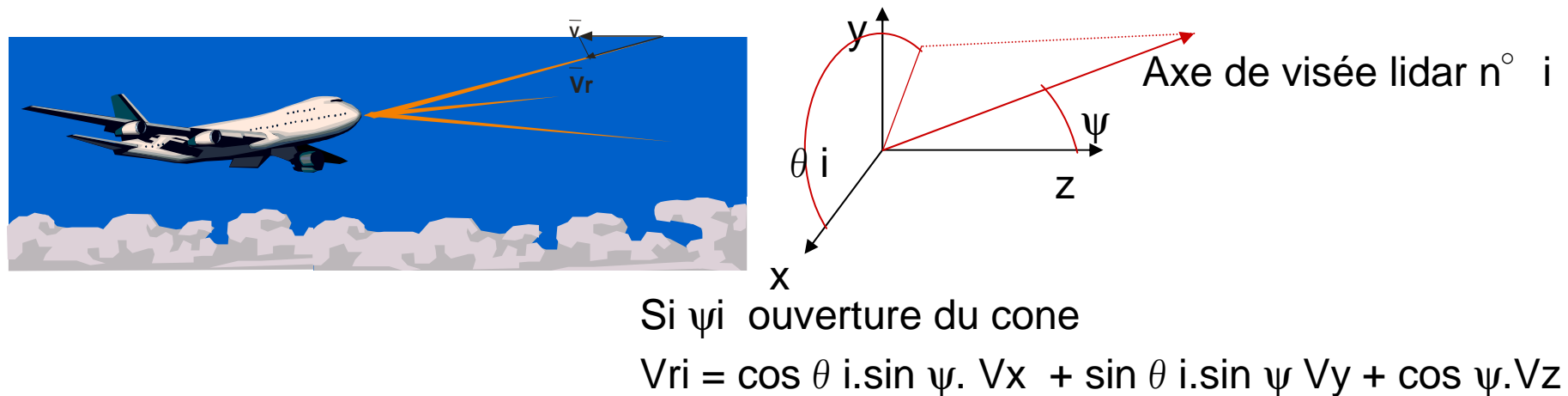
Mesure à 50 m dans un flux non perturbé  
Ou mesure à quelques mètres et on corrige

# Principe de l'anémométrie laser :

Vitesse de l'air :  $V=(V_x, V_y, V_z)$



Avec notation du "conical scan" ( $\phi$  élévation )

$$V_{ri} = \cos \theta_i \cdot \cos \phi \cdot V_x + \sin \theta_i \cdot \cos \phi \cdot V_y + \sin \phi \cdot V_z$$


Si  $\psi_i$  ouverture du cone

$$V_{ri} = \cos \theta_i \cdot \sin \psi_i \cdot V_x + \sin \theta_i \cdot \sin \psi_i \cdot V_y + \cos \psi_i \cdot V_z$$

$$V_{ri} = M_i \cdot V$$

3 inconnues  $\rightarrow$  3 axes de visée lidar minimum ( $i \geq 3$ )

## Principe de l'anémométrie laser : erreur de mesure en fonction du nombre d'axe de mesures

si  $y = A * x$  alors

variance sur  $y$  :  $\text{var}(y) = A.^2 * \text{var}(x)$  ,

ici on a  $V_r = M * V$

avec  $V$  le vecteur vitesse ( $v_x, v_y, v_z$ )

$V_r$  la matrice des vecteurs vitesse radiales des  $n$  axes ( $V_{r1}, \dots, V_{rn}$ ).

$M$  : matrice ( $n * 3$ )

$V = (M.'*M)^{-1} * M.' * V_r$  ( $M.'$  est la matrice transposée )

alors  $\text{var}(v) = ( (M.'*M)^{-1} * M.' )^2 * \text{var}(V_r)$

Critere de choix des angles :

- besoin de reconstruction du vecteur  $\rightarrow$  plus l' angle est ouvert, moins il y a d'erreur
- Homogeneité du volume de mesure
- Dynamique de mesure de l'instrument

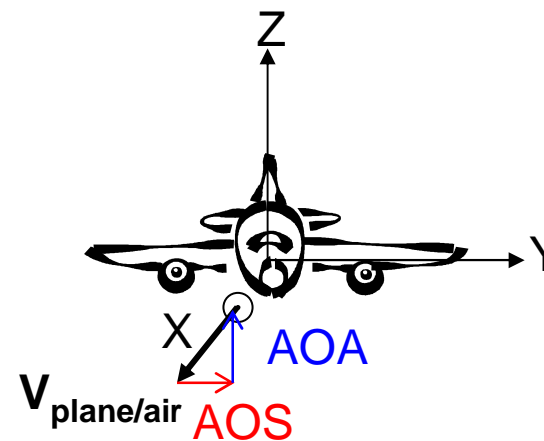
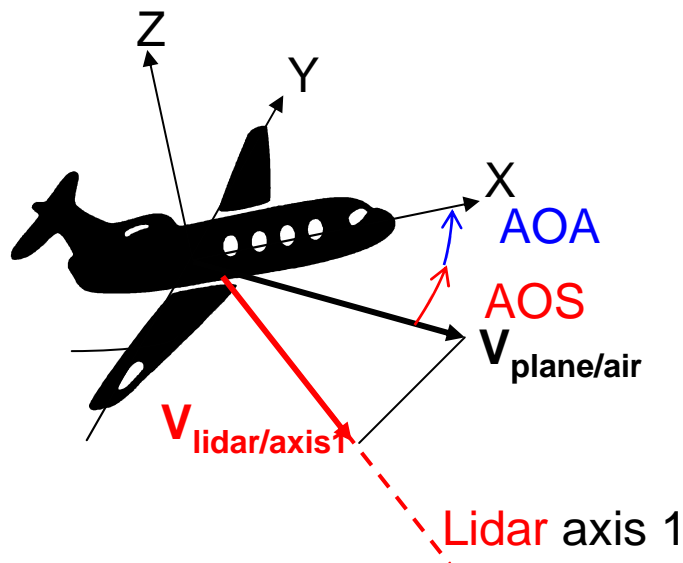
# Flow Field Measurements: lidar anemometer for flight test certification

## ➤ Aircraft data requirements for certification process given by Lidar measurement

- Angle of Attack is deduced from air speed components the XZ plane
- Angle of Sideslip is the angle between  $V_{\text{plane/air}}$  and the XZ plane
- Static error correction is deduced from full air speed vector

$$AOA = \tan^{-1}(V_z/V_x)$$

$$AOS = \tan^{-1}\left(V_y/\sqrt{V_x^2 + V_z^2}\right)$$



# lidar anemo multiparticules Alev (Thales)

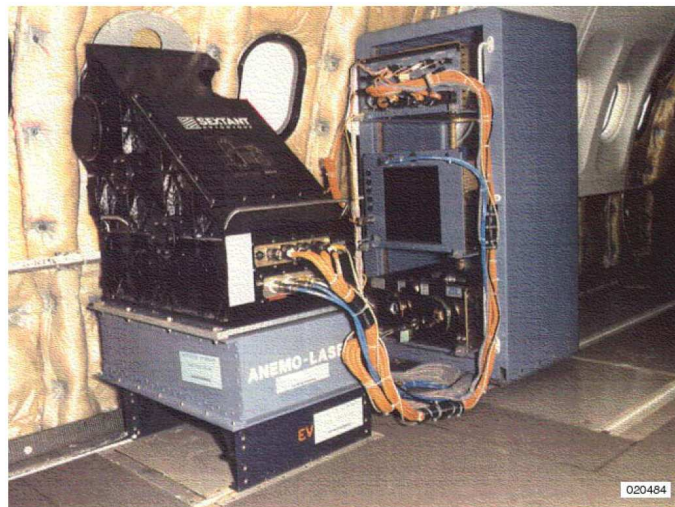
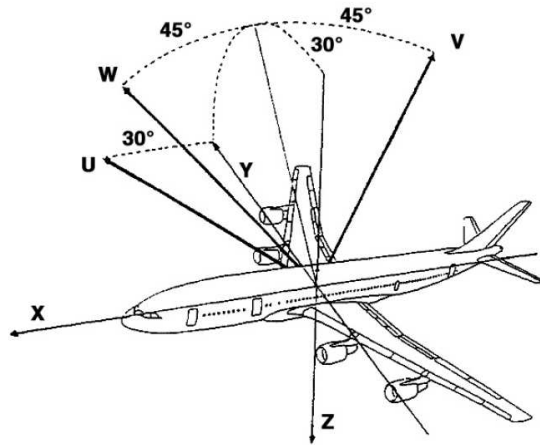


Figure 7-2: Installation of ALEV 3 system in the Airbus A340.

Table 7-1: Characteristics of the ALEV 3 system.

Factor	Detail
anemometer type	reference-beam laser anemometer
laser	CO <sub>2</sub> gas laser
wavelength	10.6 μm
operating mode	continuous wave (cw)
power	5 Watts
detection	coherent mode using a HgCdTe detector cooled to 77 K
detector cooling	Thompson cooling, expansion of pressurized nitrogen gas
measurement	vector true airspeed (TAS) angle of attack (AoA), and angle of sideslip (AoS)
focal distance	between 50 and 100 m
velocity range	10 m/s to 400 m/s
altitude range	up to FL 250 without signal loss, at FL 250 to FL 350 signal is occasionally lost because of insufficient atmospheric backscatter
TAS uncertainty	0.25 m/s (including system and installation uncertainties)
update rate	2, 4, or 8 measurements per second (measurements in the three directions are taken intermittently)
format	ARINC 429
physical characteristics	
scanning	scanning mirror
size (optical unit)	0.75 x 0.5 x 0.75 m
weight (optical unit)	70 kg
developed by:	Crouzet, Sextant, Thales

Source : “optical air flow measurement” (OTAN)



## ORIENTATIONS TECHNOLOGIQUES :

### TECHNOLOGIE 1.5 $\mu\text{m}$

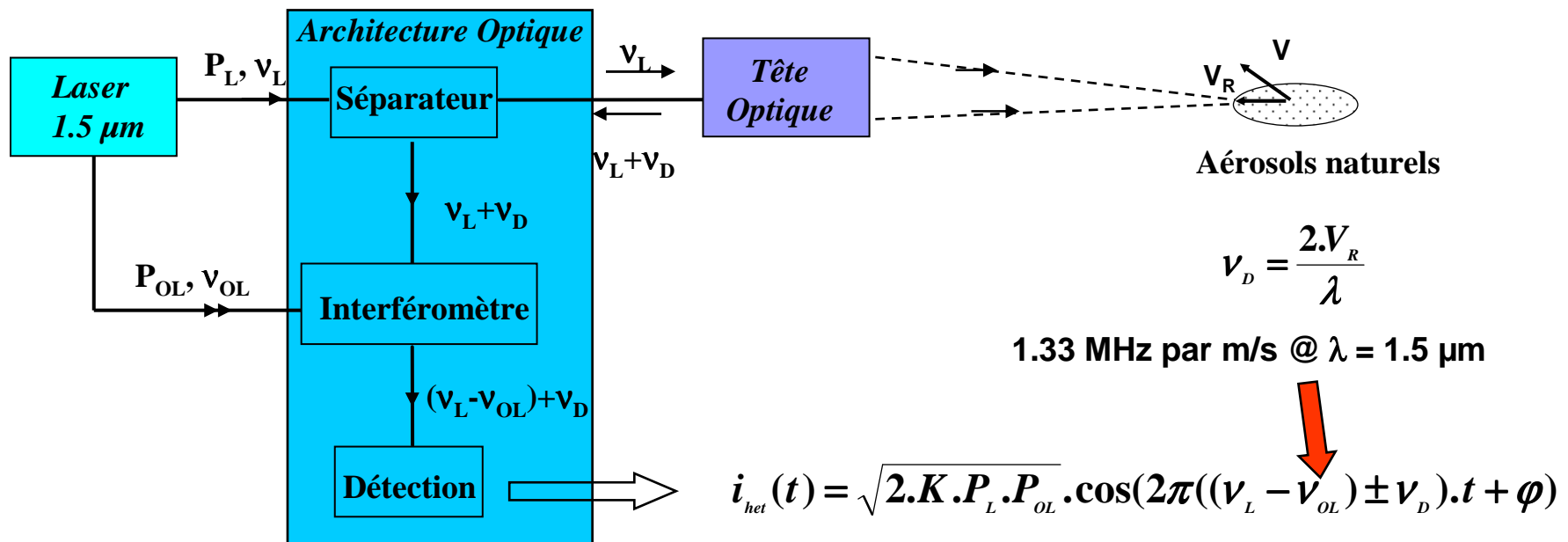
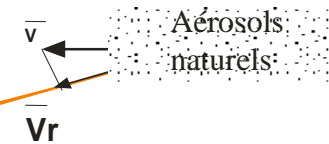
#### **SOURCE : Laser fibré Erbium**

- très bonnes qualités spectrale et spatiale
- sécurité oculaire
- bonne transmission atmosphérique
- compacité et fiabilité
- utilisation de composants fibrés

#### **ARCHITECTURE OPTIQUE FIBREE :**

- composants fibrés performants et bas coût
- facilité d'utilisation et de réglage
- compacité et fiabilité

# Anémométrie laser 1.5 μm aéroportée



## Anémométrie laser 1.5 $\mu\text{m}$ aéroportée

**DALHEC** : collaboration Onera / Thales Avionic

Realiser une sonde anémométrique 1.5  $\mu\text{m}$  embarqué sur hélicoptère

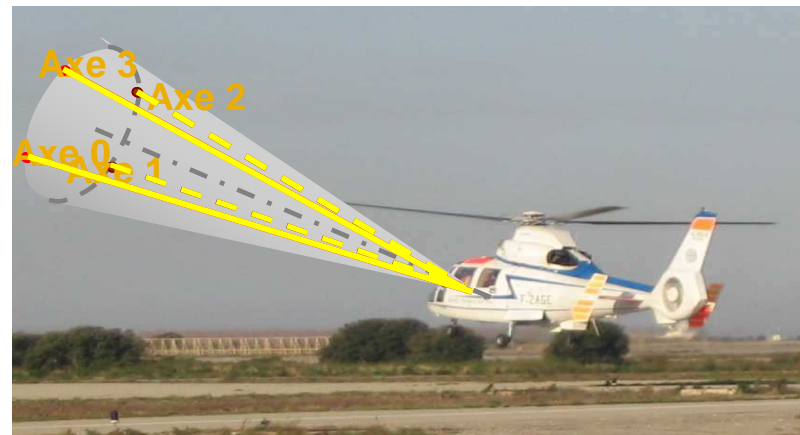
Avantage par rapport aux sondes pneumatiques classiques :

⇒ Vitesse air absolue (référence primaire)

⇒ Très bonne précision dans tout le domaine de vol

⇒ Technologie 1.5 $\mu\text{m}$  compacte, fiable et à sécurité oculaire

⇒ Sonde non intrusive




Sondes pitot : erreur 2 m/s et perturbé par le rotor à faible vitesse

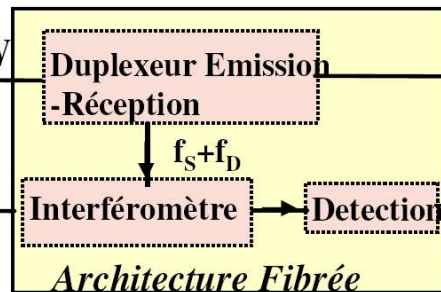
# Anémométrie laser 1.5 μm aéroportée lidar DALHEC

## SYSTEME OPTIQUE DALHEC

Laser à fibre maintien de polarisation  
PI=1W



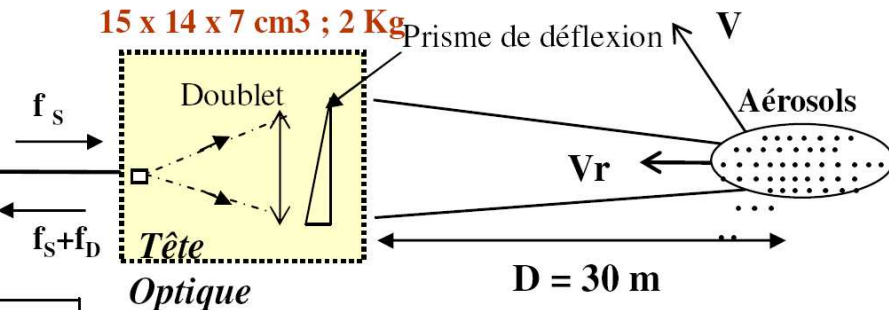
34 x 27 x 9 cm<sup>3</sup>; 7 Kg



Architecture fibrée monostatique,  
Détection équilibrée



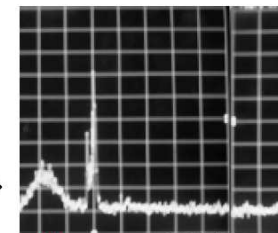
Diamètre doublet : 30 m  
Prisme en Silicium



$$(f_s - f_{OL}) \pm f_D$$

$$f_D = \frac{2Vr}{\lambda}$$

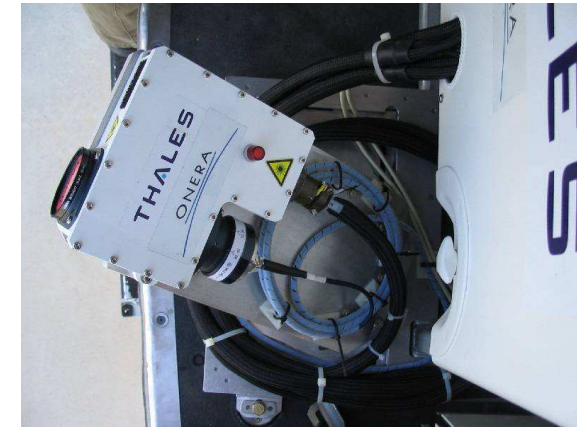
Traitement du Signal



Signal Doppler : Vr = 1.4 m/s

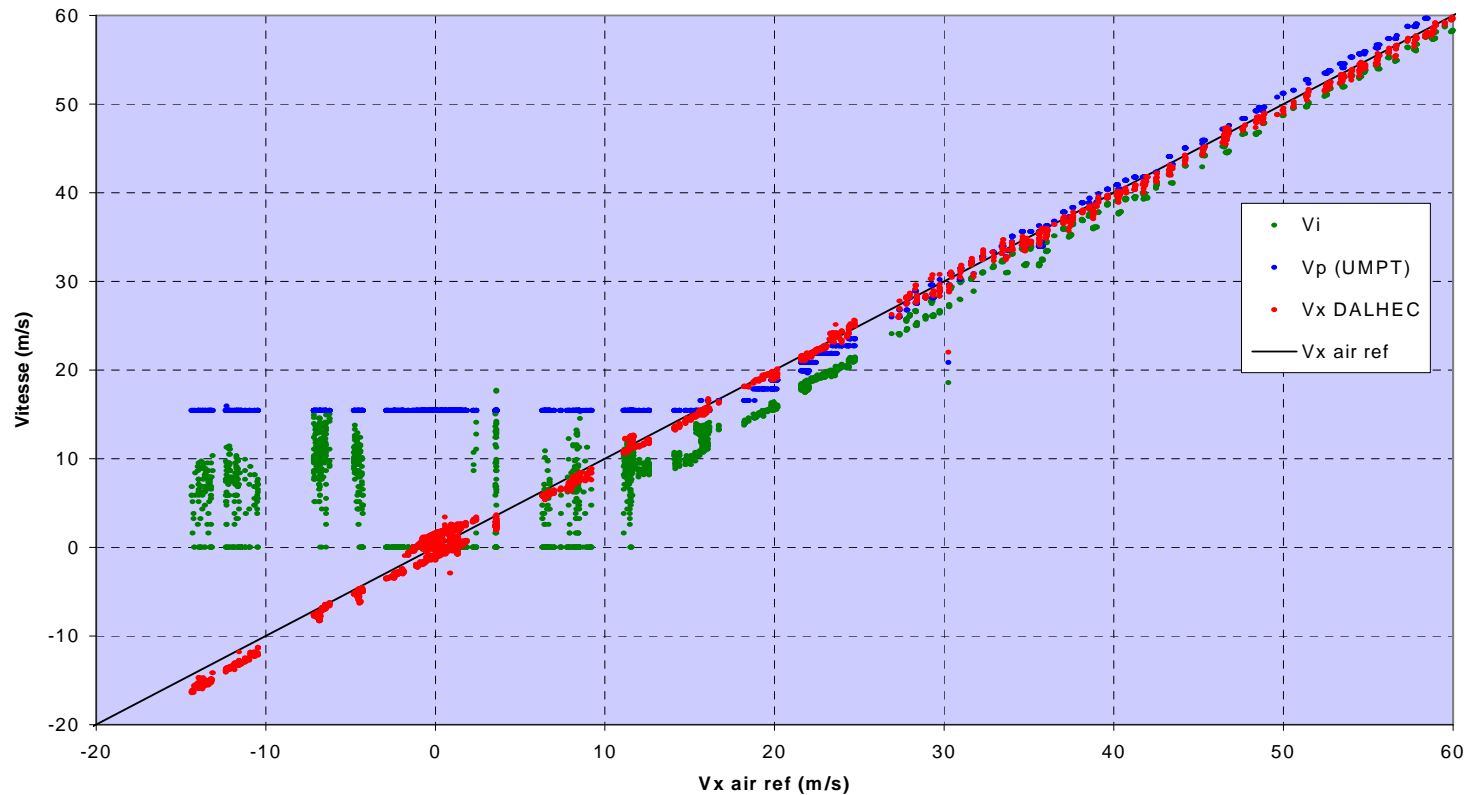
1 MHz/carreau ; 0.7 mV/carreau

# Anémométrie laser 1.5 $\mu\text{m}$ aéroportée DALHEC Sensor: Flight tests on DAUPHIN (CEV Istres)



# DALHEC Sensor: Flight measurements

## • Comparison between Dalhec and Pitot estimations



- ➔ Par rapport aux sondes classiques ( $V_i$ ), DALHEC mesure des vitesses ( $V_x$ ) conformes à la vitesse vraie avec une très bonne précision, même aux basses vitesses
- ➔ Validation de la mesure jusqu'à des altitudes de 3000 m

# Development of an airborne anemometer for in-flight testing onboard on a Piaggio P180 aircraft (AIM2 WP5.1.4)

## 1.5 $\mu\text{m}$ lidar anemometer design

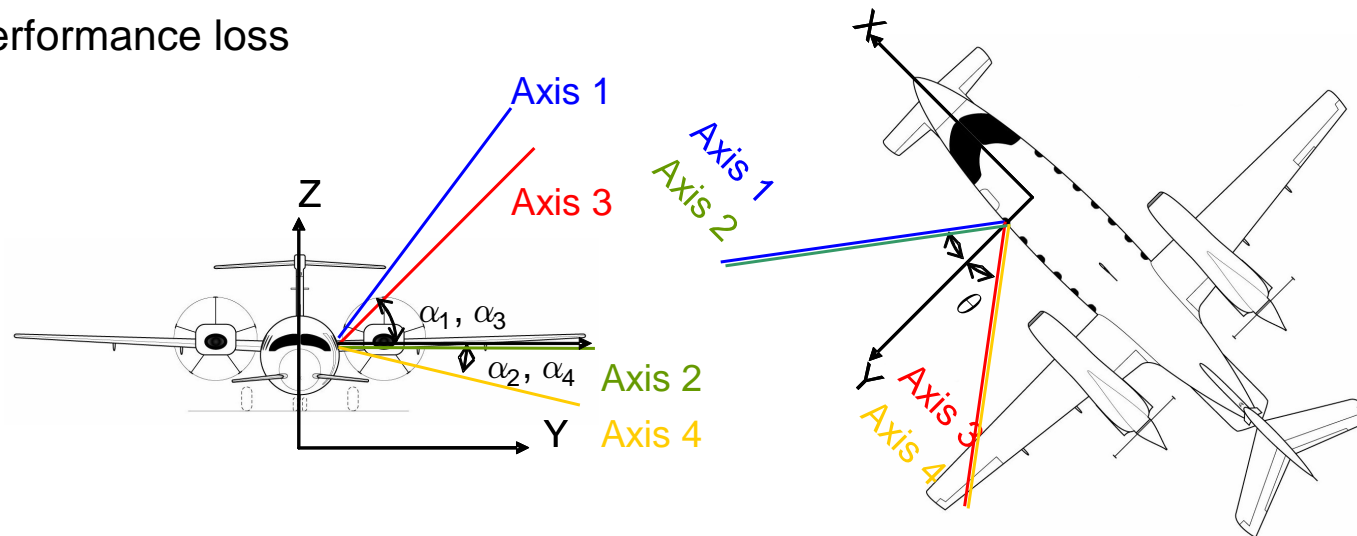
AOA and AOS retrieval from lidar data ( $V_x$ ,  $V_y$ ,  $V_z$ ) with 4 measurement axes V1, V2, V3, V4

- ✓ Benefit of **redundancy** in airspeed measurement  $\rightarrow$  data integrity check
- ✓ Narrower  $\alpha$  angle has less impact on  $V_z$  with 4 axes than 3 axes
- ✓ Higher optical head cost and complexity

Chosen geometrical angles:  $\alpha_1 = 45^\circ$  ,  $\alpha_2 = 0^\circ$  ,  $\alpha_3 = 40^\circ$  ,  $\alpha_4 = -5^\circ$  ,  $\theta = 25^\circ$

The 4 Lidar axes are time multiplexed by using a fiber optical switch:

- ✓ Cost effective (fits inside the project envelope)
- ✓ But less integration time due to multiplexing and axis commutation time  $\rightarrow$  performance loss



# Development of an airborne anemometer for in-flight testing onboard on a Piaggio P180 aircraft (AIM2 WP5.1.4)

## 1.5 $\mu$ m lidar anemometer design

### ➤ Lidar technical specifications $\Rightarrow$ Lidar axes geometry

✓ Geometrical angles :  $\alpha_1 = 45^\circ$  ,  $\alpha_2 = 0^\circ$  ,  $\alpha_3 = 40^\circ$  ,  $\alpha_4 = -5^\circ$  ,  $\theta = 25^\circ$

✓ Airspeed error function of error per axis (noted  $\text{std}_{\text{axis}}$ ):

$$\text{std}_{V_x} = 1.35 \text{std}_{\text{axis}}, \text{std}_{V_y} = 0.75 \text{std}_{\text{axis}}, \text{std}_{V_z} = 1.25 \text{std}_{\text{axis}}$$

$$\text{var}(v) = (M \cdot M^{-1})^{-1} \cdot \text{var}(V_r)$$

### $\Rightarrow$ Compatible with operational requirements:

Angle dynamic:  $-20 \leq \text{AOS} \leq +20^\circ$  ;  $-2 \leq \text{AOA} \leq +15^\circ$

AOA or AOS accuracy:  $0.5^\circ$

TAS dynamic:  $50\text{m/s} \leq V_x \leq 200\text{m/s}$

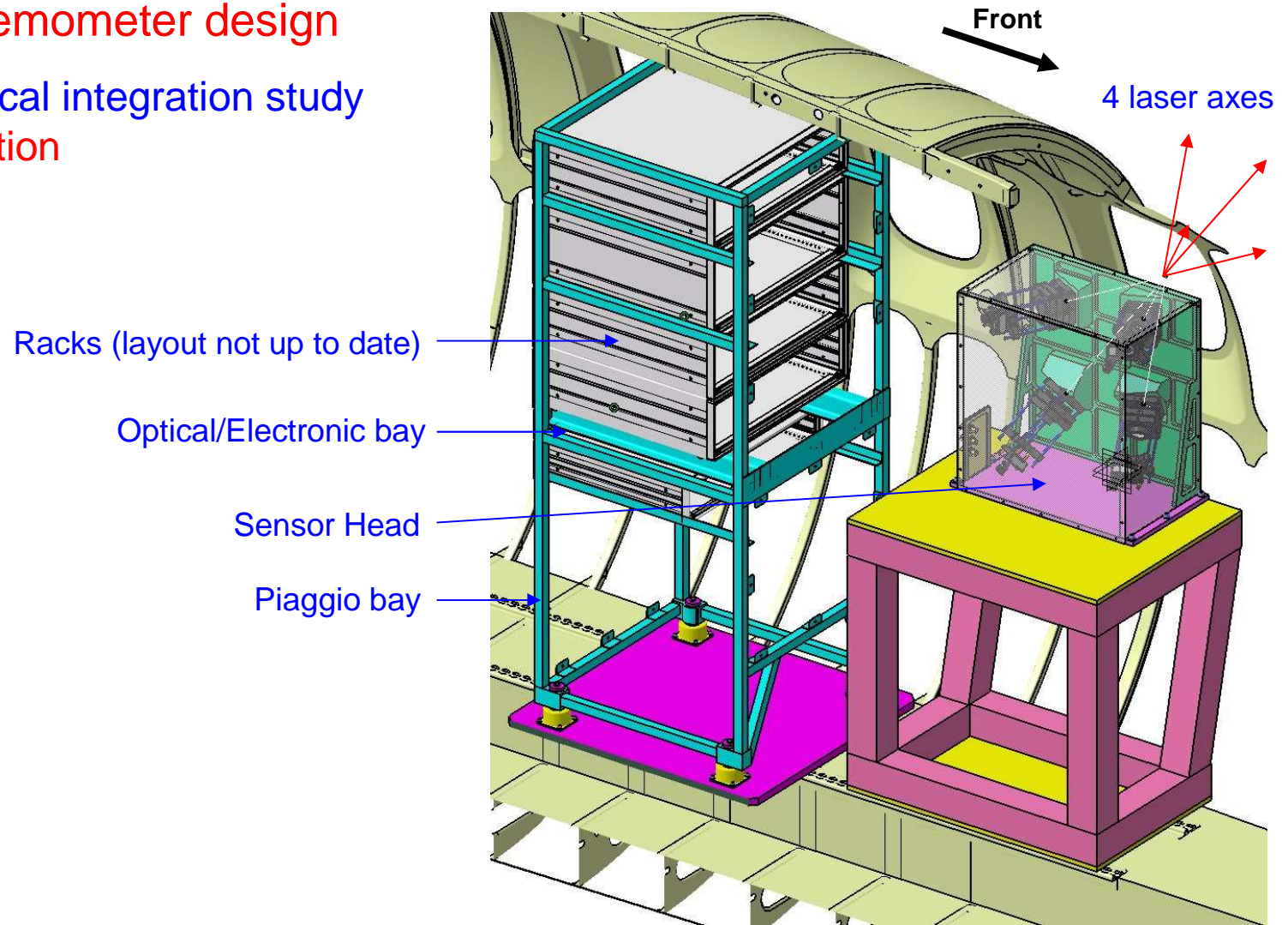
TAS accuracy:  $0.2\text{m/s} \Rightarrow \text{std}_{V_x} = 1.35 \text{std}_{\text{axis}} \leq 0.2\text{m/s} \Rightarrow \text{std}_{\text{axis}} \leq 0.15\text{m/s}$



# Development of an airborne anemometer for in-flight testing onboard on a Piaggio P180 aircraft (AIM2 WP5.1.4)

## 1.5 $\mu$ m lidar anemometer design

- Lidar mechanical integration study
- ⇒ Lidar description

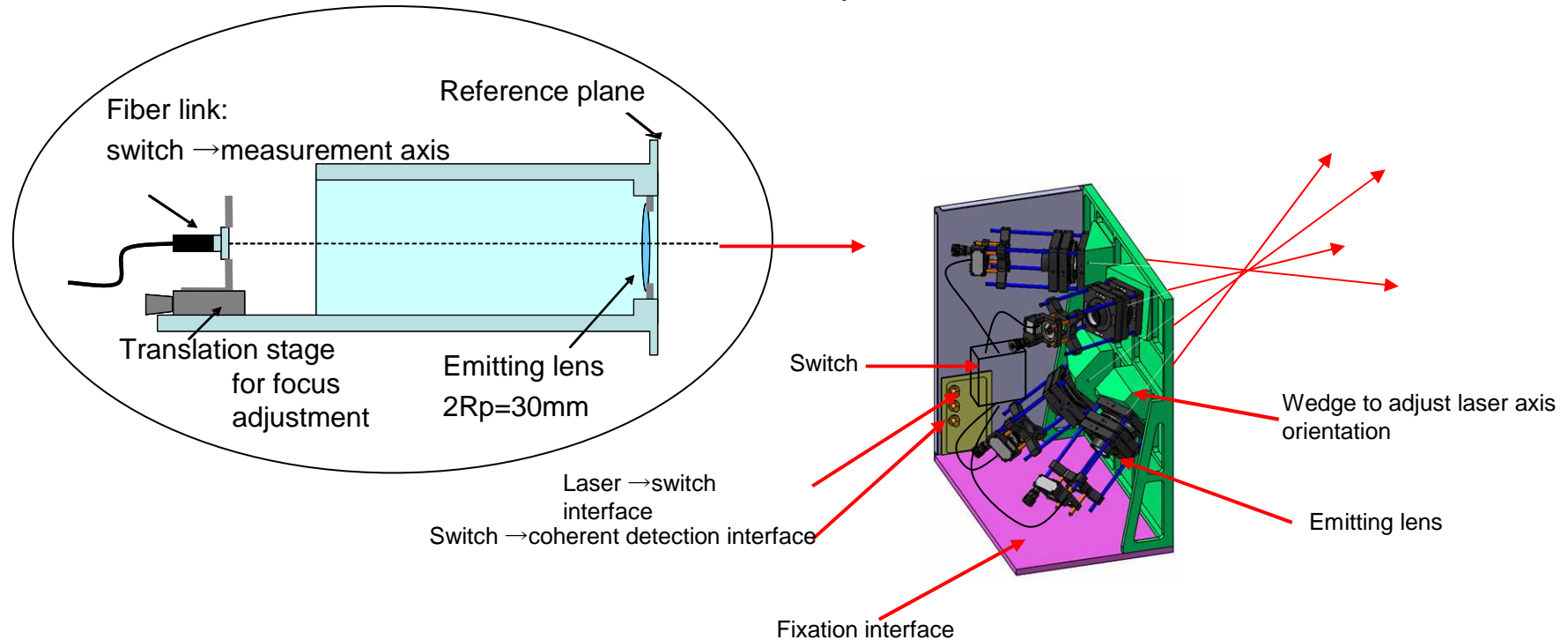


# Development of an airborne anemometer for in-flight testing onboard on a Piaggio P180 aircraft (AIM2 WP5.1.4)

## 1.5 $\mu$ m lidar anemometer design

### ➤ Lidar mechanical integration study $\Rightarrow$ Sensor head definition

- ✓ Dimensions : 403X251.5X431.5mm
- ✓ Weight: 14kg
- ✓ Includes 4 measurement axes orientated as specified

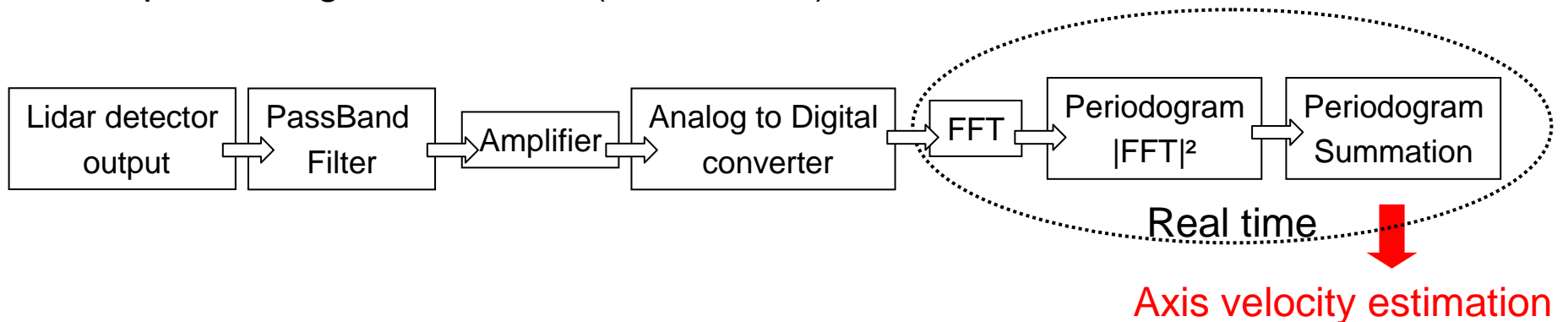


# Development of an airborne anemometer for in-flight testing onboard on a Piaggio P180 aircraft (WP5.1.4)

## 1.5 $\mu$ m lidar anemometer design

➤ Lidar technical specifications  $\Rightarrow$  Lidar signal processing performance

✓ Lidar processing for each axis (Onera work):

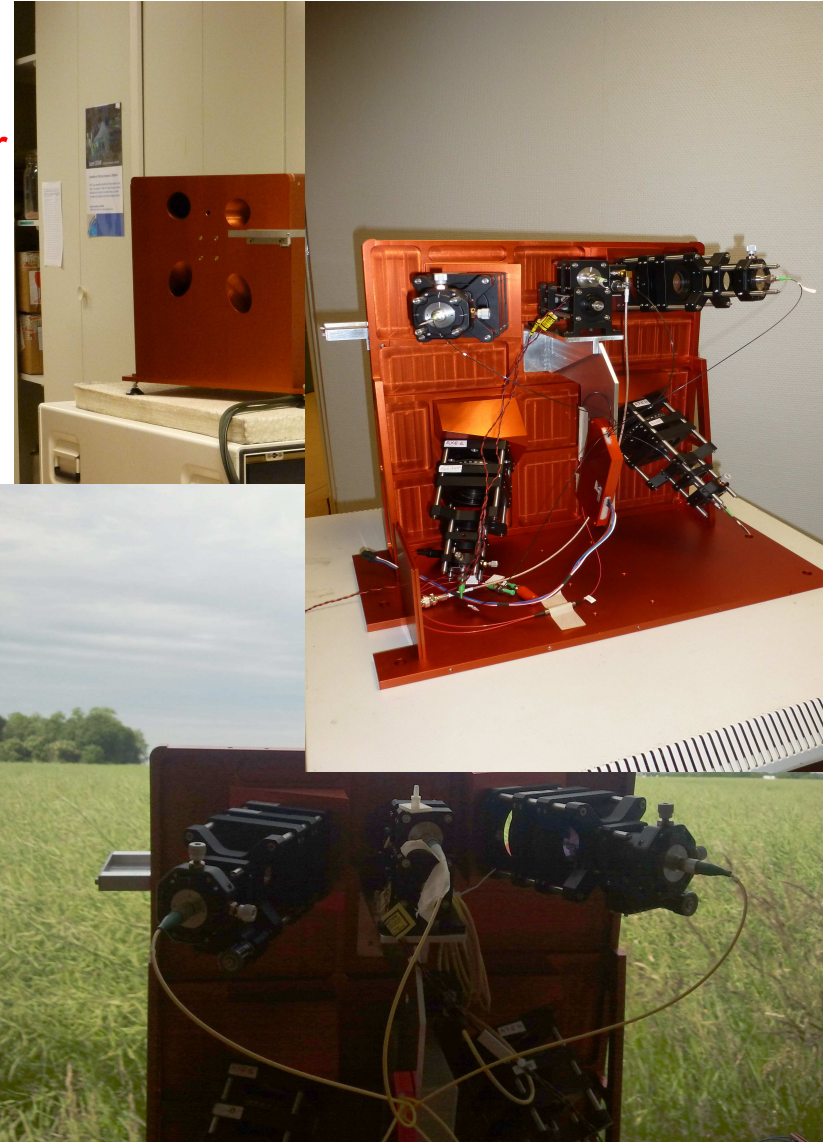
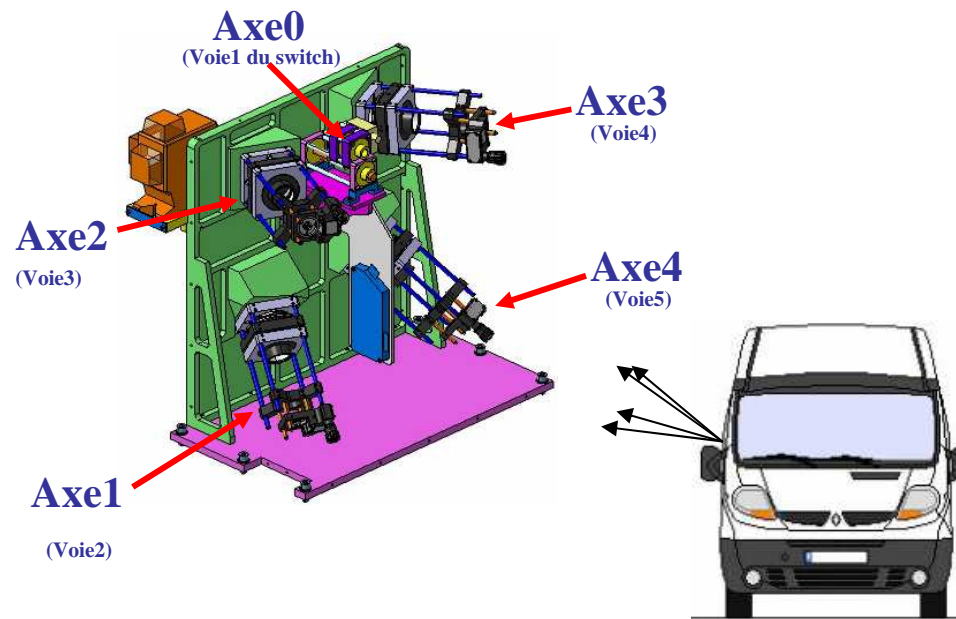


✓ Airspeed vector, AOA and AOS reconstruction (post-processing)

✓ Comparison Lidar measurements/Piaggio calibration procedure (post-processing)  
 $\Rightarrow$  Temporal synchronization using common GPS time

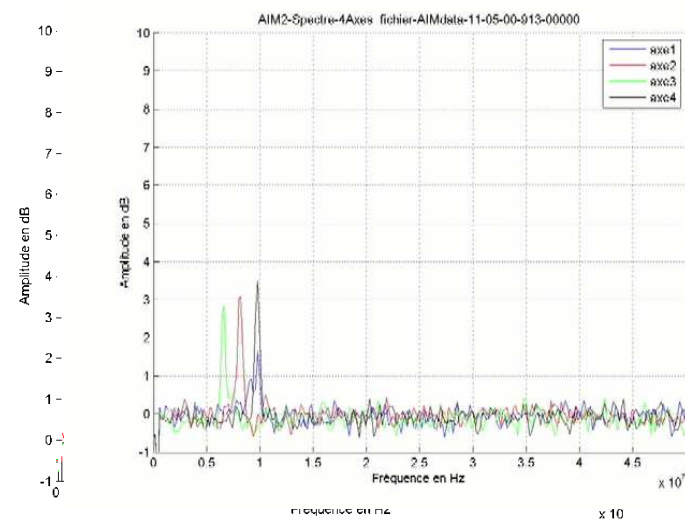
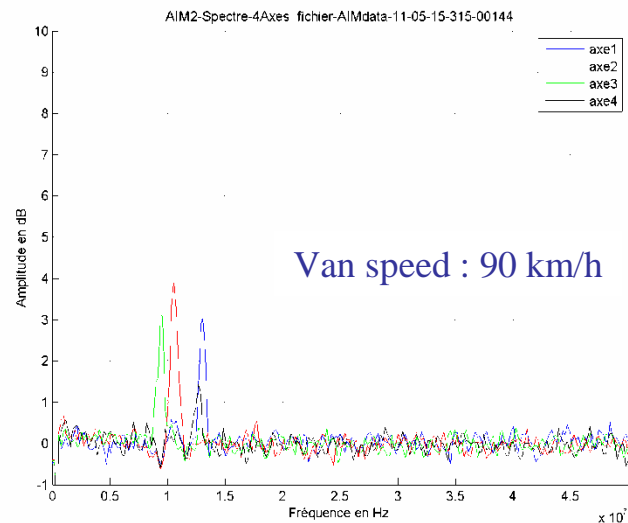
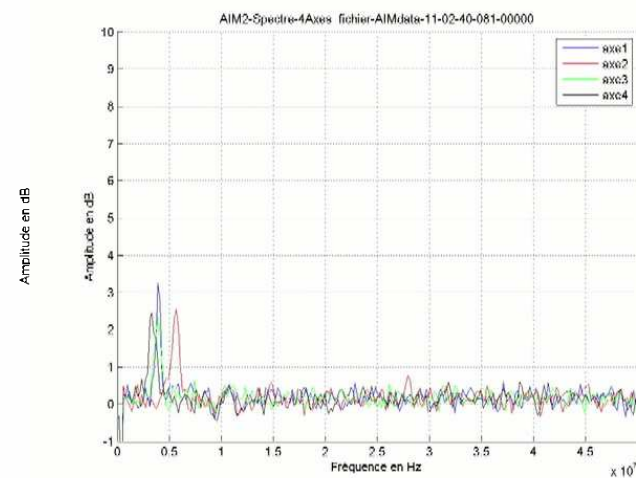
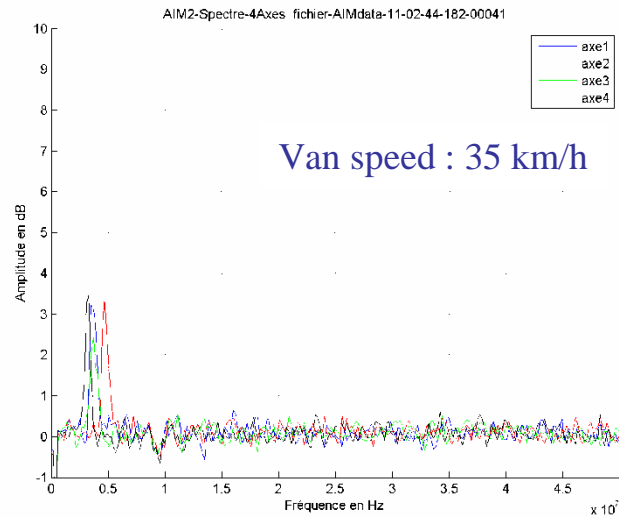
# AIM2: Advanced In-flight Measurement technique 2

Lidar Tests onbaord van : Side aiming lidar



# AIM2: Advanced In-flight Measurement technique 2

Airspeed measured by each lidar axis for a van speed between 30km/h et 90km/h.

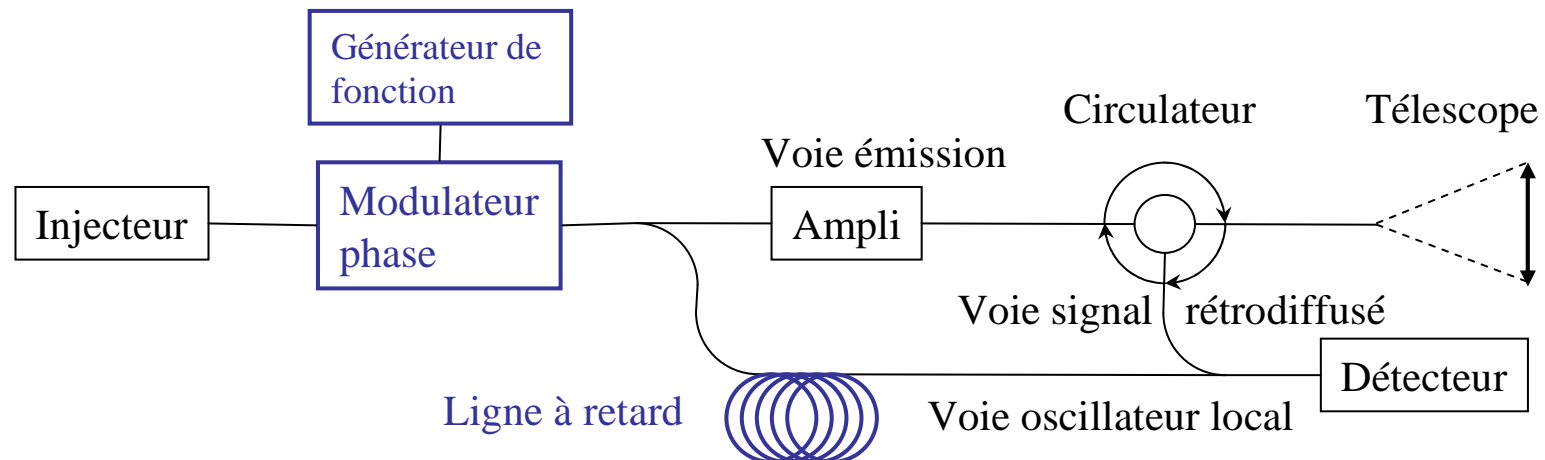


## Lidar embarqué: échos de nuages



## Solution: codage en fréquence

Modification de l'architecture lidar pour modulation de fréquence : ajout d'un modulateur de phase.



- Modulation de fréquence : le modulateur de phase génère un décalage fréquentiel (commande électrique en dents de scie)
- Modulation sur la voie signal et oscillateur local : aucun changement du traitement du signal.

# travaux pour amélioration de l'anémomètre

Modulation de type saut de fréquence à code dispersif

Objectif: atténuer la réponse du nuage

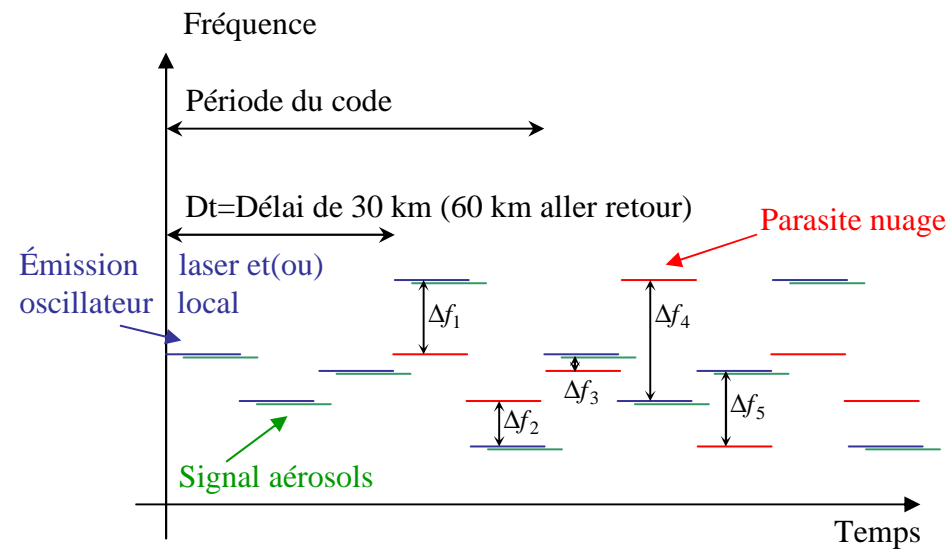
Pas d'impact sur le traitement du signal si la durée du mot du code est égale à la durée d'un spectre.

Dispersion du parasite nuage :

⇒ Atténuation égale à la longueur du code.

⇒ Levée d'ambiguïté entre le parasite et le signal aérosol par sa largeur spectrale.

Intérêt: Code économe en bande passante.





# Proposition de travaux pour amélioration de l'anémomètre DALEV

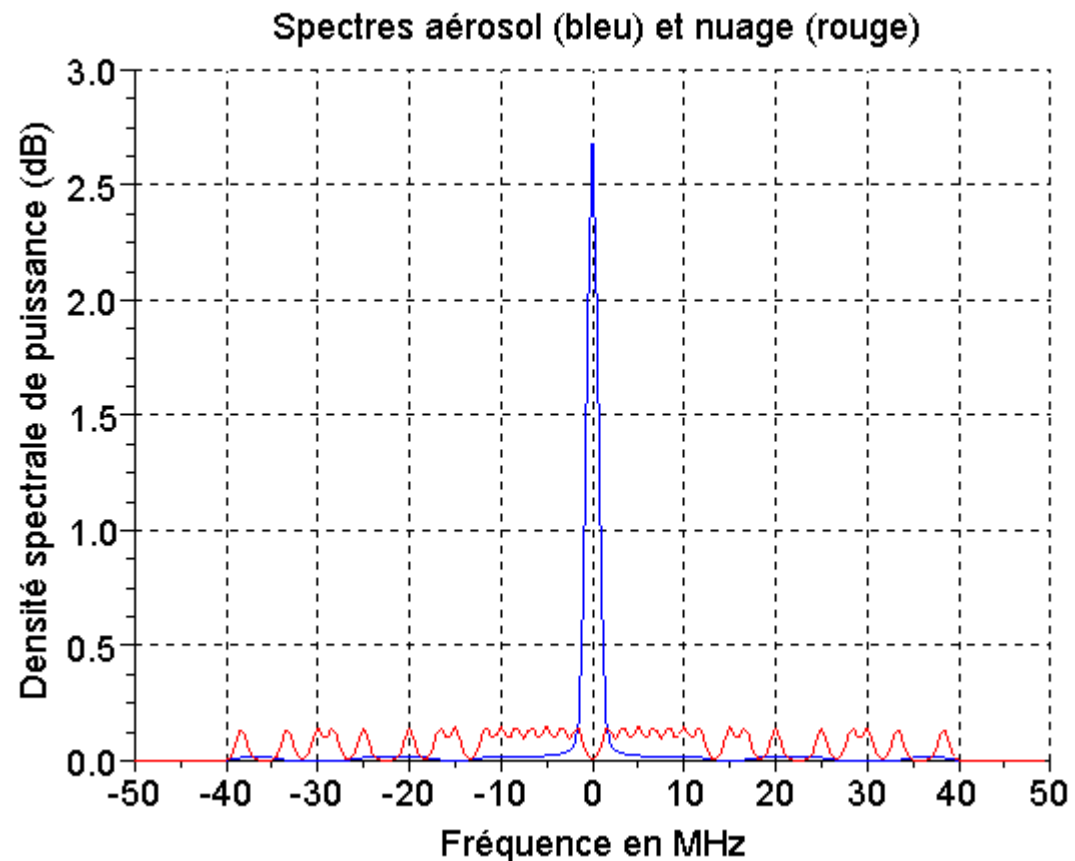
Simulation type saut de fréquence:

code de 30 symboles

Puissance signal aérosol = puissance parasite nuage

CNR = 0 dB

⇒ atténuation  
d'un facteur 30



# Applications aéronautiques des lidars vent

## Applications éoliens des lidars vent

### Applications aéronautiques des lidars vent

#### Senseurs de navigation

- **mesure de vitesse air 1 point 3 composantes**
  - Mie multiparticules
  - **Mie monoparticules**
  - Rayleigh

#### Senseurs d'alertes

- **Au sol**
  - Turbulence de sillage / wake vortex
  - Cisaillements ( « wind hazard » )
- **Embarqués**
  - Turbulence de sillage /wake vortex
  - Cisaillements / Turbulence en air clair

### Applications éoliens des lidars vent

- **Caracterisation de site**
- **Optimisation des turbines**

# Lidar Anemometre monoparticule

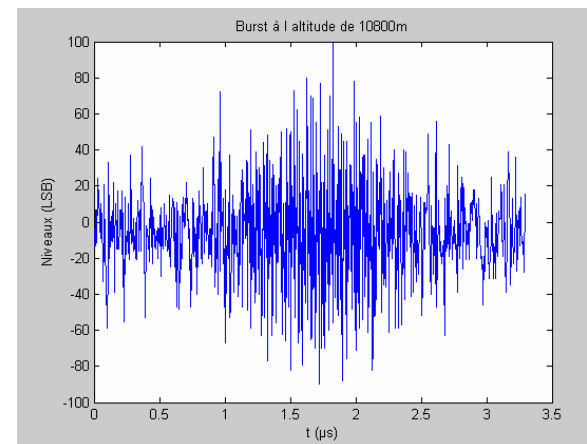
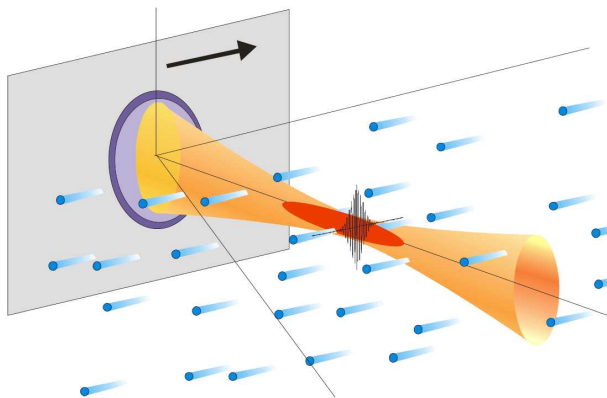
A haute altitude , la concentration en aerosol peut devenir très faible

→ Lidar monoparticule :

mesure avec un seul aerosol dans le volume de mesure

Avantage : pas de bruit de speckle .

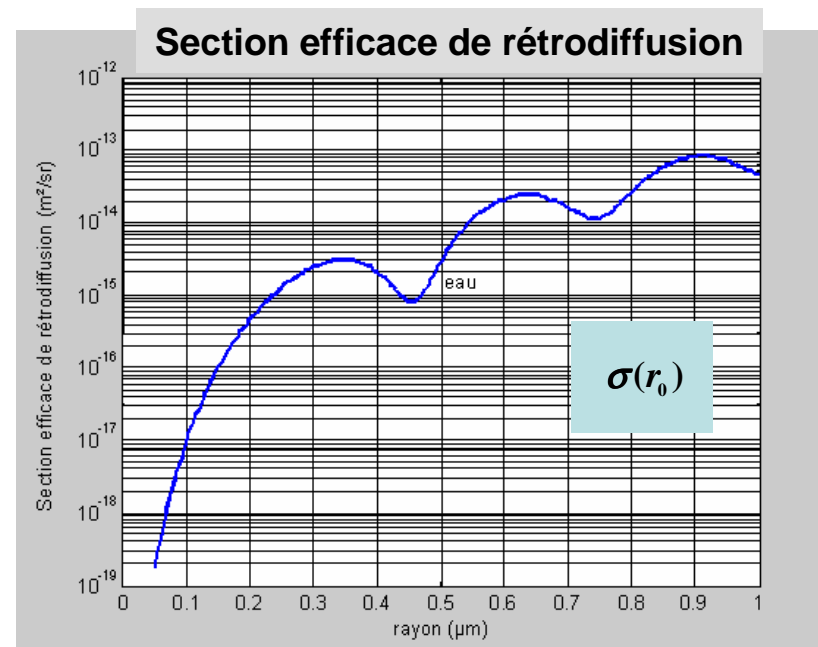
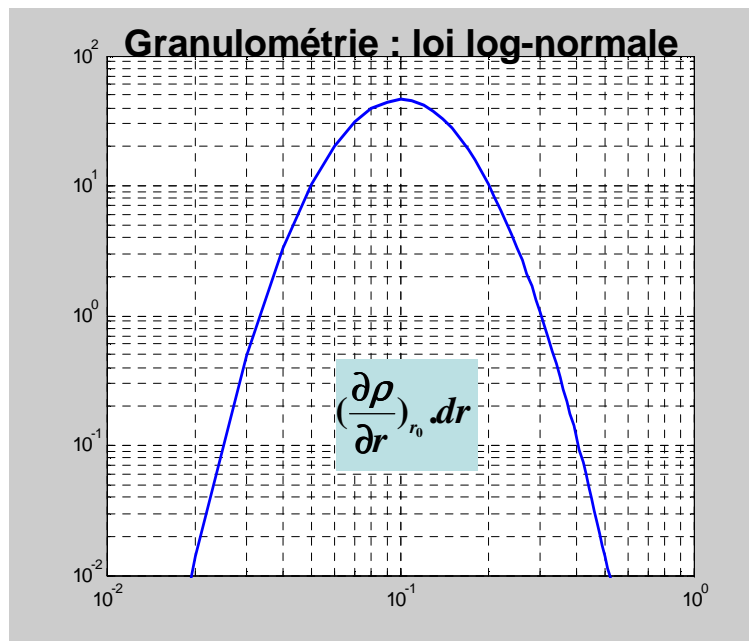
Statistique de mesure liée à la statistique de repartition des particules



# Lidar Anemometre monoparticule

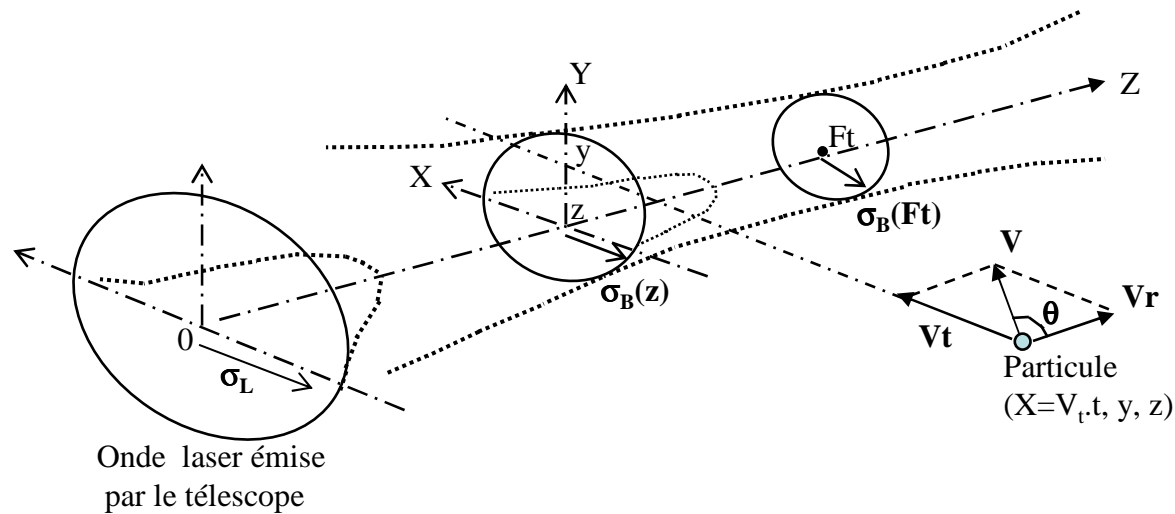
## Étude de l'atmosphère : tropopause (10 km)

- ⇒ Aérosols majoritaires du fond : noyaux d'Aitken
- ⇒ Concentration :  $N_p = 5 \text{ parts/cm}^3$
- ⇒ Taille :  $0.1 \mu\text{m}$
- ⇒  $\sigma$  : section efficace de rétrodiffusion  $\sigma = \beta / 4\pi$
- ⇒ Coefficient de rétrodiffusion :  $\beta = 10^{-9} \text{ m}^{-1} \cdot \text{sr}^{-1}$



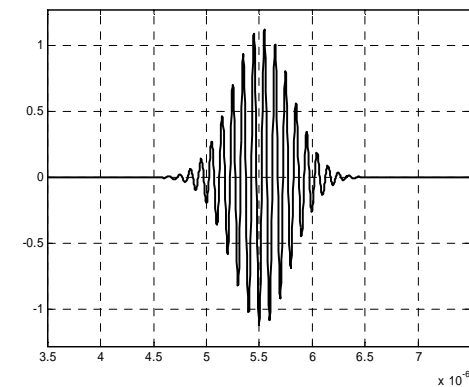
# Lidar Anemometre monoparticule : Modélisation instrumentale

⇒ Une particule en mouvement :  $x = V_t \cdot t$  ;  $Z = V_r \cdot t$



Doppler  $\alpha$  à  $V_r$  vitesse longitudinale (suivant l'axe lidar)

Temps de passage  $\alpha$  proportionnel à  $V_t$



# Lidar monoparticule

Courant heterodyne pour une particule en (p,Z)

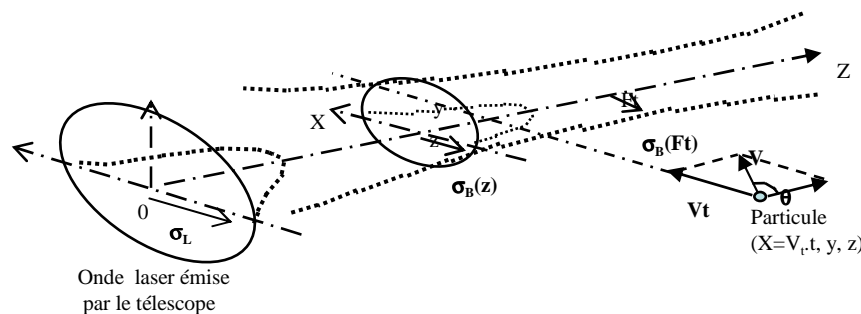
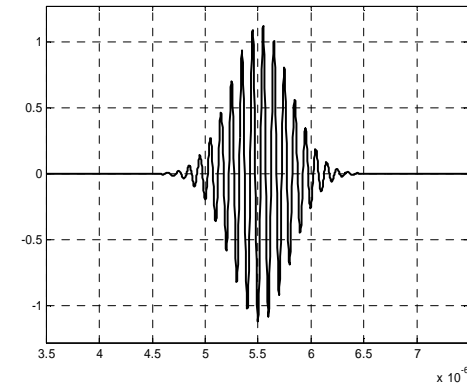
$$i_{het}(t) = \sqrt{2 \cdot \langle i_{het}^2 \rangle_{(p,Z)}} \cdot \cos(-2\pi(\nu_L - \nu_{OL}) \cdot t + 2kZ)$$

Courant heterodyne maximum lorsque la particule passe en (0, Ft) (centre du faisceau, waist)

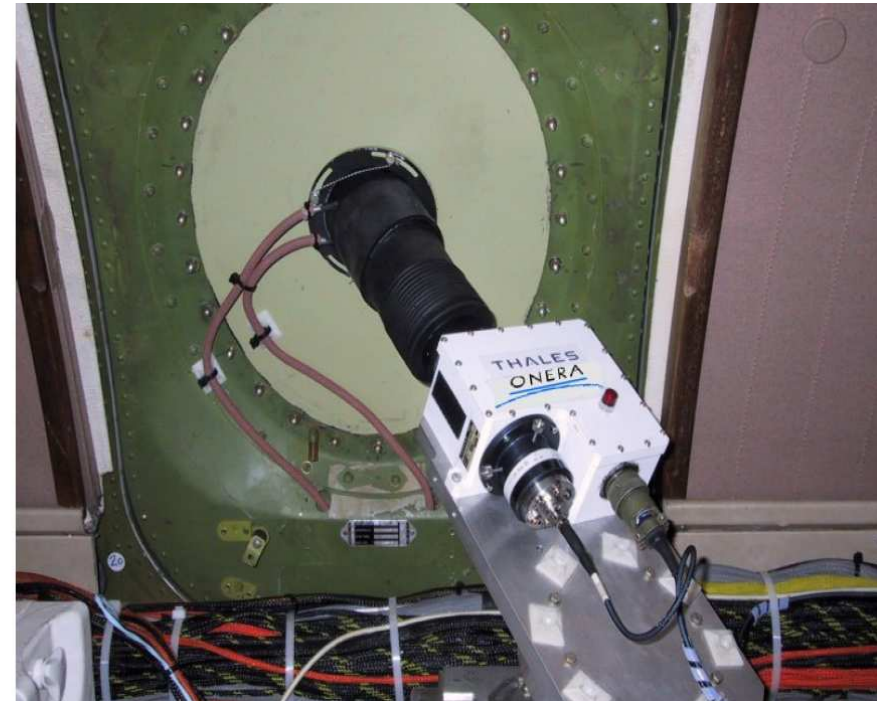
$$\langle i_{het}^2 \rangle_{(p,Z)} = \langle i_{het}^2 \rangle_{(0,Ft)} \cdot \frac{\sigma_B^4(F_t)}{\sigma_B^4(Z)} \cdot \exp\left(-4 \cdot \frac{p^2}{\sigma_B^2(Z)}\right)$$

$$\langle i_{het}^2 \rangle_{(0,F_t)} = \sigma \cdot 2 \cdot S^2 \cdot T_{inst.} \cdot 4 \cdot P_{OL} P_L \cdot \frac{\lambda^2}{\pi^2} \cdot \frac{1}{\sigma_B^4(F_t)}$$

$$\sigma_B^2(Z) = \frac{\lambda^2 \cdot Z^2}{\pi^2 \sigma_L^2} + \sigma_L^2 \left(1 - \frac{Z}{F_t}\right)^2$$



# Lidar monoparticule DALAS



**MYSTERE XX**

## Essais en vol de la sonde DALAS (sonde DALHEC modifiée)

L'objectif est de valider l'anémométrie  $1.5 \mu\text{m}$  monoparticule et d'évaluer les caractéristiques de rétrodiffusion de l'atmosphère avec :

- ⇒ altitude
- ⇒ météo (ciel clair/nuage)
- ⇒ variation journalière (jour/nuit)
- ⇒ zone géographique (mer/terre/montagne)
- ⇒ réglages de mesure ( focale, vitesse avion)

### Moyen d'essais

- ⇒ Mystère XX du CEV d'Istres



# Lidar monoparticule DALAS

## Préparation de la sonde DALAS (sonde DALHEC modifiée)

- ⇒ Modification de la tête optique pour permettre la focalisation aux distances focales retenues
- ⇒ Modifications laser : suppression du MAO, augmentation de la puissance optique de l'OL
- ⇒ Nouvelle architecture HF permettant de s'adapter aux fréquences Doppler rencontrées en configuration avion à haute altitude

DALHEC

Distance de mesure : 30m

Pupille : 30mm

DALAS

Distance de mesure : 1m

Pupille : 30mm

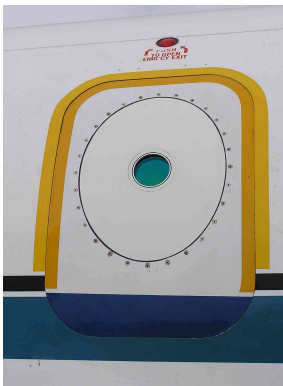
Tache focale <100  $\mu$ m



# Lidar monoparticule DALAS



## Installation de la sonde DALAS



Le Hublot intégré à l'issue de secours



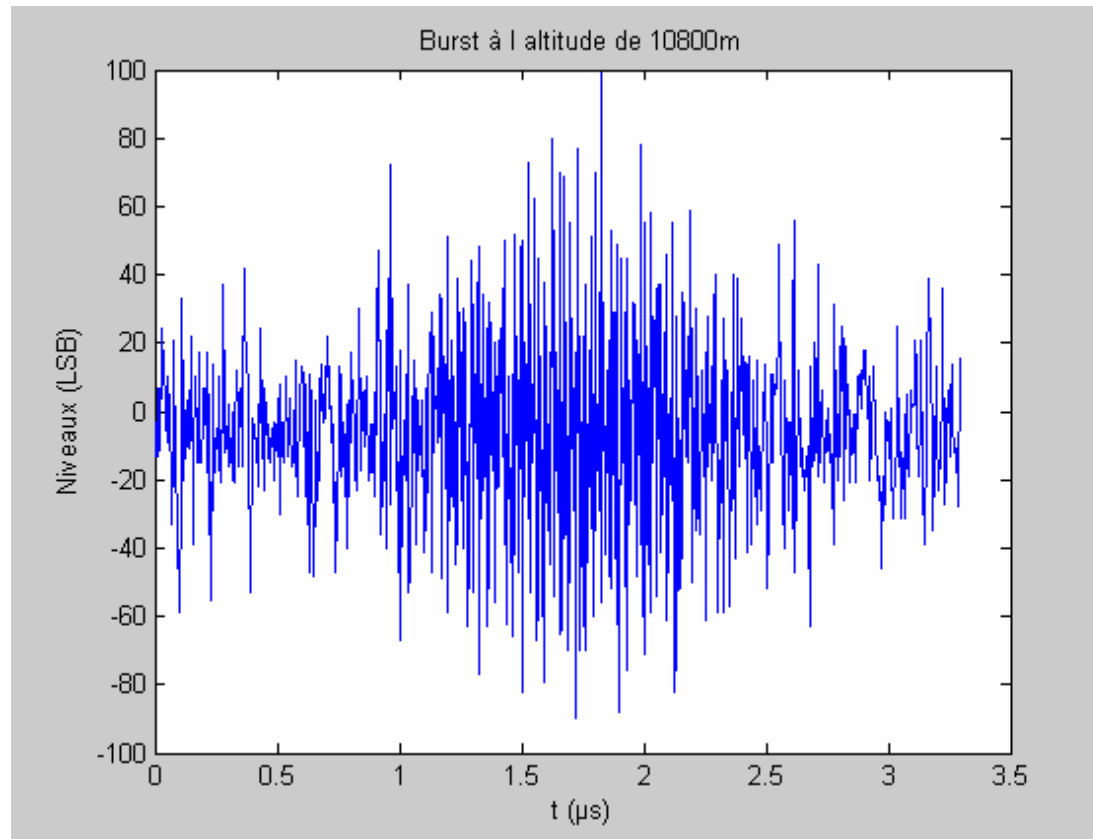
La tête optique DALAS installée à bord du MYSTERE XX



Le boîtier de commande DALAS

# Lidar monoparticule DALAS : essais en vol

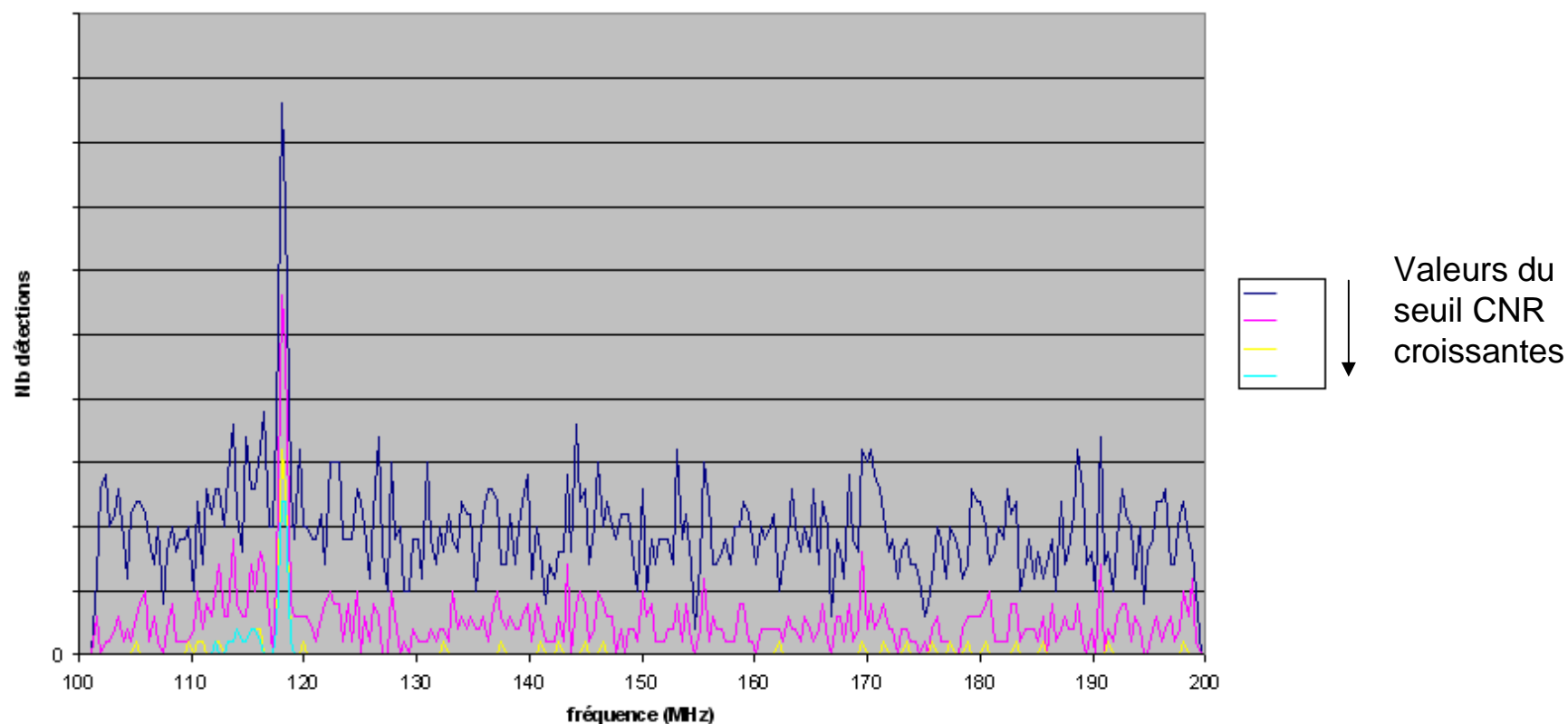
Vol n° 4 : Exemple de burst (11000m, ciel clair)



# Lidar monoparticule : essai en vol de la sonde DALAS

Vol n° 2 : Exemple d'histogramme (6000m, ciel clair)

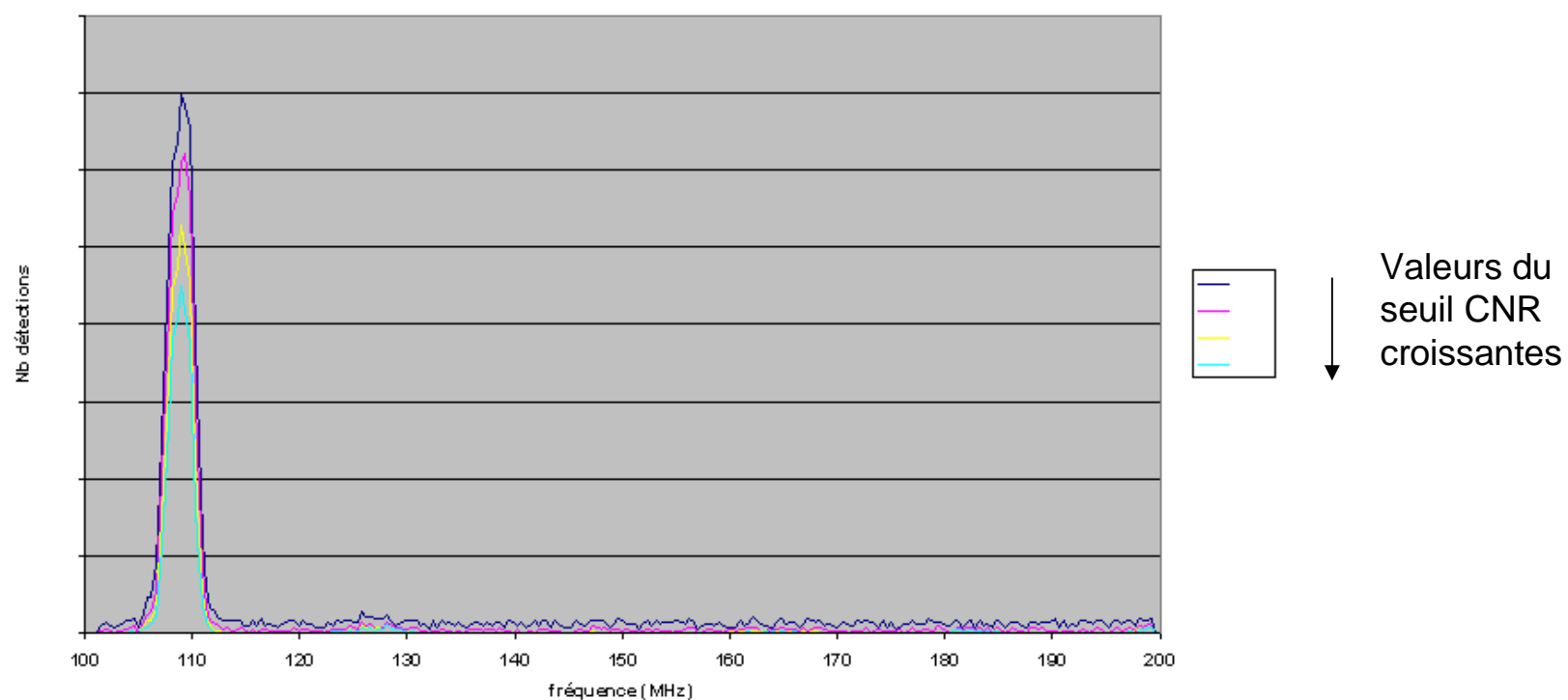
Histogramme brut\_04-12-14\_14h01m37



# Lidar monoparticule DALAS : essais en vol

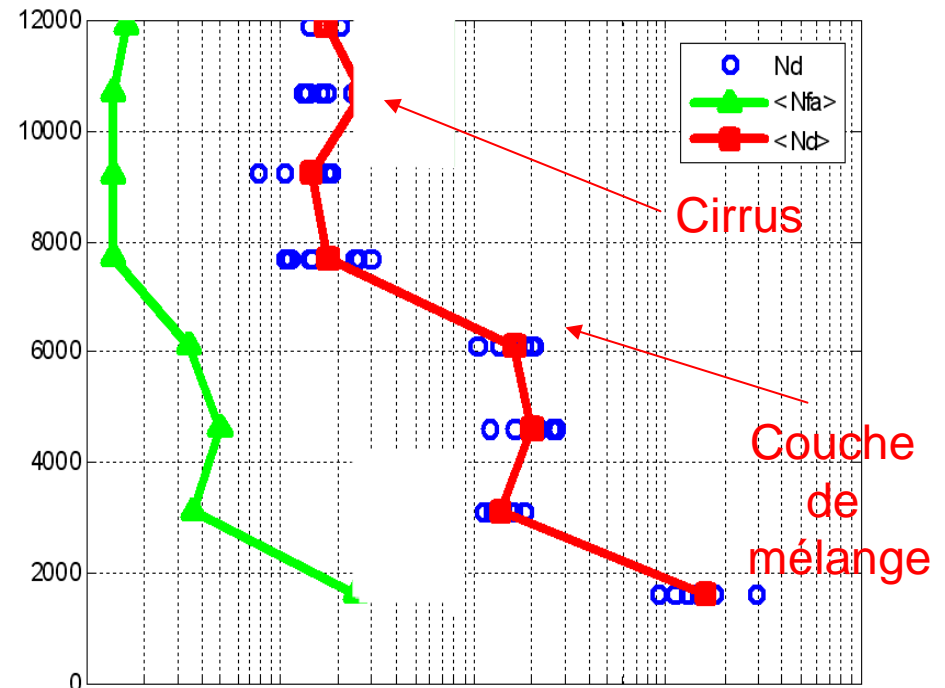
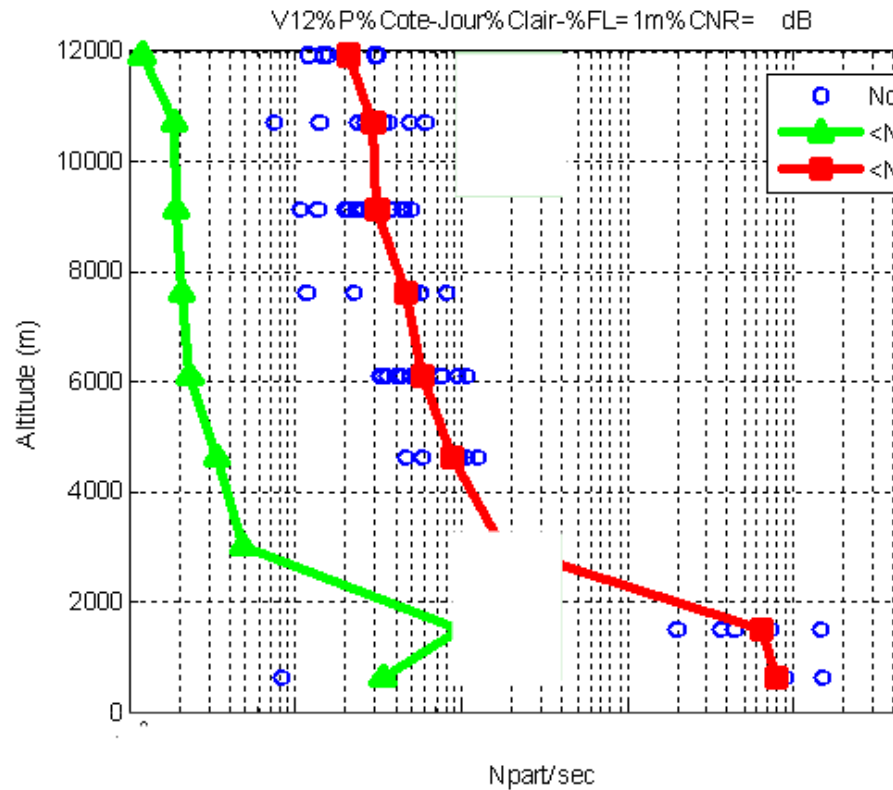
Vol n° 2 : Exemple d'histogramme (6000m, nuage)

Histogramme brut\_04-12-14\_14h05m48



# Lidar monoparticule DALAS : essais en vol

NbDétection = f(altitude)



Suite des essais dans les projets UE Neslie et Daniela pour caractériser l'atmosphère

# Autre lidar anemo monoparticules

Table 7-2: Characteristics of the Boeing Doppler lidar airspeed system.

Factor	Detail
anemometer type	reference-beam laser anemometer
laser	NdYAG
wavelength	1.064 $\mu$ m
operating mode	continuous wave (cw)
power	0.5 Watt
detection	coherent mode using an indium gallium arsenide detector
measurement	single component flow velocity at a point
focal distance	between 1 and 2 m
velocity range	10 m/s to 400 m/s
altitude range	tested up to FL 410
TAS uncertainty	1 m/s
update rate	dependent upon particle passage rate
format	RS 232
physical characteristics	
scanning	none
size (optical unit)	7.5 x 17.5 x 27.5 cm
weight (optical unit)	<5 kg
developed by:	Boeing Information Systems

## Boeing Doppler lidar airspeed system.

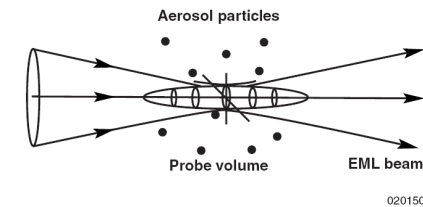


Figure 7-3: Detection volume geometry.

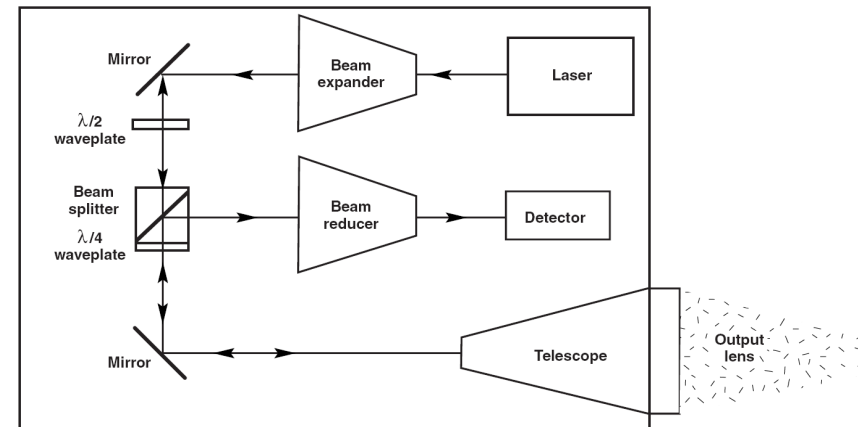


Figure 7-4: Continuous-wave Doppler lidar brass board configuration.

Source : "optical air flow measurement" (OTAN)

# Applications aéronautiques des lidars vent

## Applications aéronautiques des lidars vent

### Senseurs de navigation

- **mesure de vitesse air 1 point 3 composantes**
  - Mie multiparticules
  - Mie monoparticules
  - **Rayleigh**

### Senseurs d'alertes

- **Au sol**
  - Turbulence de sillage / wake vortex
  - Cisaillements ( « wind hazard » )
- **Embarqués**
  - Turbulence de sillage /wake vortex
  - Cisaillements / Turbulence en air clair

### Applications éoliens des lidars vent

- **Caracterisation de site**
- **Optimisation des turbines**



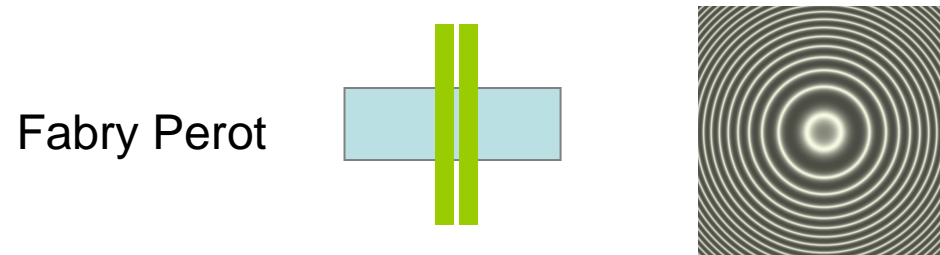
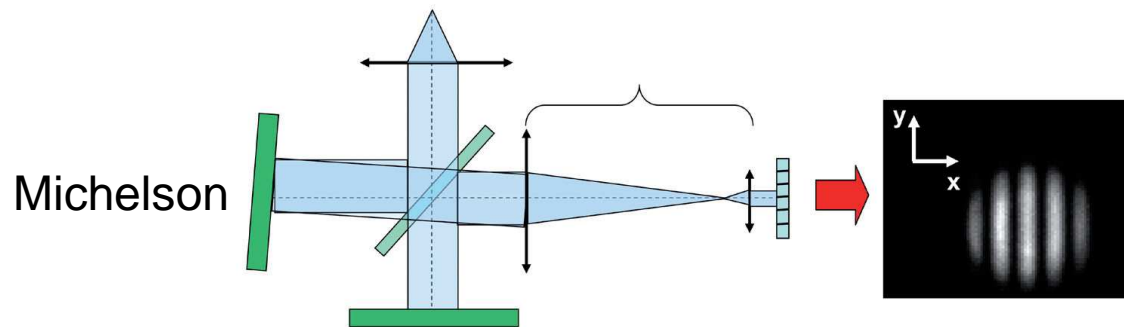
## Lidar Rayleigh – Mie Detection directe

En haute altitude , la presence d'aerosol peut être faible →  
mesure sur la diffusion par les molécules (diffusion Rayleigh )

Longueur d'onde UV plus favorable

Spectre Rayleigh très large ( due à l'agitation thermique ) →  
detection heterodyne impossible

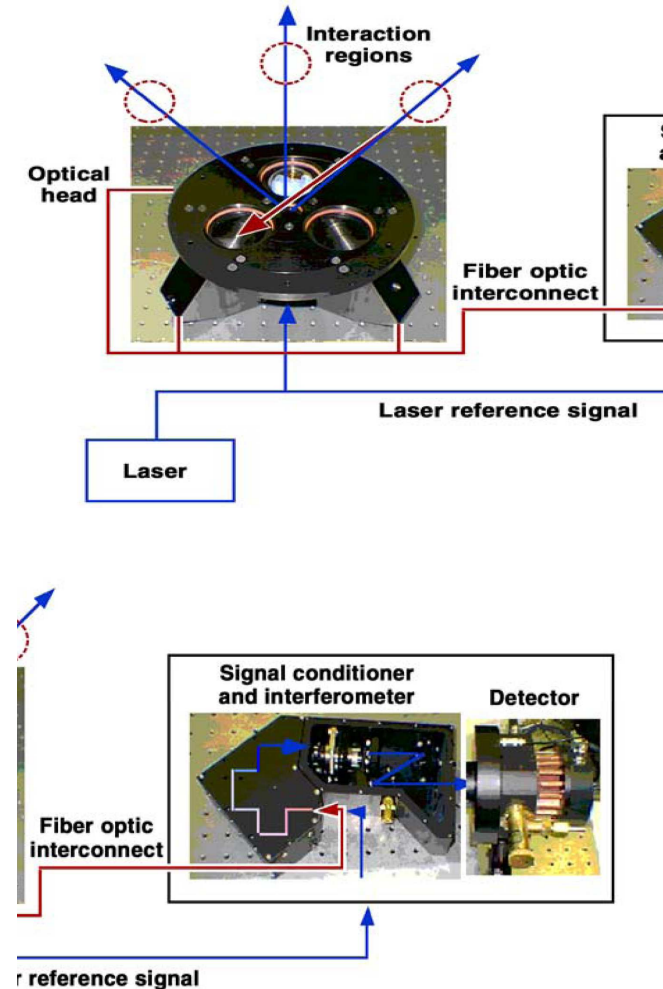
Determination du Doppler par Interferometrie optique + detection  
directe ou imageur



# lidar Rayleigh : optical air data sensor MOADS

Table 7-3: Characteristics of Michigan Aerospace Molecular Optical Air Data Sensor (MOADS).

Factor	Actual Detail (as tested in the laboratory)	Projected Detail
anemometer type	spectrometric anemometer, bistatic configuration	
laser	NdYAG laser quadrupled	
wavelength	1.064 mm quadrupled to 0.266 mm	
operating mode	continuous wave or pulsed	continuous wave or pulsed
power	.5 W (dependent on update rate)	.5 W
detection	direct mode detection by a high-finesse etalon using a charge-coupled-device (CCD) detector	
measurements	vector true airspeed (TAS, AoA, and AoS), static pressure, and temperature. Derived measurements include: Mach and Pressure Altitude	
measurement distance	2m. and 10m.	2m. and 15 m
velocity range	0 to 25 m/s	0 m/s to 1200 m/s
altitude range	Sea level (SL)	SL to FL 1000
TAS uncertainty	±0.57 m/s (1 sec. integration) (1W laser power)	±.2 m/s (80 Hz update) (2 W laser power)
update rate	1 Hz	80 Hz for AoA and AoS 20 Hz for others
pressure uncertainty	± 700 Pa (127mW laser power)	± 63 Pa (80 Hz update) (2 W laser power)
temperature uncertainty	none quoted	± .9 °C (10 Hz update)
format	RS 232	MIL-1553
physical characteristics		
scanning	none (measurements from 3 separate axes)	
size	0.127 m <sup>3</sup> (not including laser)	.04 m <sup>2</sup>
weight	42 kg	20 kg
developed by	Michigan Aerospace Corporation, Ann Arbor, MI and University of Michigan, Ann Arbor, MI	
funded by	US Navy and US Air Force (AFRL)	

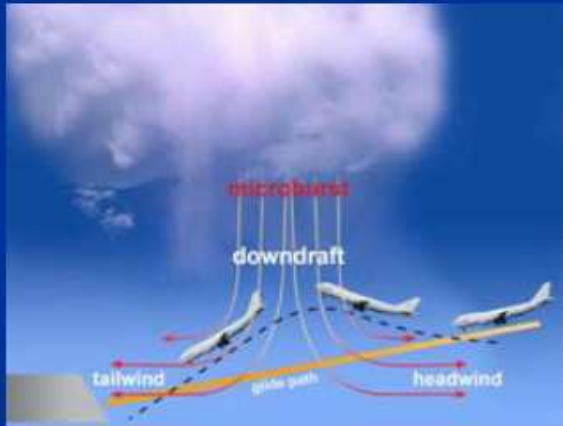


Source : "optical air flow measurement" (OTAN)

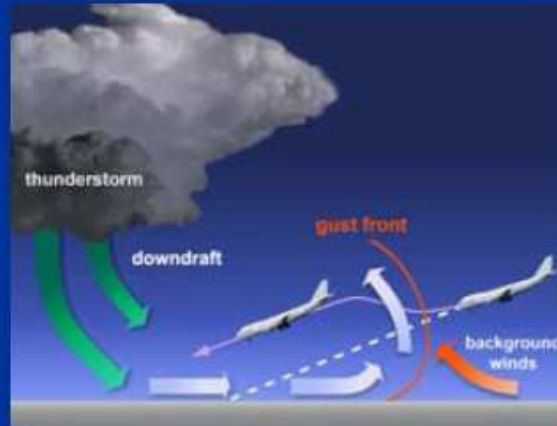
020152

- **Au sol**
  - ② **Turbulence de sillage /wake vortex**
  - ② **Cisaillement / rafale (Wind hazard)**
  
- **Embarqués**
  - ② **Turbulence de sillage /wake vortex**
  - ② **Turbulence en air clair**
  - ② **Cisaillement / rafale (Wind hazard)**

# Menaces liées au champ de vent en aéronautique



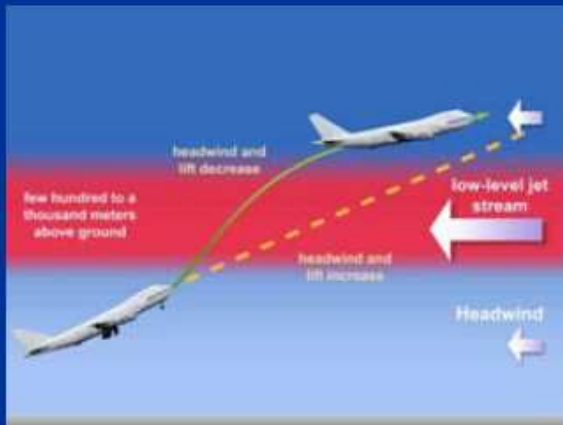
**Microburst Wind Shear**



**Gust Front Shear**



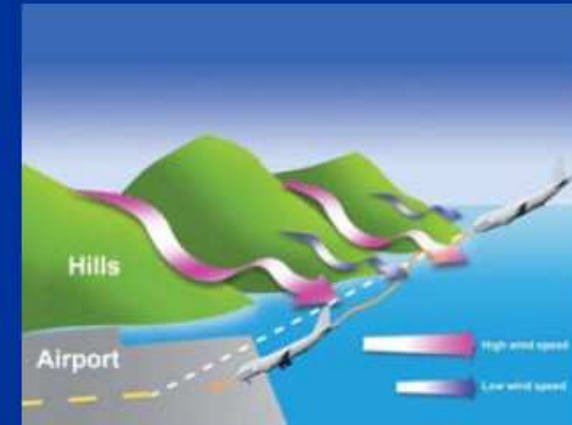
**Sea Breeze Shear**



**Low-Level Jets and Other Vertical Shear**

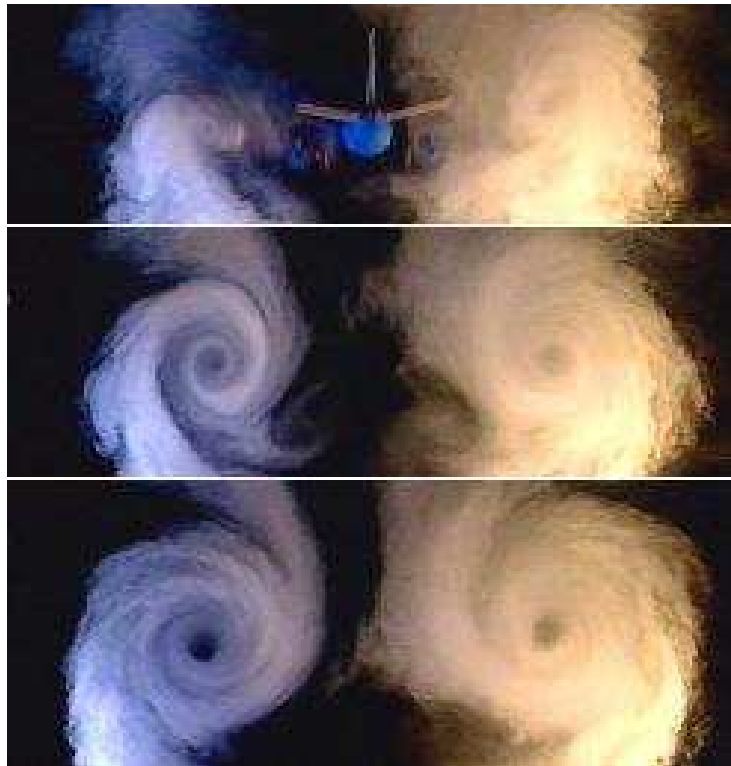


**Turbulence**



**Terrain-Induced Shear and Turbulence**

# Les turbulences de sillage ( « wake vortex » )



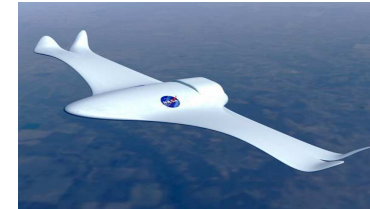
*@ Joseph P. Willems, 2002*

Courtesy from  
S. Wolf, IFALPA



### Conception des voilures / réduction des traînées :

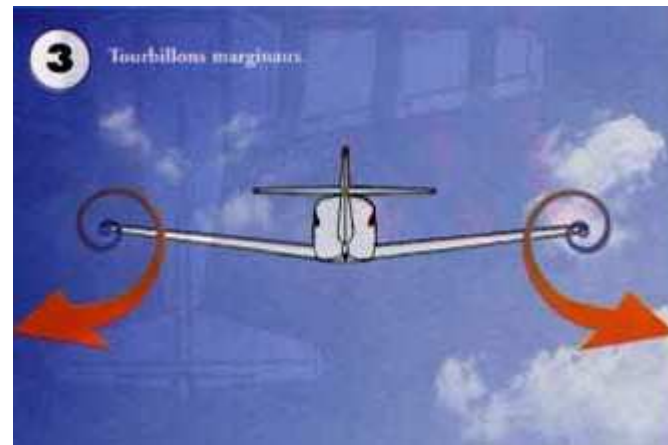
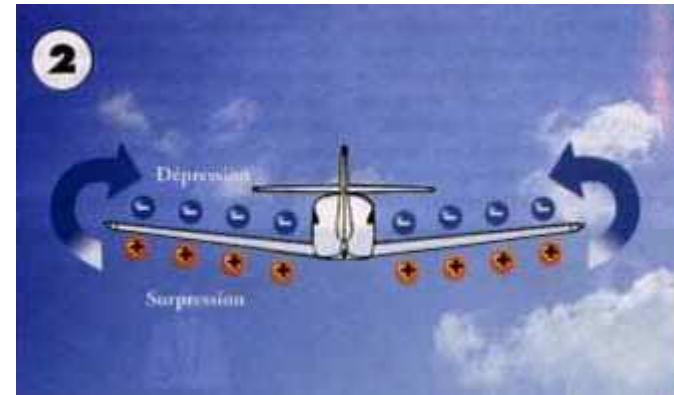
- **mesures sur maquettes**
- **mesures sur site aéroportuaire**



### Sécurité du vol :

- **mesures embarquées**
- **mesures sur site aéroportuaire**
  - **Augmentation du trafic aéroportuaire : Réduction des espacements entre les décollages et entre les atterrissages**

# origine aérodynamique la turbulence de sillage



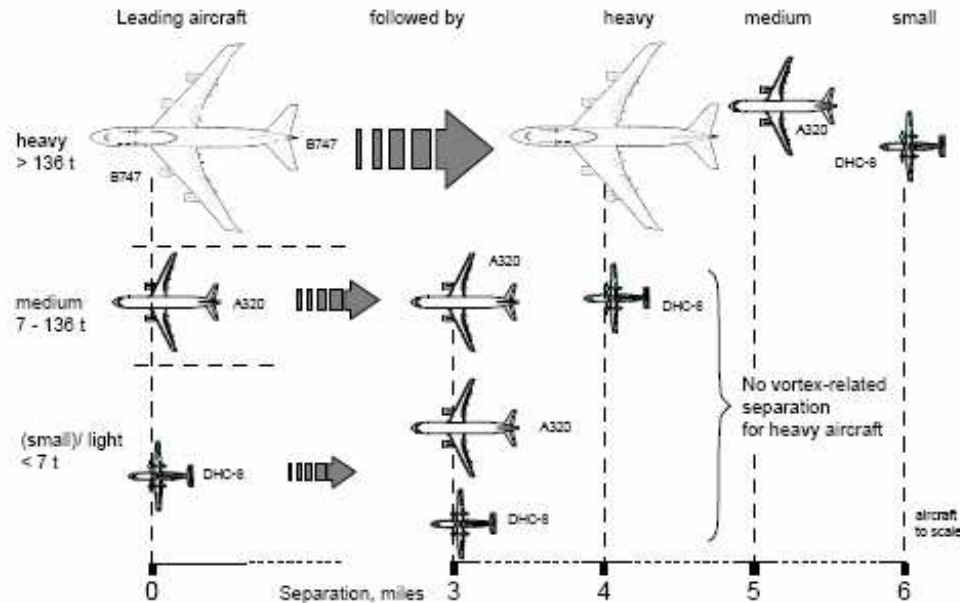


## Anti- vortex : « winglets »



Reduction de la traînée de 5 à 7 %

# Les espacements à l'atterrissage

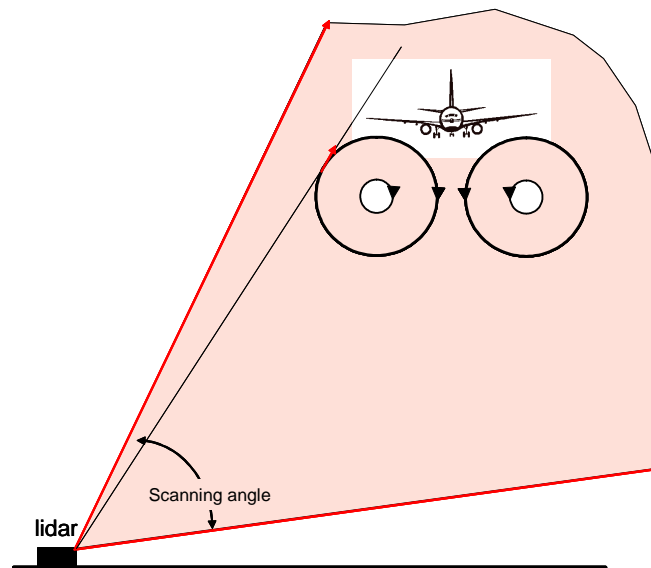


	Leading aircraft	Following aircraft	Separation distance		Time delay (approach speed $70ms^{-1}$ )
			(Nm)	(km)	
(a)	Heavy ( $>136000kg$ )	Heavy	4	7.4	106
		Medium	5	9.3	133
	Medium ( $7-136000kg$ )	Light ( $<7000kg$ )	6	11.1	159
(b)	A380-800	Heavy	6	11.1	158
		Medium	7	13	186
		Light	8	14.8	211

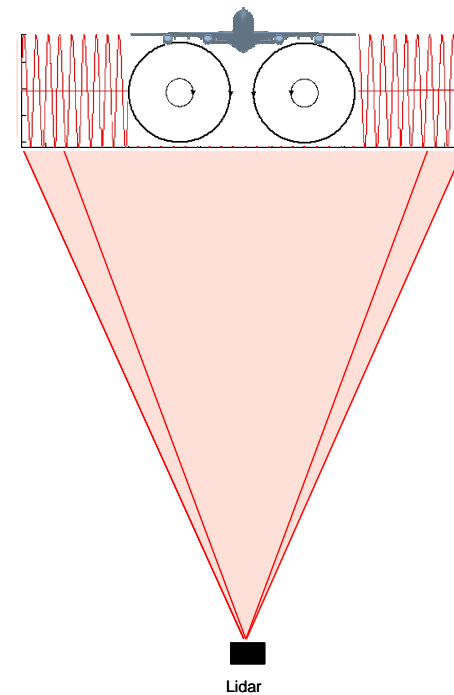
ICAO aircraft separation distances to avoid wake vortex encounters during approach: (a) standards, (b) provisional values for the A380 (2008).

→ SESAR : Single European Sky Air traffic management Research

# Mesure des « wake vortex » par lidar

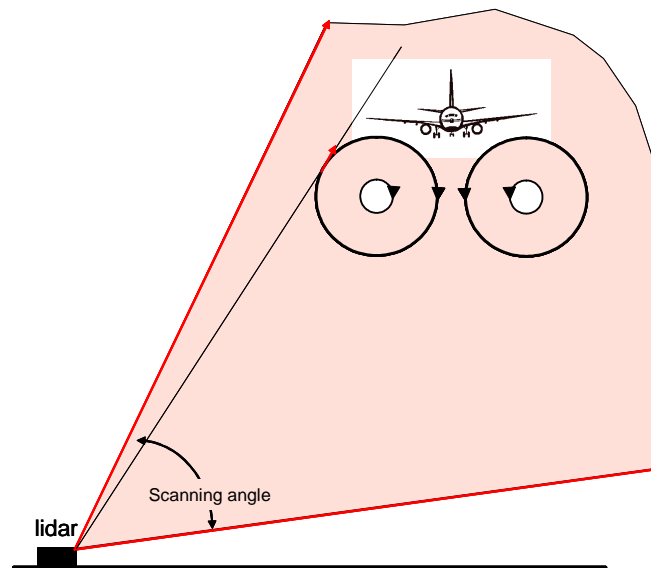


Détection transversale Sol



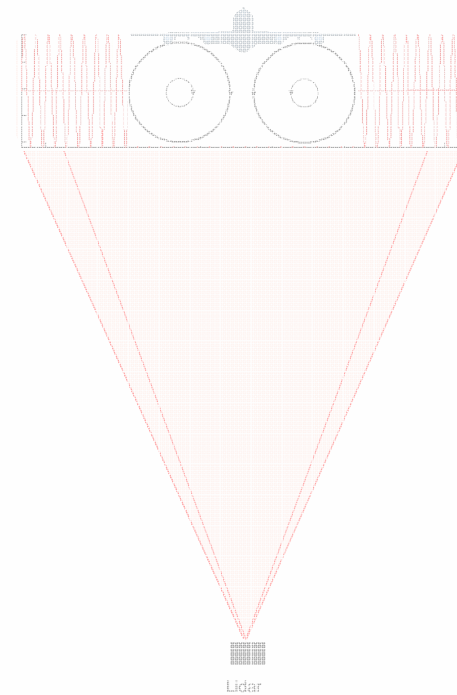
Détection axiale  
Embarquée ou sol

# Mesure des « wake vortex » par lidar



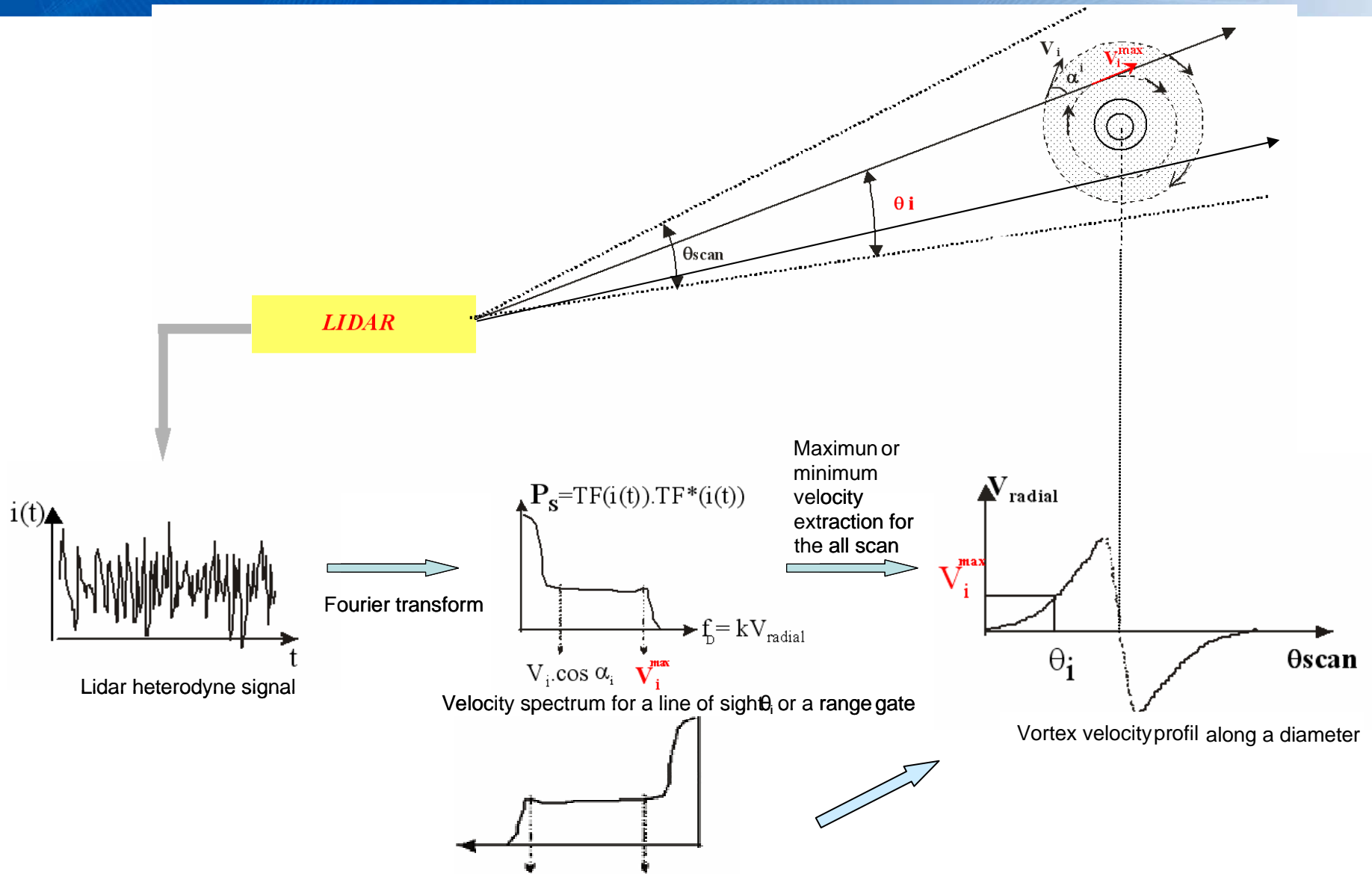
## Détection transversale sol :

- mesures sur maquettes
- mesures sur site aeroportuaire

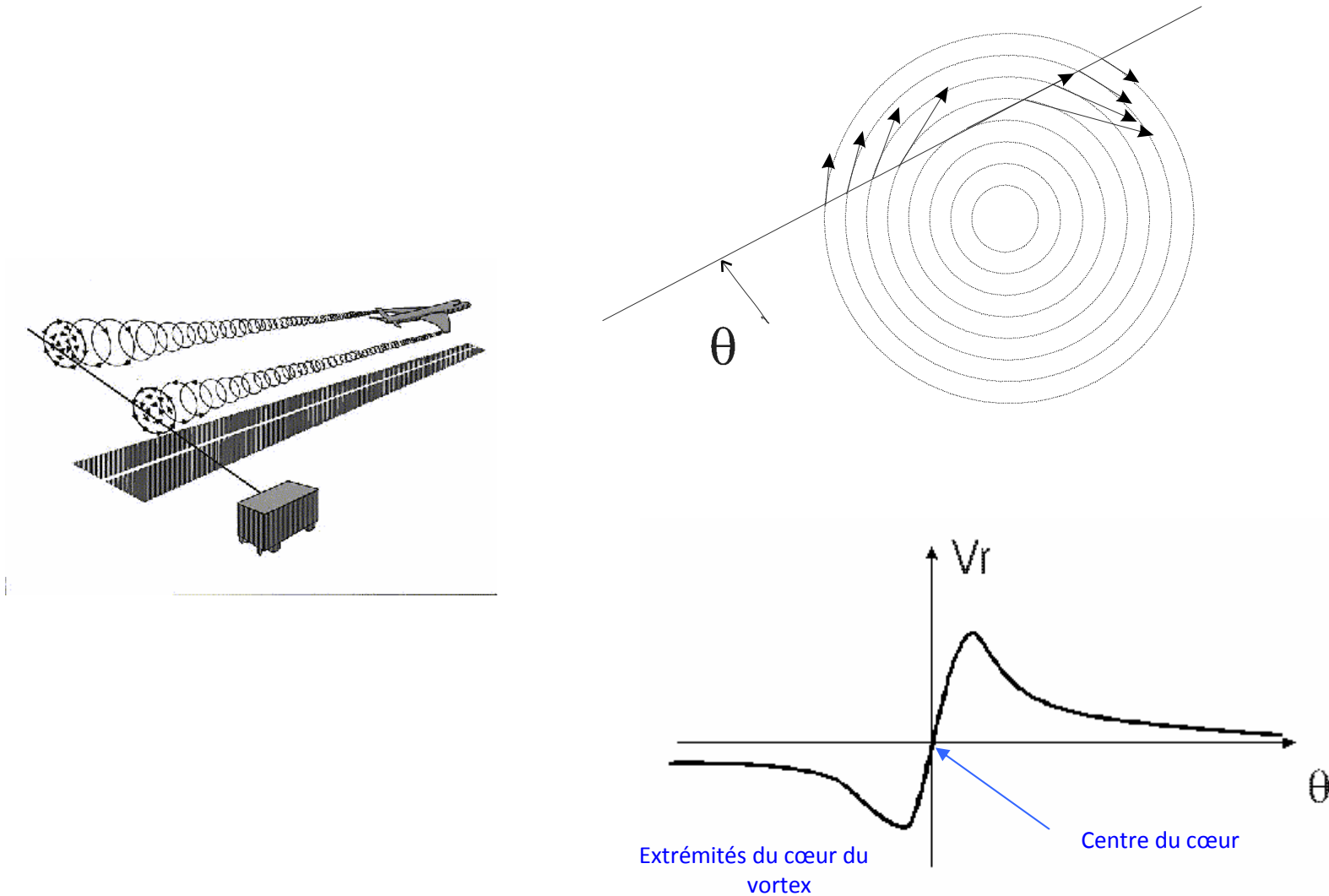


## Détection axiale Embarquée ou sol

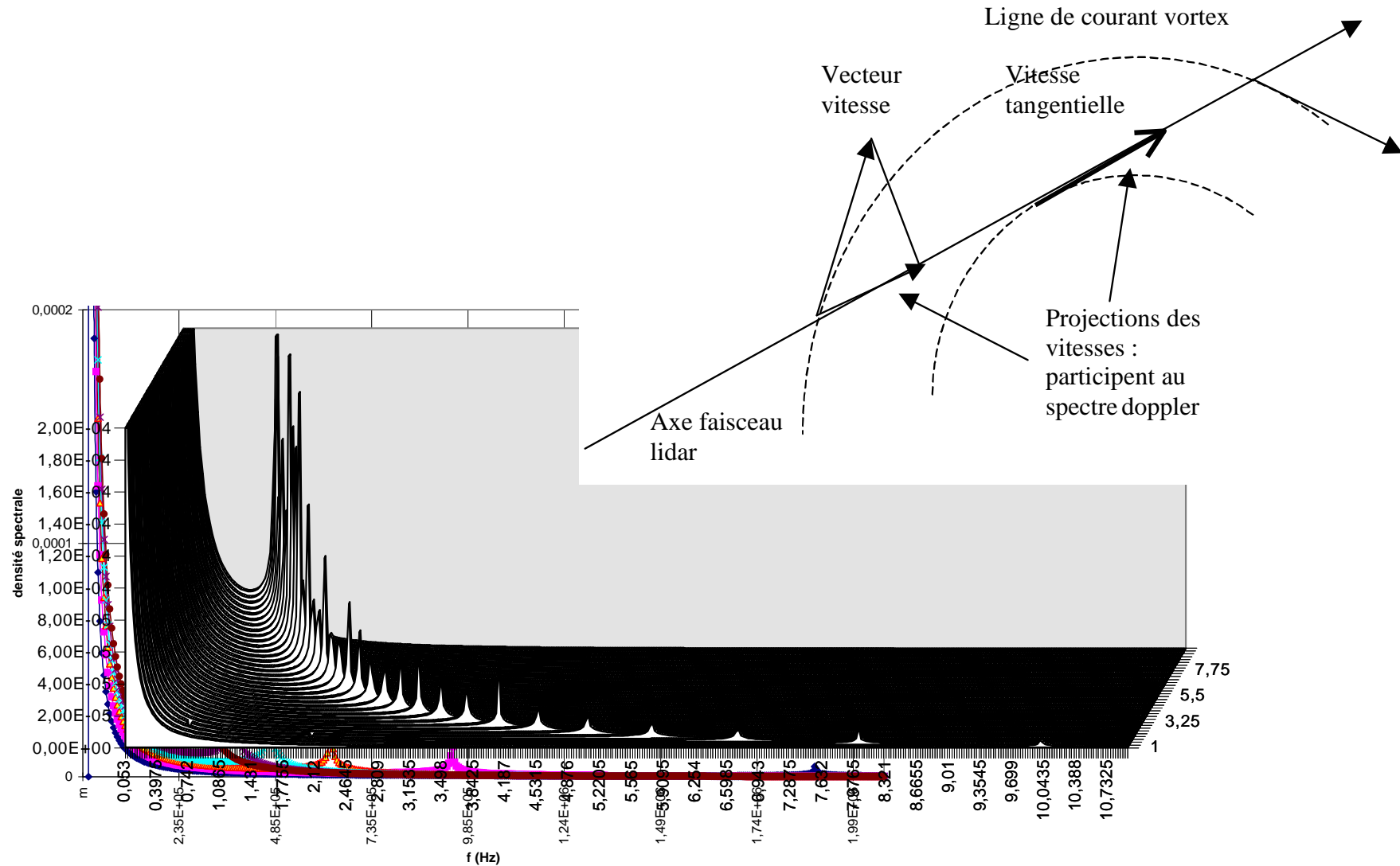
# Lidar Doppler wake vortex : Mesure transverse



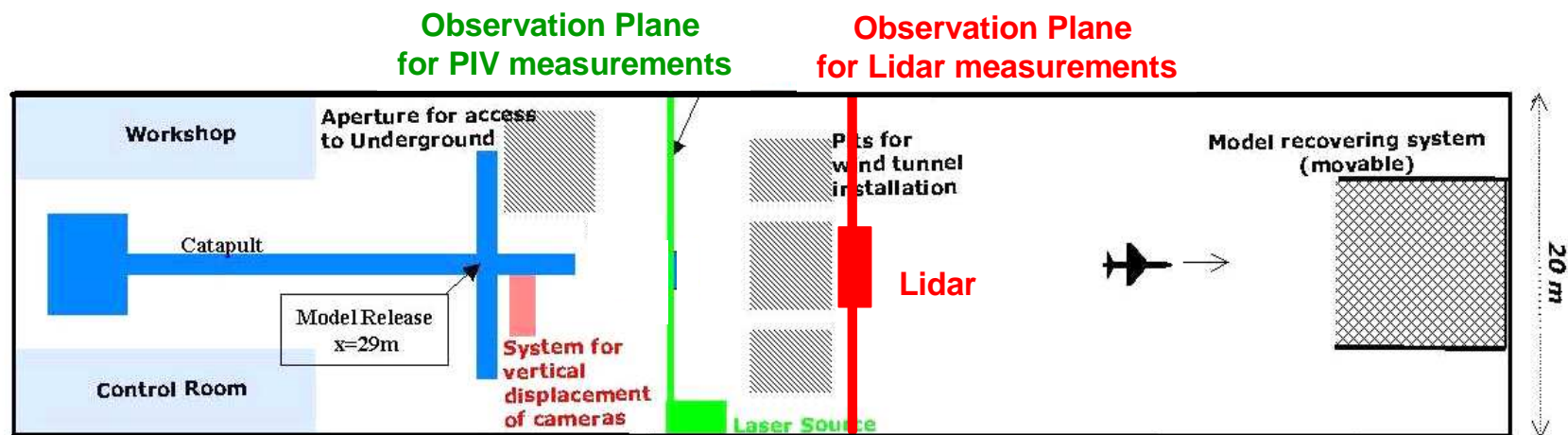
# Lidar Doppler wake vortex : Mesure transverse



# Lidar Doppler wake vortex : Mesure transverse

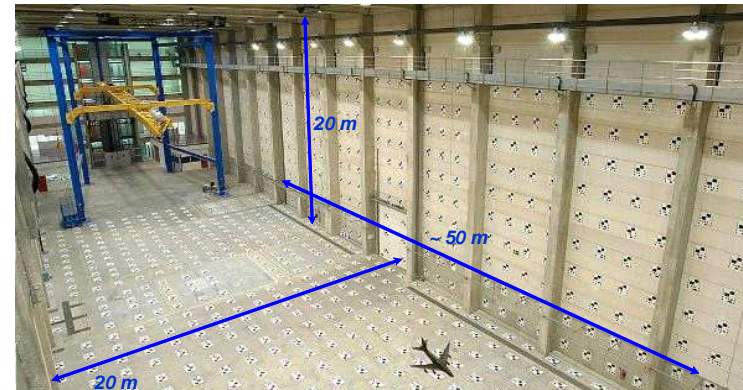
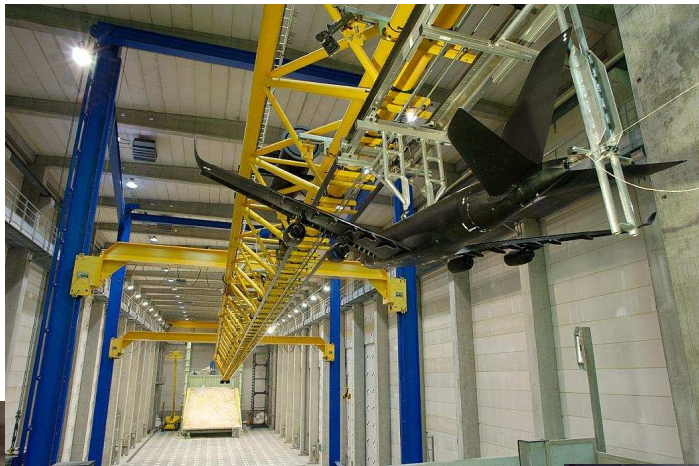


# Wake vortex de maquettes d'avions : Mesures au B20

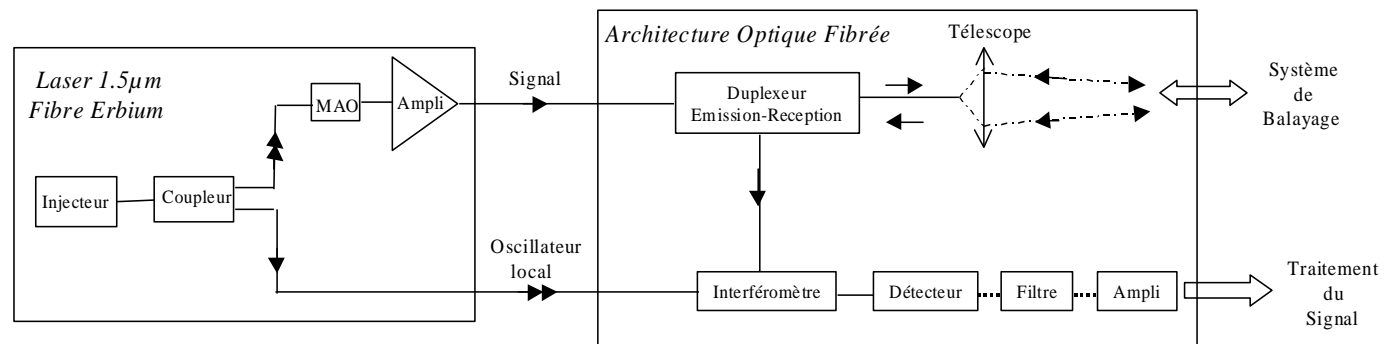
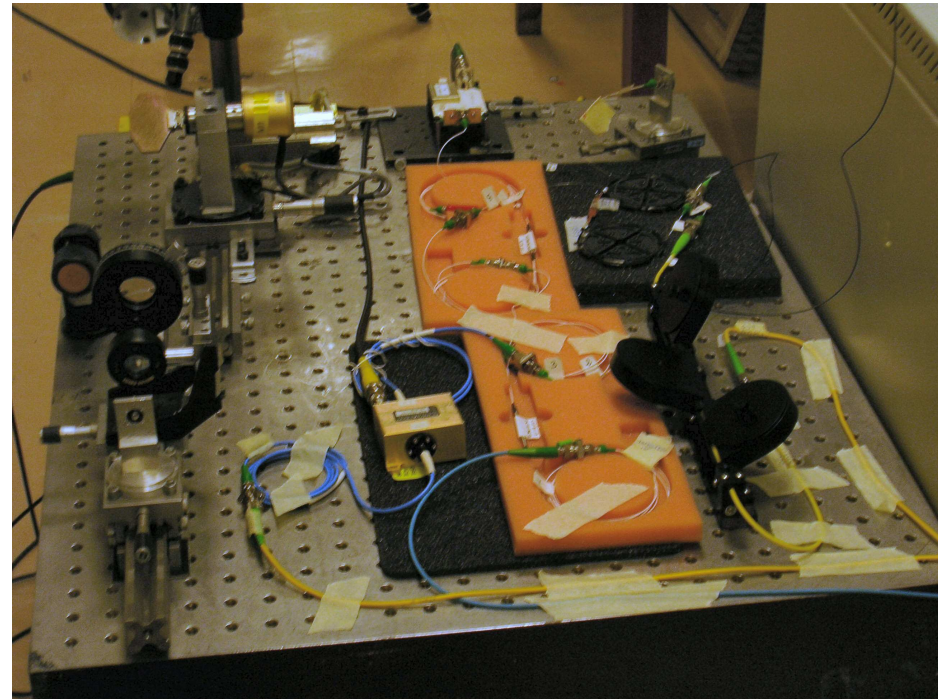
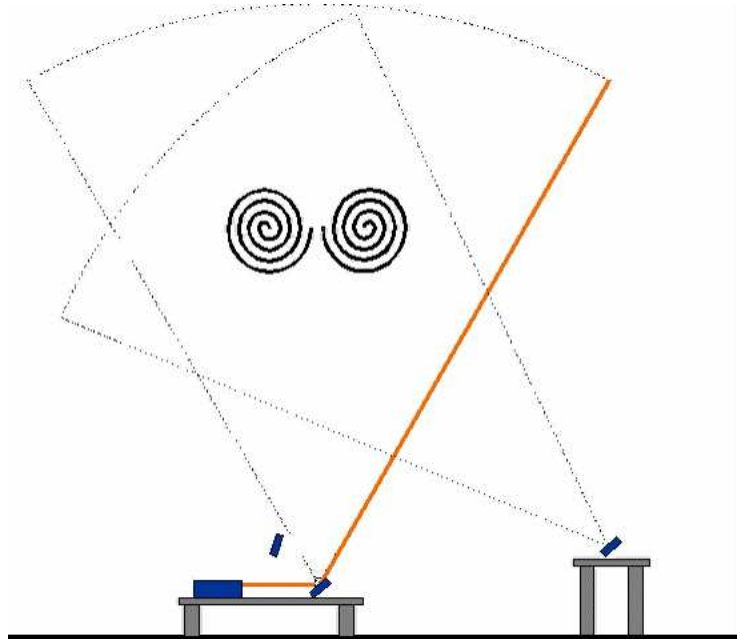




# Wake vortex de maquettes d'avions : Mesures au B20

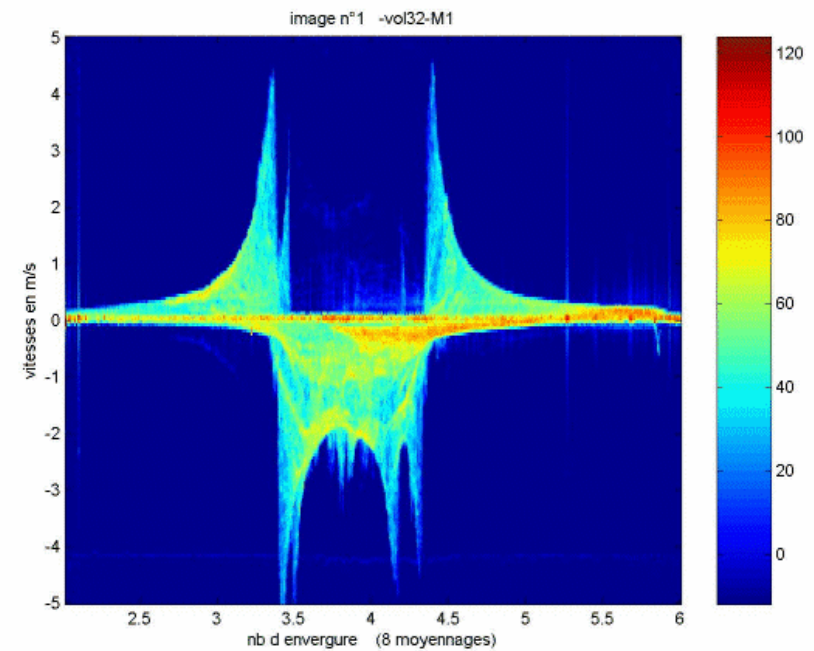
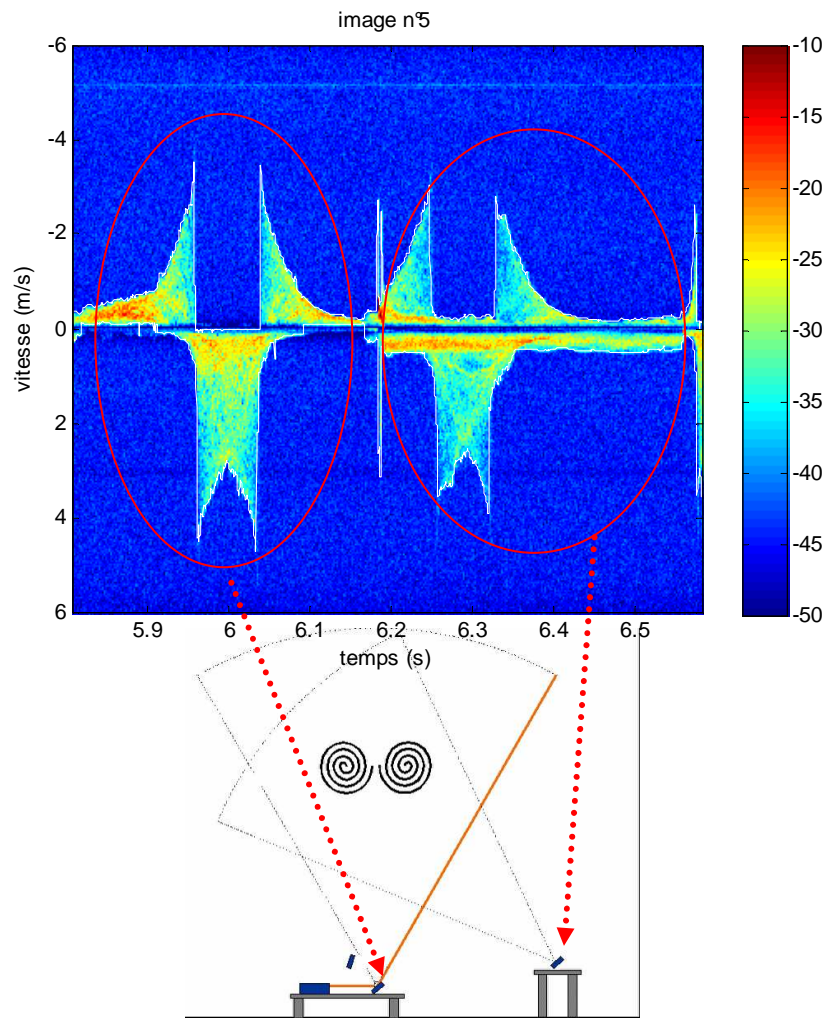


# Mesure de turbulence de sillage en échelle réduite



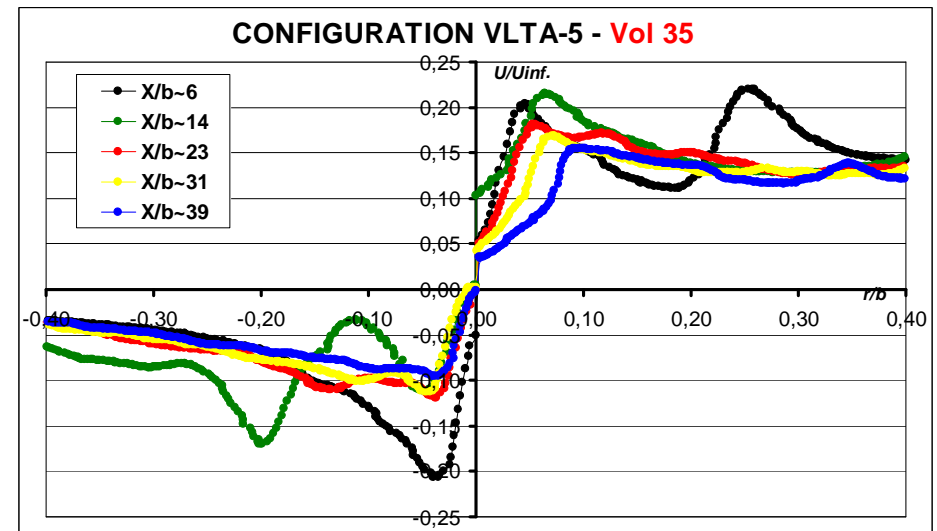
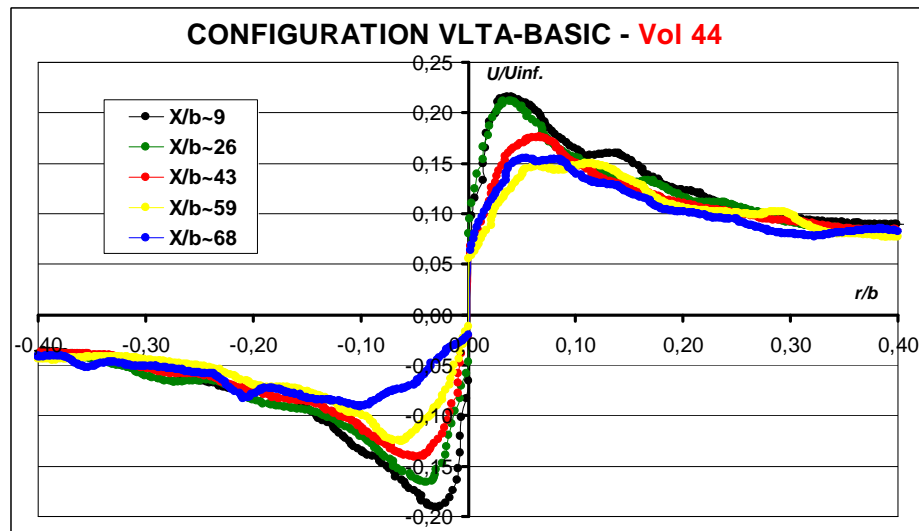
# Mesure de turbulence de sillage en échelle réduite

l'atmosphère estensemencée avec de fines gouttelettes d'huile d'olive.

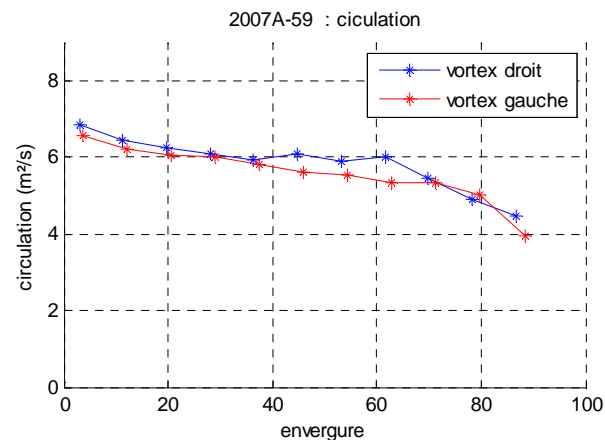
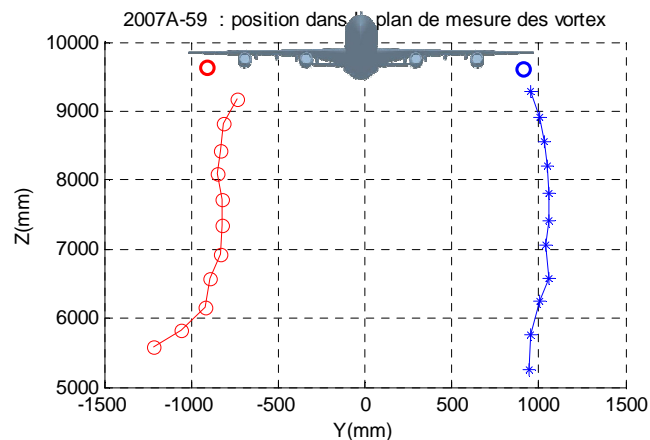
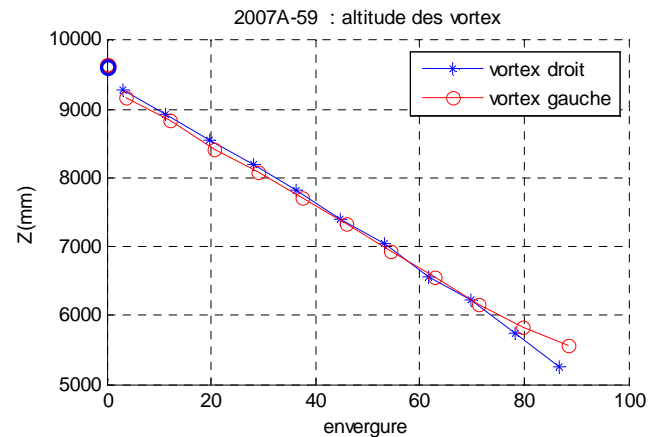
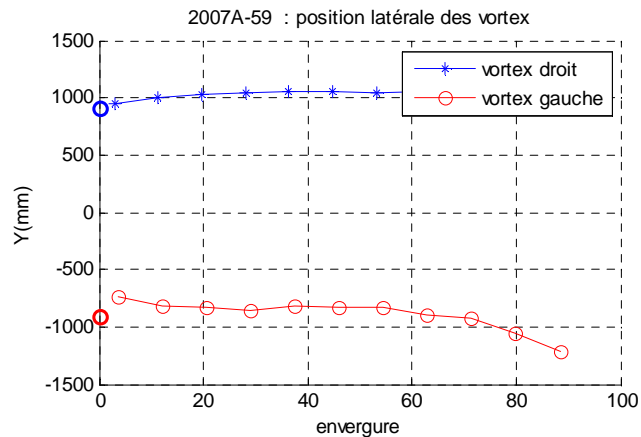


# Mesure de turbulence de sillage en échelle réduite

## Comparaison de configurations de voilure

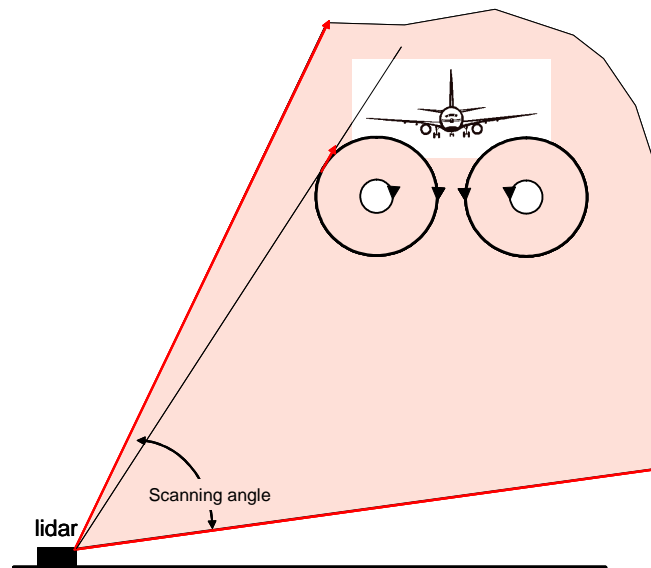


# Mesure de turbulence de sillage en échelle réduite



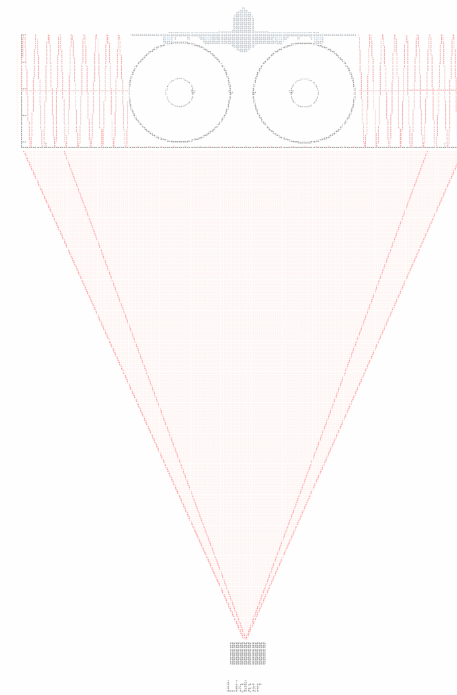
Circulation :  $\Gamma(r) = 2\pi r v_{\theta}(r).$

# Mesure des « wake vortex » par lidar



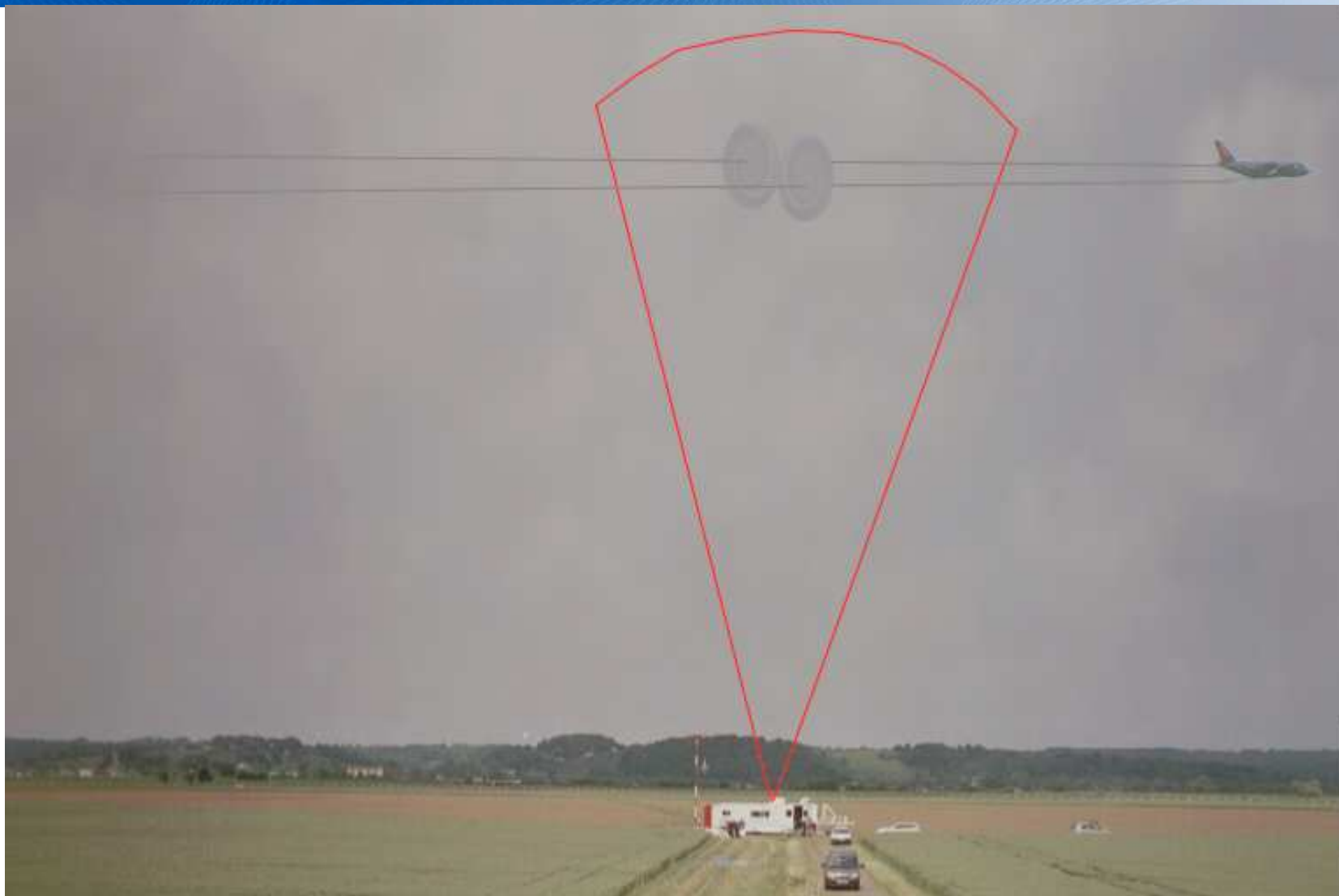
## Détection transversale sol :

- mesures sur maquettes
- mesures sur site aeroportuaire



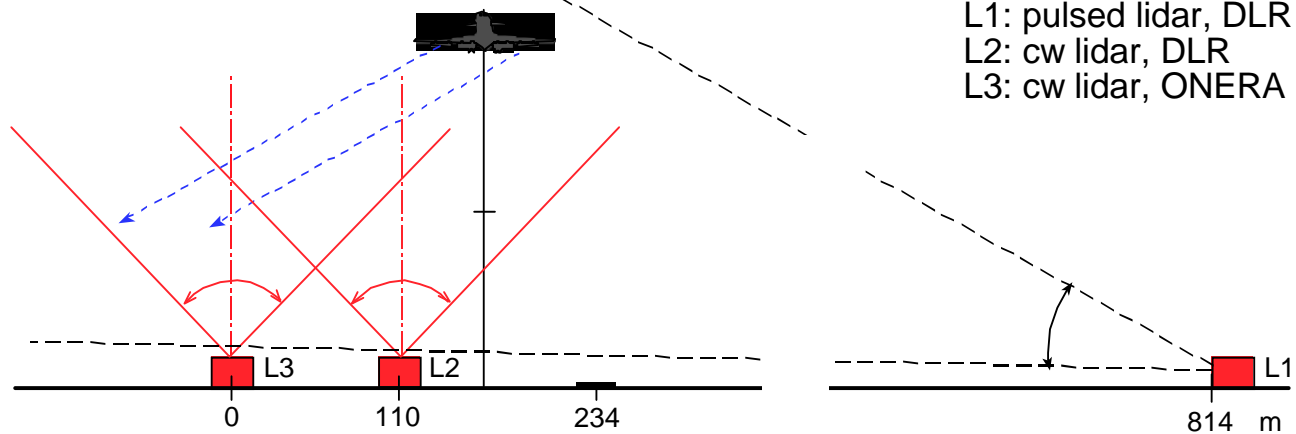
## Détection axiale Embarquée ou sol

# Mesures sur site aéroportuaire

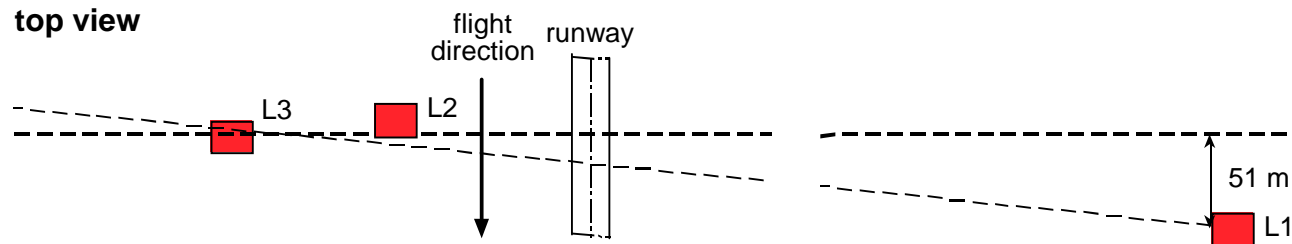


# Mesures sur site aéroportuaire Campagne AWIATOR à Tarbes

view along  
LOS of lidar L1

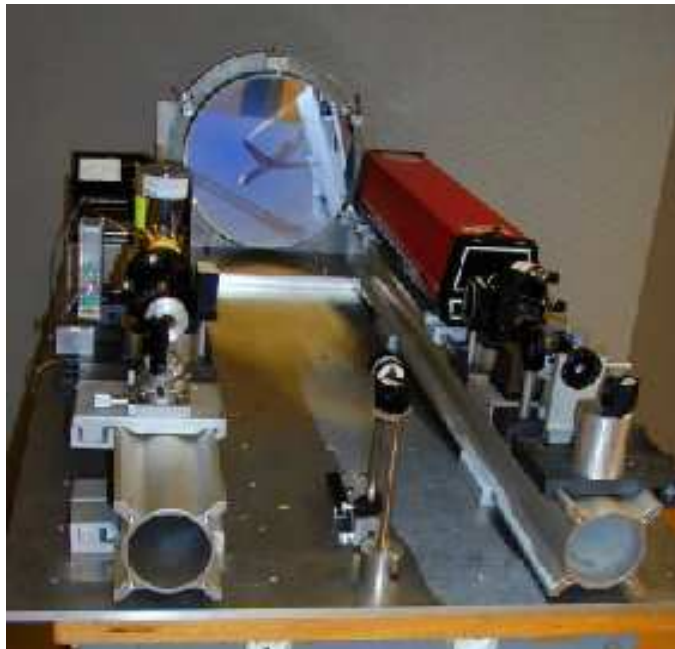


top view





# Mesures sur site aéroportuaire Campagne AWIATOR à Tarbes



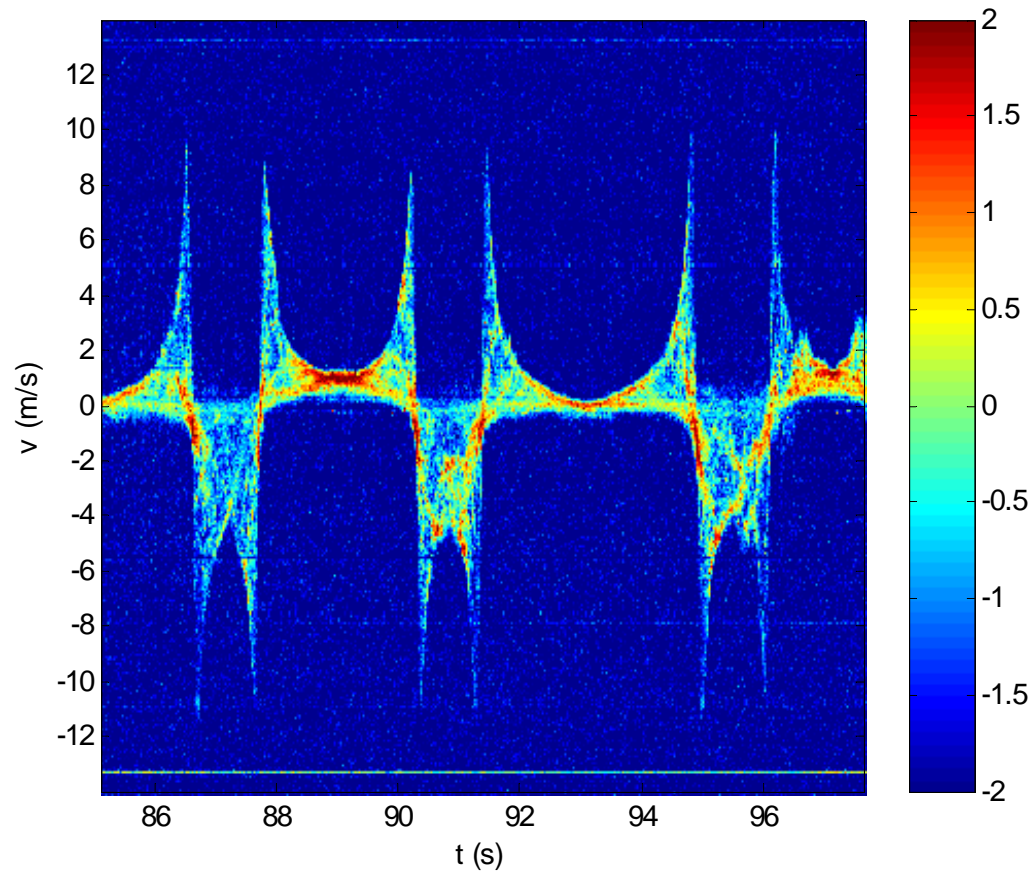
30 cm diameter aperture  
6W CO<sub>2</sub> CW laser  
+ heterodyne detection  
velocity resolution      5 cm/s  
velocity range:          +/-50m/s



Maximum speed :      35° / s  
Max acceleration : 200° /s<sup>2</sup>  
Position accuracy :    0.04°

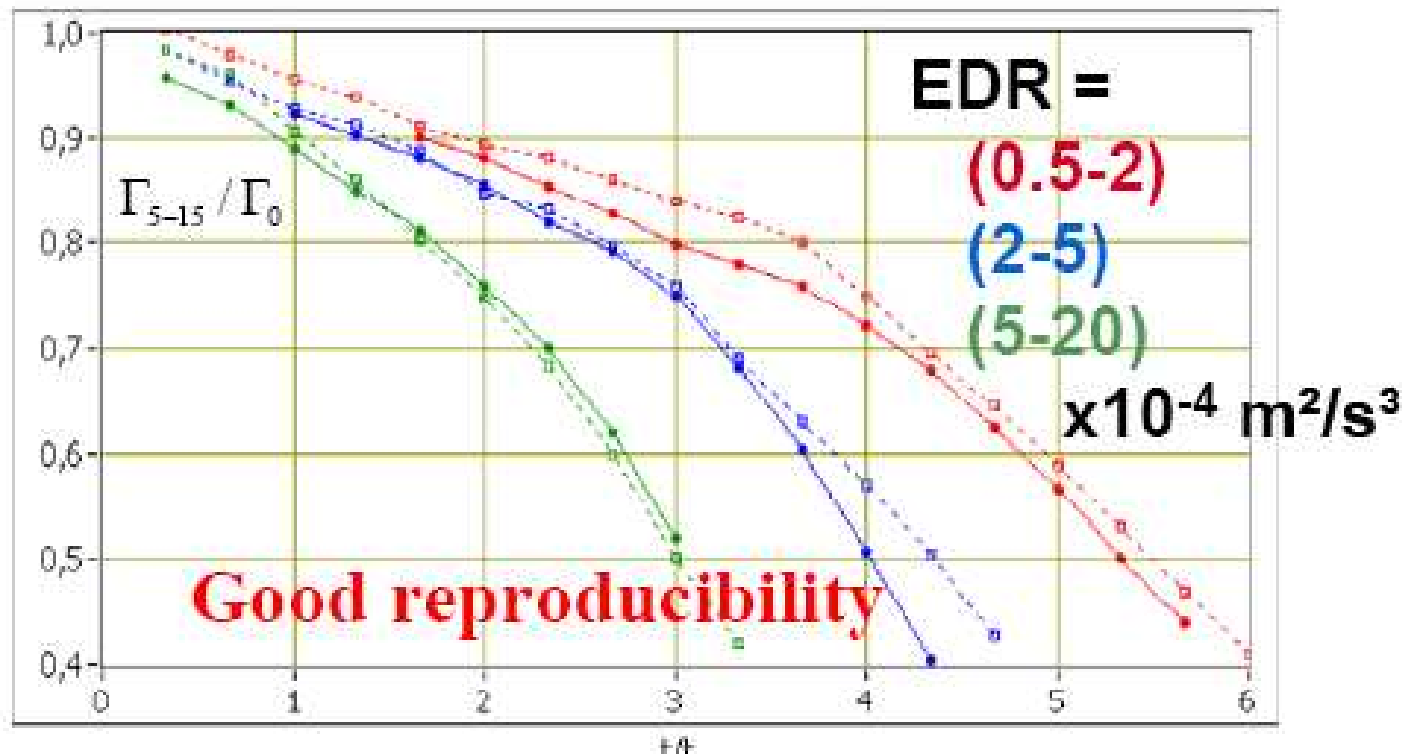
# airport measurements

Velocity (au)



Time (s)

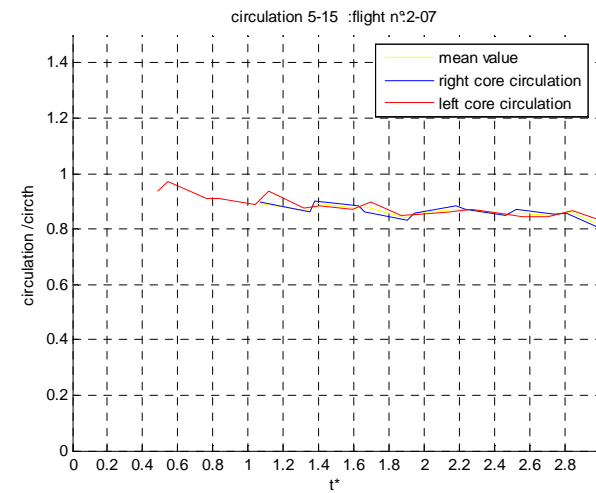
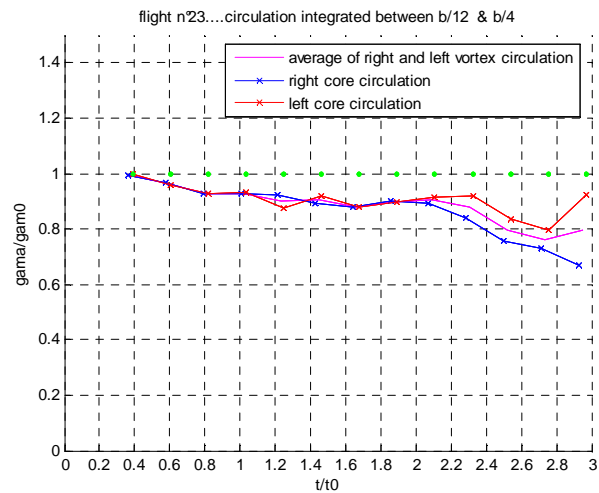
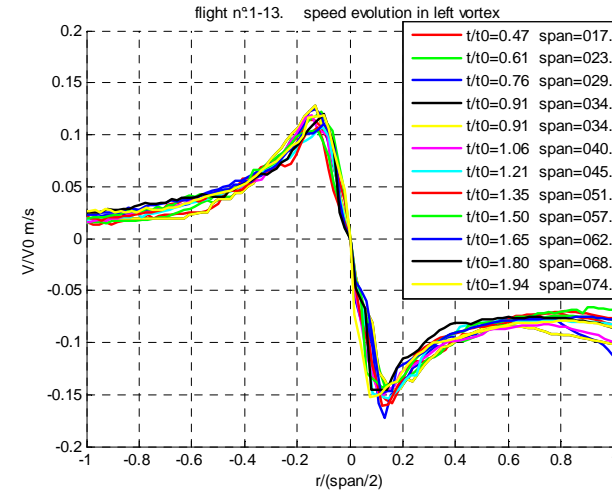
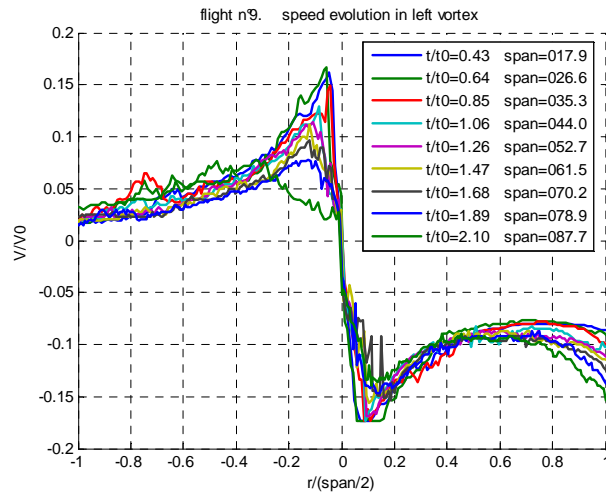
# Influence de l'atmosphère sur la durée de vie des vortex



EDR mesurés par le lidar pulsé 2  $\mu\text{m}$

# Comparison des mesures échelle réduite / aéroport

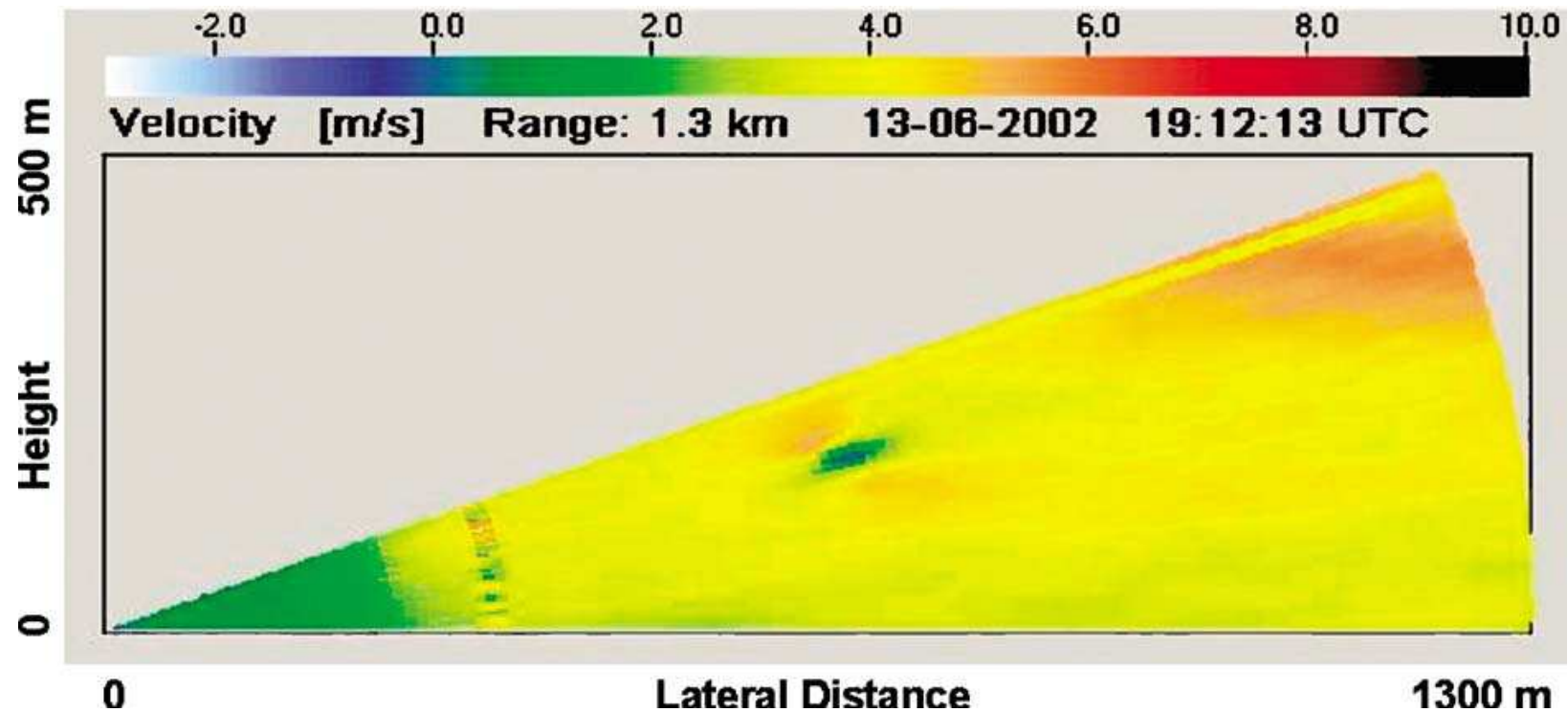
Utilisation d'échelles réduites (spatiale  $x/b$ , vitesse  $V/V_0$ , temporelle  $t/t_0$ )



## Détection des vortex par lidar impulsif

Etat de l'art : techno laser solide à 2 $\mu$ m

Système lidar du DLR avec source laser Looked Martin Coherent Technologie (LMCT)



# Détection des vortex par lidar impulsif

## Technical details of DLR's Lidar

pulsed Doppler, heterodyne  
light backscattered by aerosols

Transceiver MAG-1 (prototype CTI -> LM):

Tm:LuAG laser	
wavelength	2.022 $\mu\text{m}$
repetition rate	500 Hz
pulse energy	2 mJ
pulse length	0.5 $\mu\text{s}$

Off-axis telescope:

aperture	10 cm
----------	-------

Scanner (2 prisms):

elevation sector	0 - 30°
scan speed	2 °/s

Data acquisition:

early digitising with quick-look	500 MHz
-------------------------------------	---------

Signal processing:

four-stage algorithm



Deutsches Zentrum  
für Luft- und Raumfahrt e.V.  
in der Helmholtz-Gemeinschaft

WakeNet-3 / GreenWake WS on

Physik der Atmosphäre  
des R&D in Palaiseau, 4

# Détection des vortex par lidar impulsif

Etat de l'art : techno laser solide à  $2\mu\text{m}$

Windtracer ( LMCT)

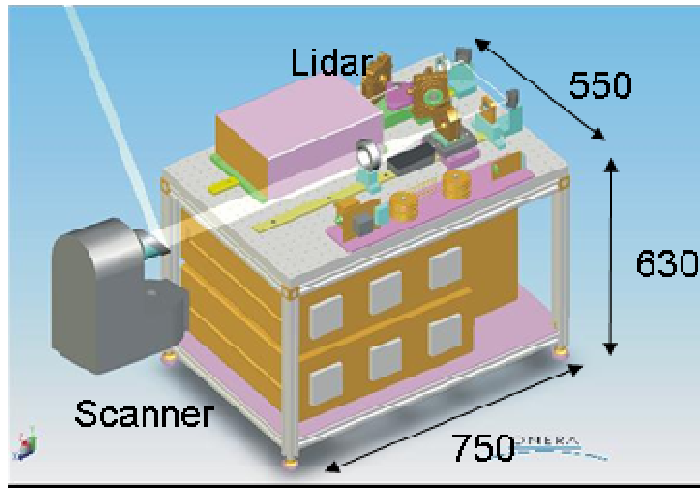


Techno chère

Alternative : laser à fibre impulsif  $1.5\mu\text{m}$

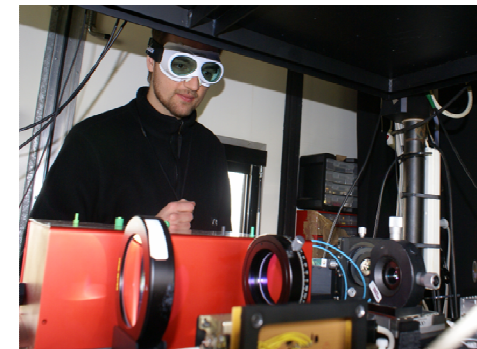
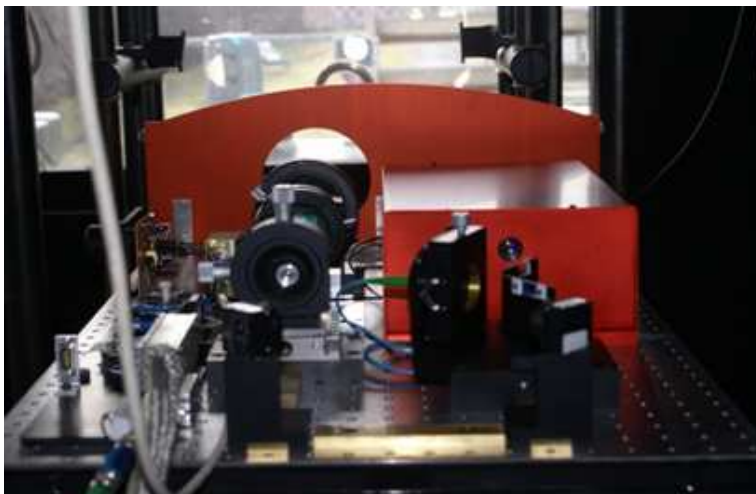
Utilisation de composants optiques telecom

# Description du lidar SWAN réalisé pour la campagne de mesures CREDOS à Francfort (Février-Mars 2007)



## Caractéristiques du lidar

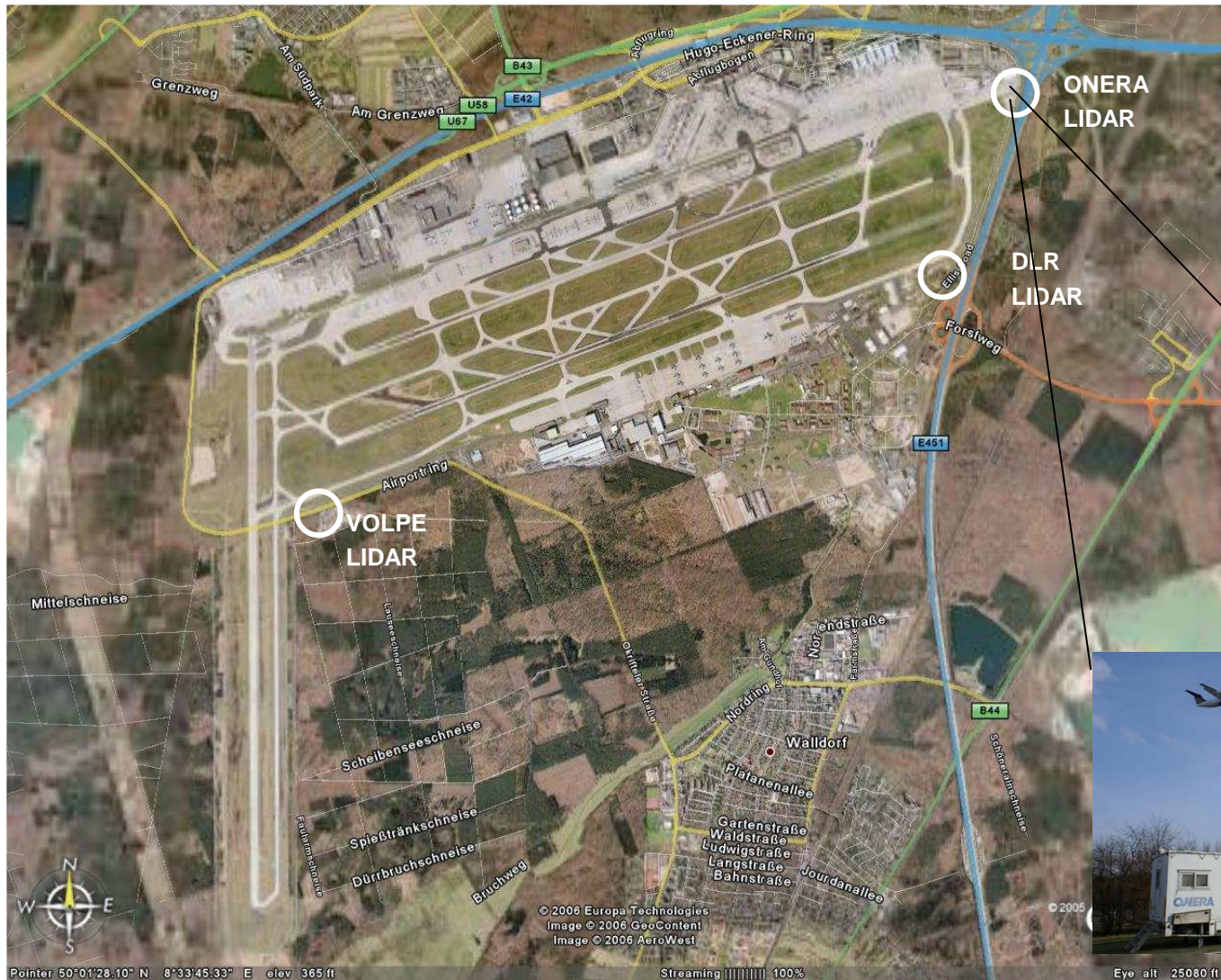
- Longueur d'onde: **1.55  $\mu\text{m}$**
- Energie laser: **60  $\mu\text{J}$**
- Durée pulse laser : **200ns** Paramètres ajustables
- Cadence laser: **15kHz**
- largeur spectrale laser: **<0.5MHz**
- M2=1.3
- Maintien de polarisation



- Portée : **50m à 400m**
- Résolution en vitesse: **< 1 m/s**
- Cadence image : **0.25Hz**



# Tests CREDOS à l'aéroport de Francfort (Février-Mars 2007)



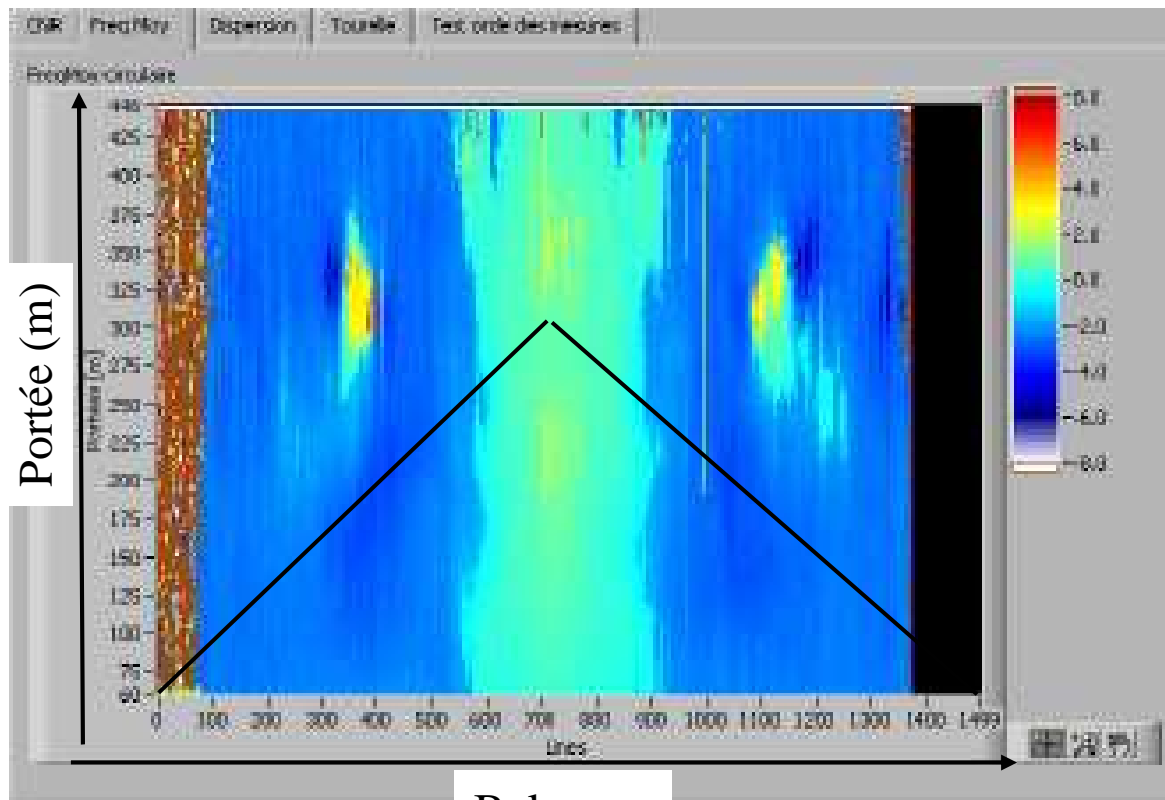
# CREDOS : Affichage temps réel du champ de vitesses

Développement d'un traitement et affichage temps reel du champ de vitesse

Résolution spatiale longitudinale : 2.4 m

Résolution spatiale latérale : 35 cm@200m(0,1° )

Résolution vitesse: < 1 m/s



Carte des barycentres de vitesse

Temps 1 balayage=4s

Nombres cases distance=185

# CREDOS : Affichage temps réel du champ de vitesses

Résolution spatiale longitudinale : 2.4 m

Echantillonnage 500 MHz,

FFT sur des portes de de 512 points, et décalage de 8 points

→ resolution spatiale =  $c * (8 / 500E6) / 2 = 2.4$  m

Résolution spatiale latérale : 35 cm@200m(0,1° )

laser 15 kHz + balayage 15° /s : un tir laser tout les 0.001 °

**moyennage de 100 spectres** → 0.1 °

Résolution vitesse: < 1 m/s

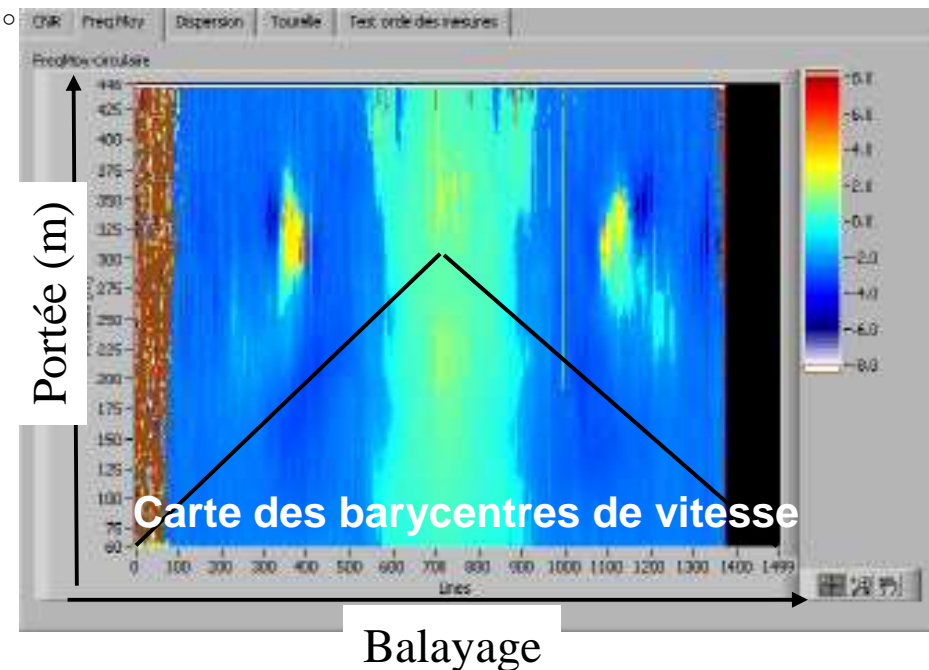
Fech=500Mhz → Fmax = 250 Mhz

$$v_{\max} = \frac{F_{\max} * \lambda}{2} \quad v_{\max} = 193 \text{ m/s}$$

$$\Delta V = v_{\max} / 512 * 2 = 0.75 \text{ m/s}$$

Temps 1 balayage=4s

Nombres cases distance=185



# Traitement du signal pour le lidar vortex

Les paramètres des vortex à mesurer sont :

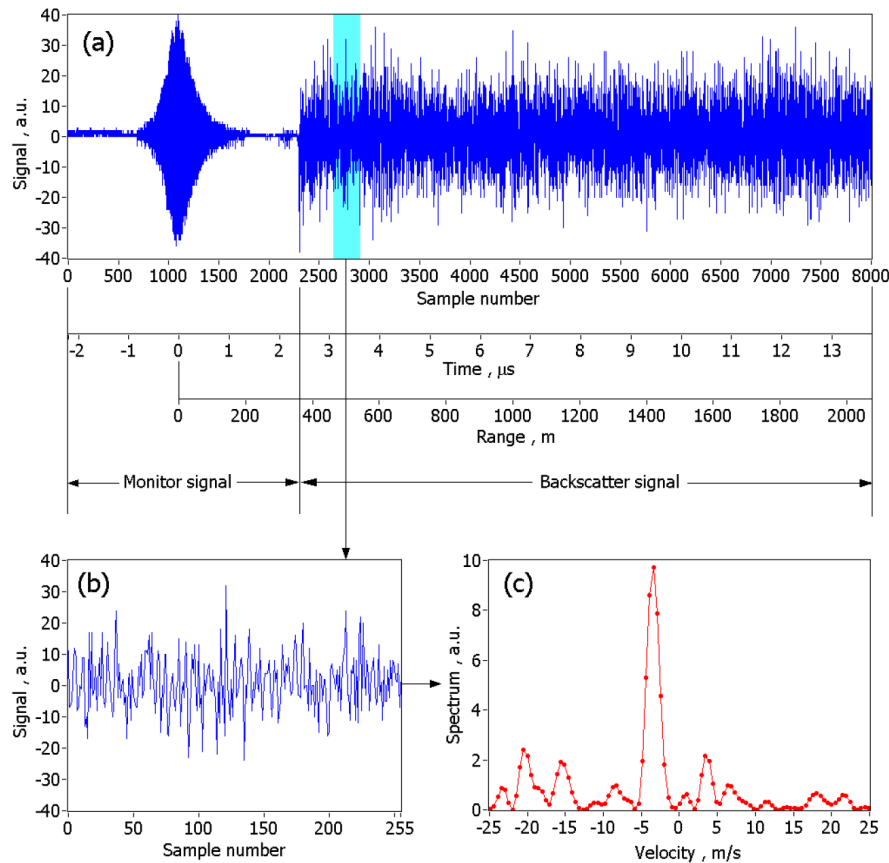
- La position des cœurs des tourbillons
- Les profils de vitesse des tourbillons
- La circulation

# Traitement du signal pour le lidar Doppler vortex pulsé (1/6)

## Four-stage process: Stage 0

raw data:

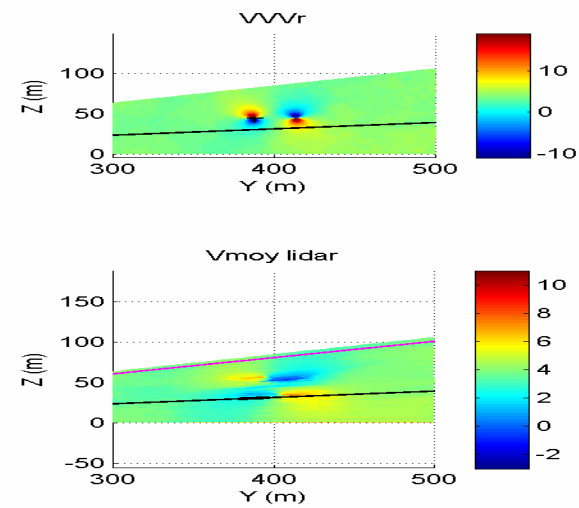
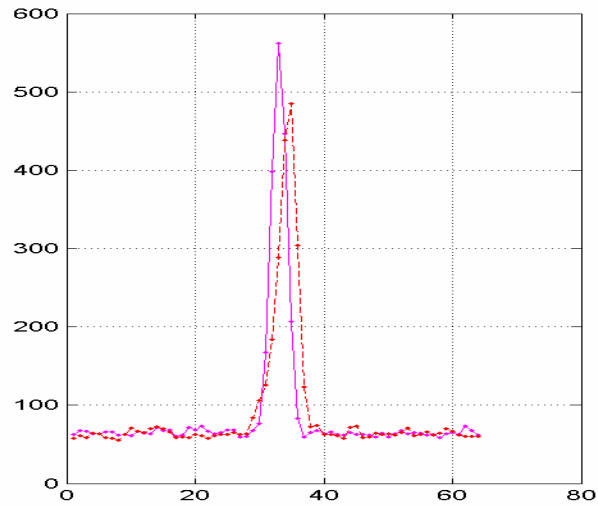
- heterodyne signal of laser pulse
- atmospheric backscatter signal (2 ns/sample)



Doppler spectra:

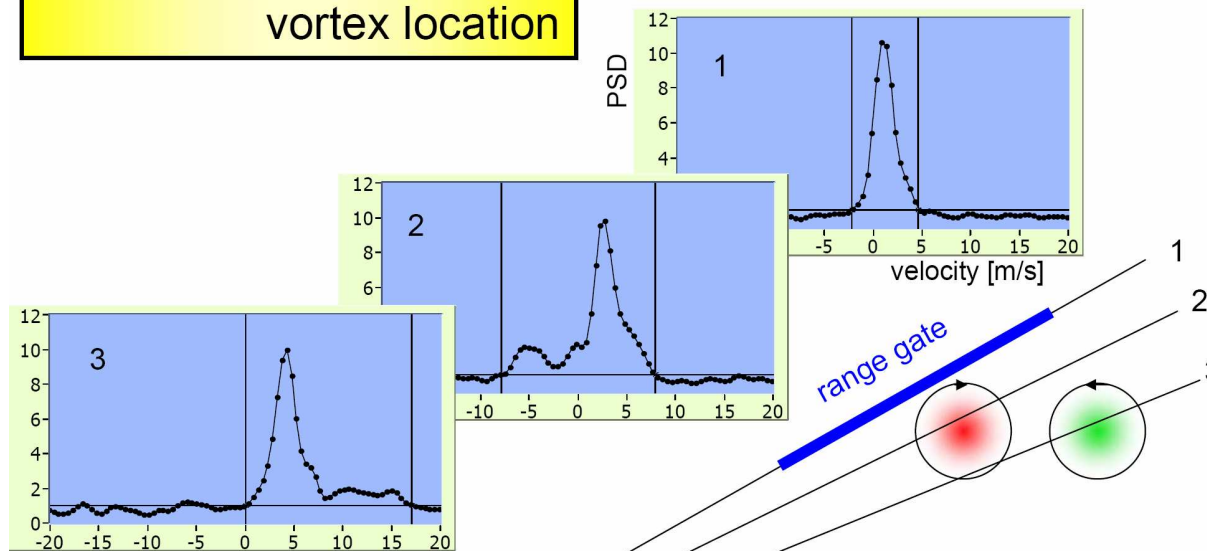
- Fourier transform (256 samples)
- with zero padding (768 samples)

# Traitement du signal pour le lidar Doppler vortex pulsé



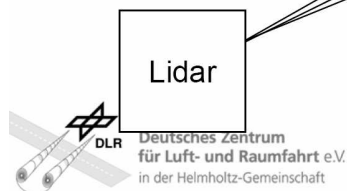
# Traitement du signal pour le lidar Doppler vortex pulsé (2/6)

Stage 1: Spectra at wake vortex location



25 shots accumulated  
definition of velocity minima and maxima:

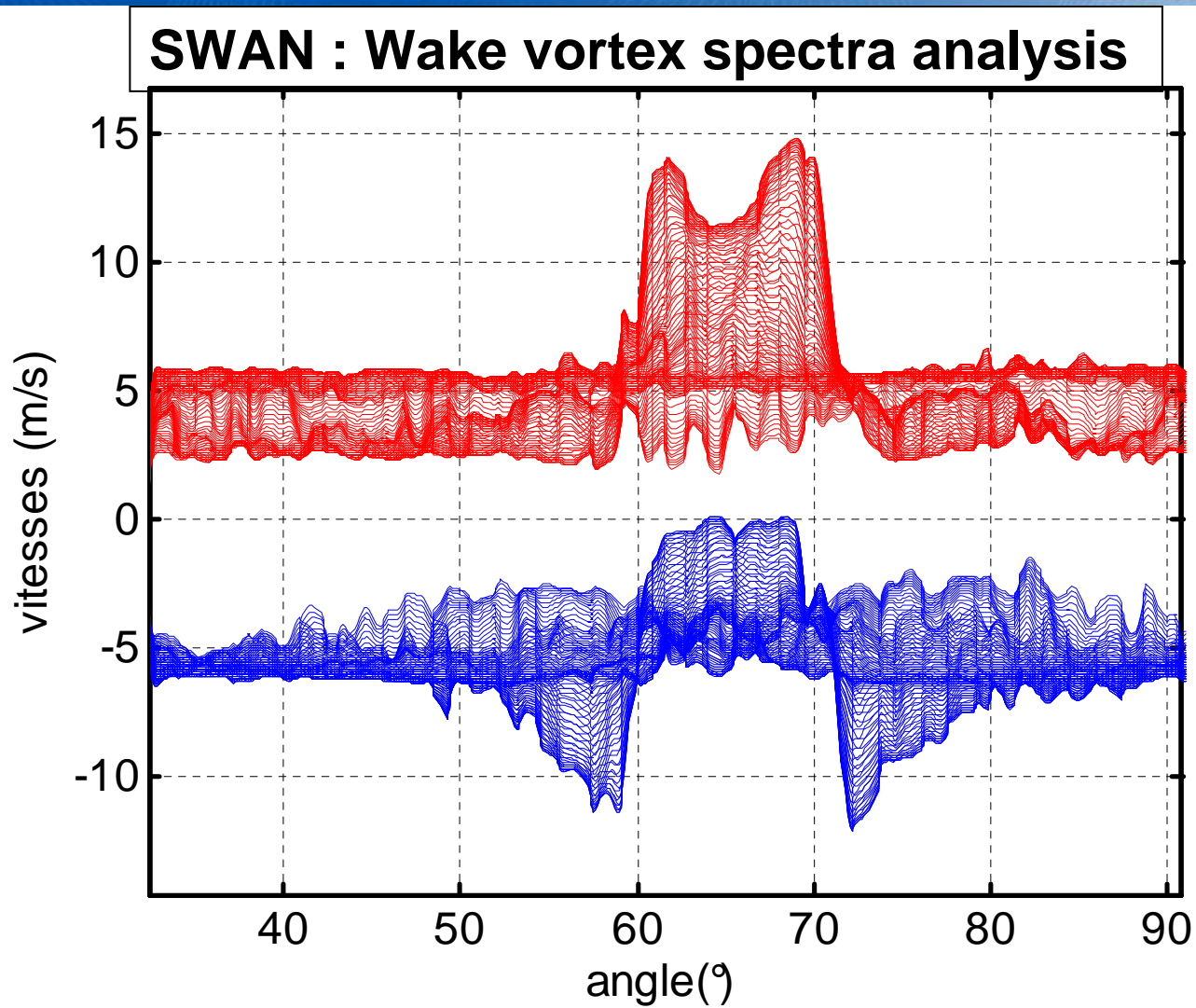
- selection of threshold
- search of first intersections  
left and right of main spectral peak



Thomas Gerz, Institut für Physik der Atmosphäre

WakeNet-3 / GreenWake WS on WV & Wind Monitoring, 29. -30. March 2010 at Thales R&D in Palaiseau, 6

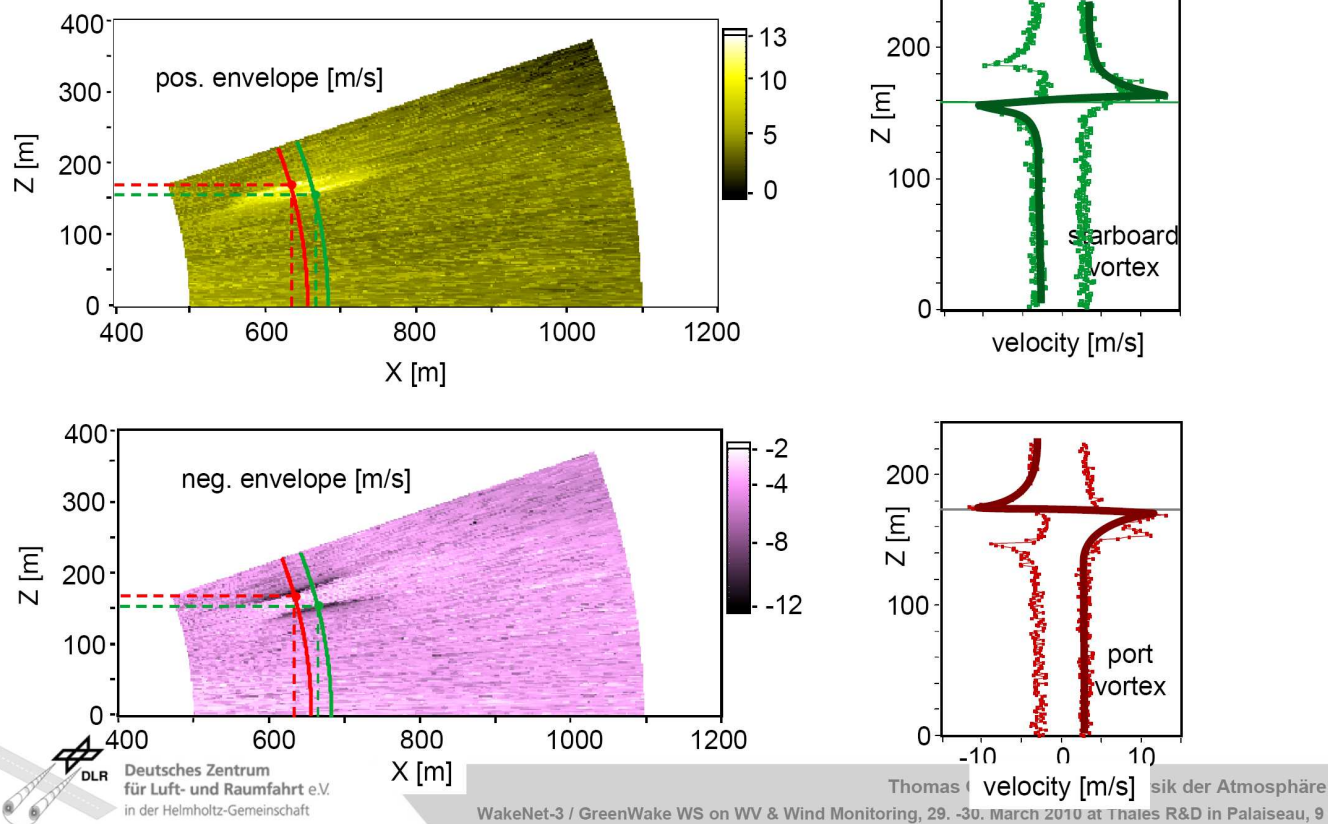
## Traitement du signal pour le lidar Doppler vortex pulsé (4/6)





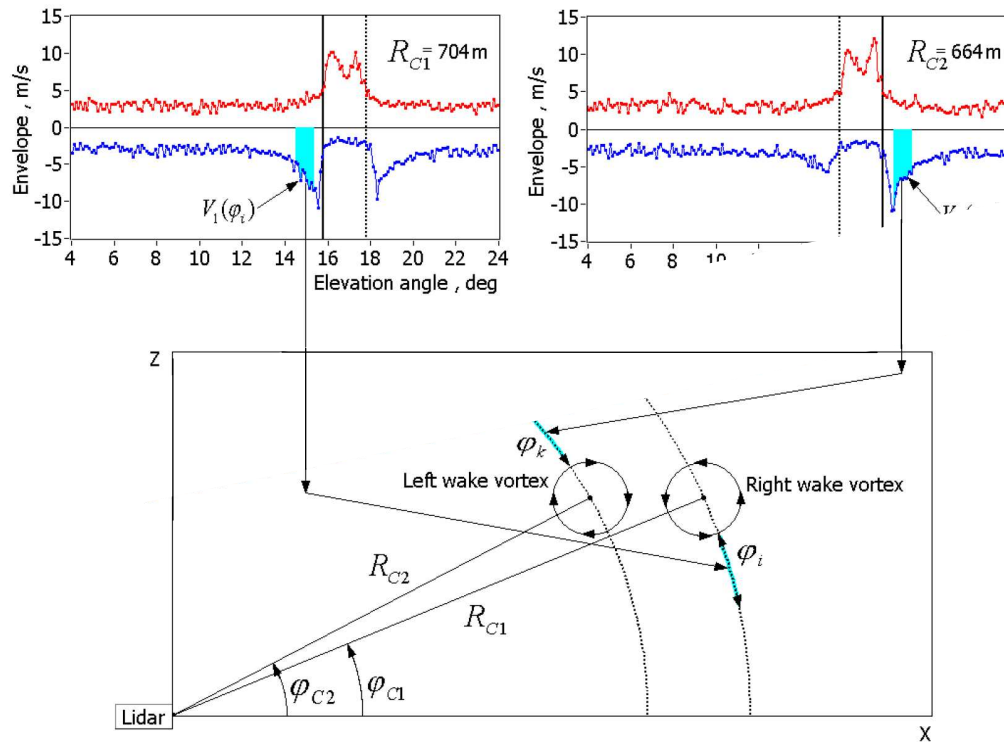
# Traitement du signal pour le lidar Doppler vortex pulsé (5/6)

**Stage 3:** (i) range and elevation of max/min signal strength:  
estimation of core position  
(ii) profiles of tangential velocity at identified ranges



# Traitement du signal pour le lidar Doppler vortex pulsé (6/6)

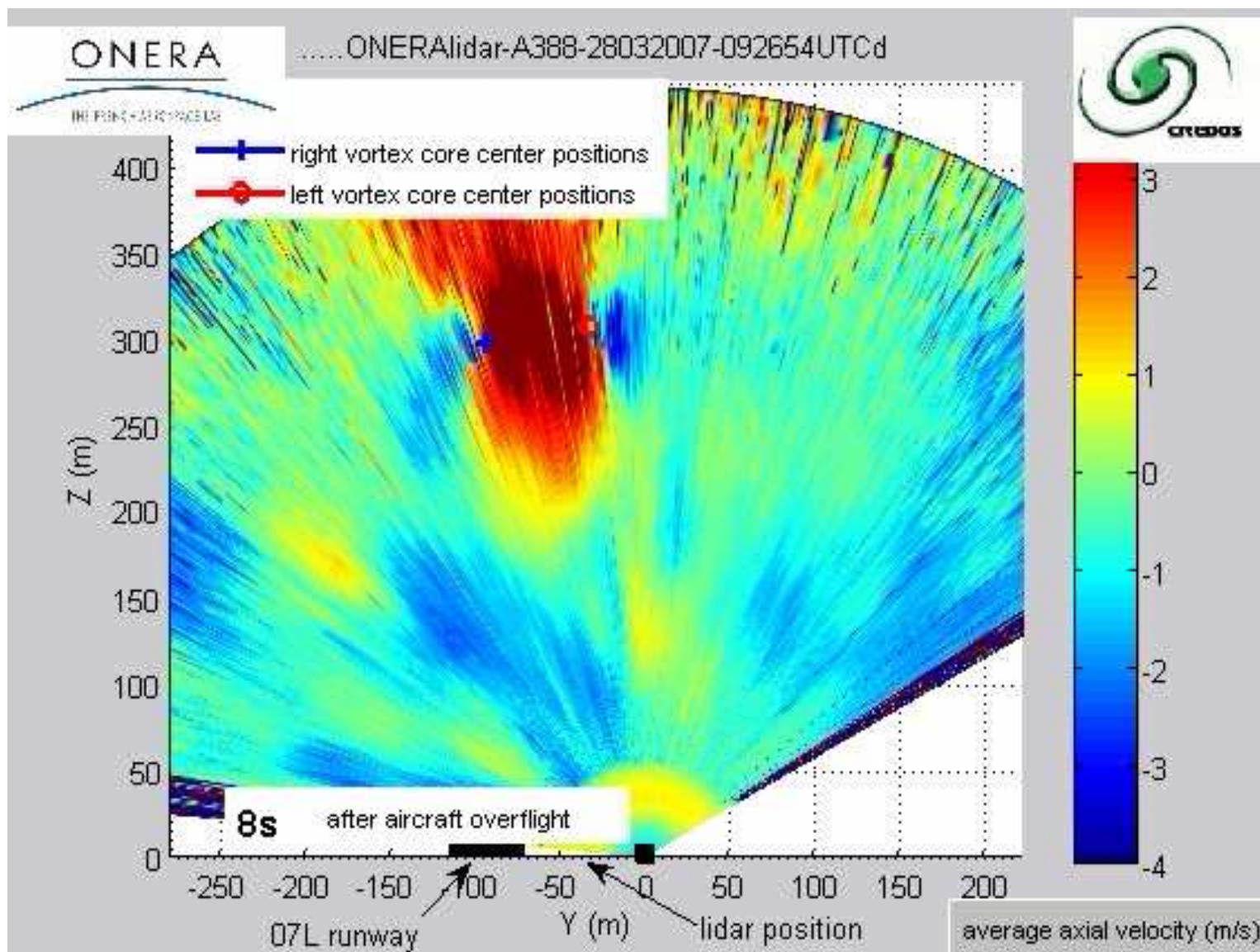
## Stage 4: compute circulation



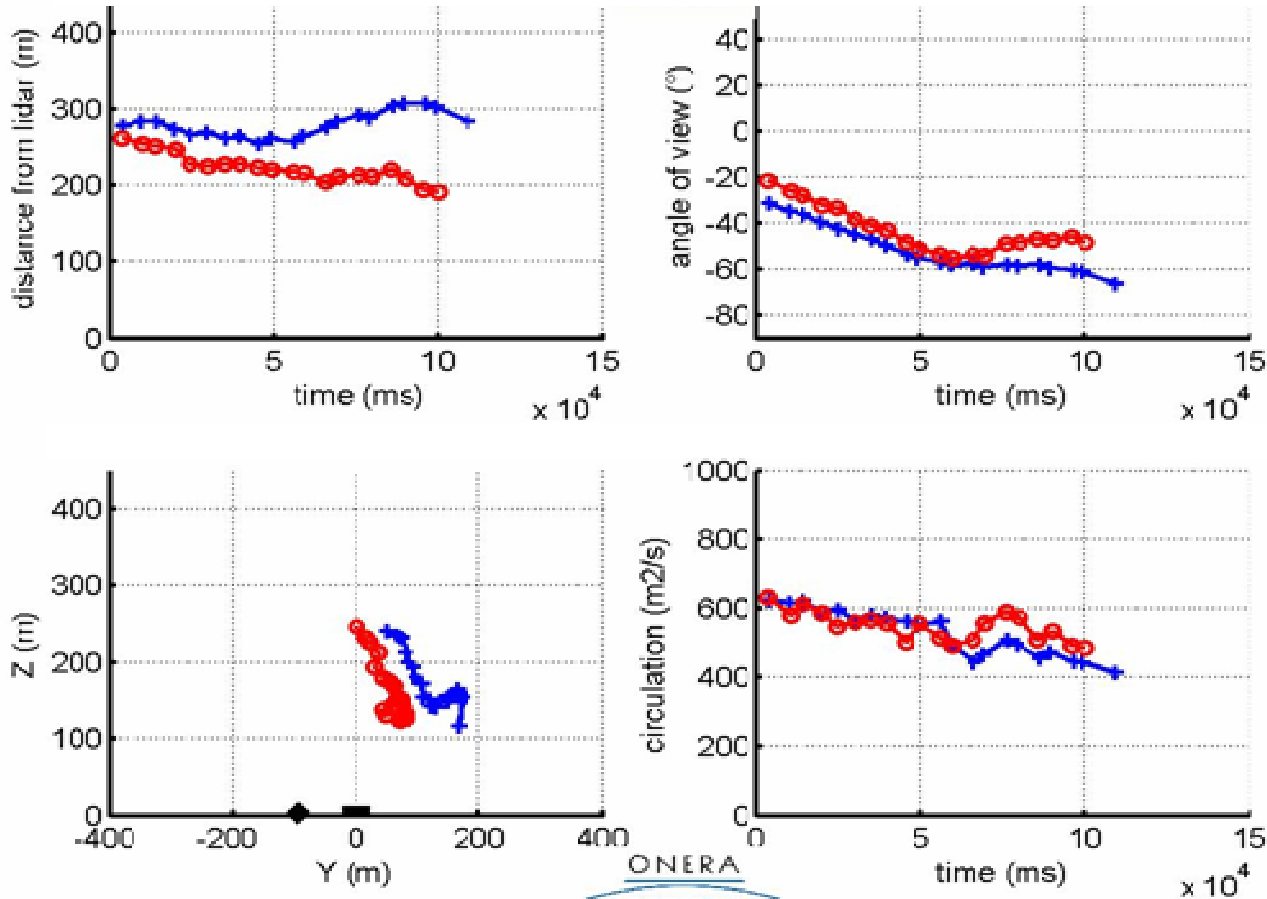
vortex circulation:  
integration method  
e.g. 5 - 15 m for  
vortices of large  $a/c$

# CREDOS CAMPAIGN Orly/Francfort 2007

## B744



# Données vortex



Ex : B747

The core position error is about  $\pm 2$  m

The circulation error is about 20%.

## Lidar deployment during SESAR XP1 Campaign

### Objectives for the lidar deployment

Proof of concept of the WV detection in real time

Perform a statistical analysis on the WV detection

Evaluate the performances in terms of detection rate and circulation

CDG Airport – France

September/October 2012

Parameters	Settings
Scanning mode	Vertical RHI
Scanner Speed	10° /s
Angular res.	0.2° (3,4m at 1km)
Spatial res.	5m (with overlap)
Time res.	20ms
Max range	~1km



# Lidar deployment during XP1 Campaign



## Development and process of the real-time WV algorithm

### WV detection algorithm

Developed and tested in CREDOS Eu project

Improved and evaluated during SESAR XP0 experiment in 2011

Very encouraging results

For the WVAS, need to have a real-time detection

### Some improvements realized for the real time detection

Increase CPU power for reducing the computation time of spectra

Focus on the region above the landings runway to quickly detect the first plot

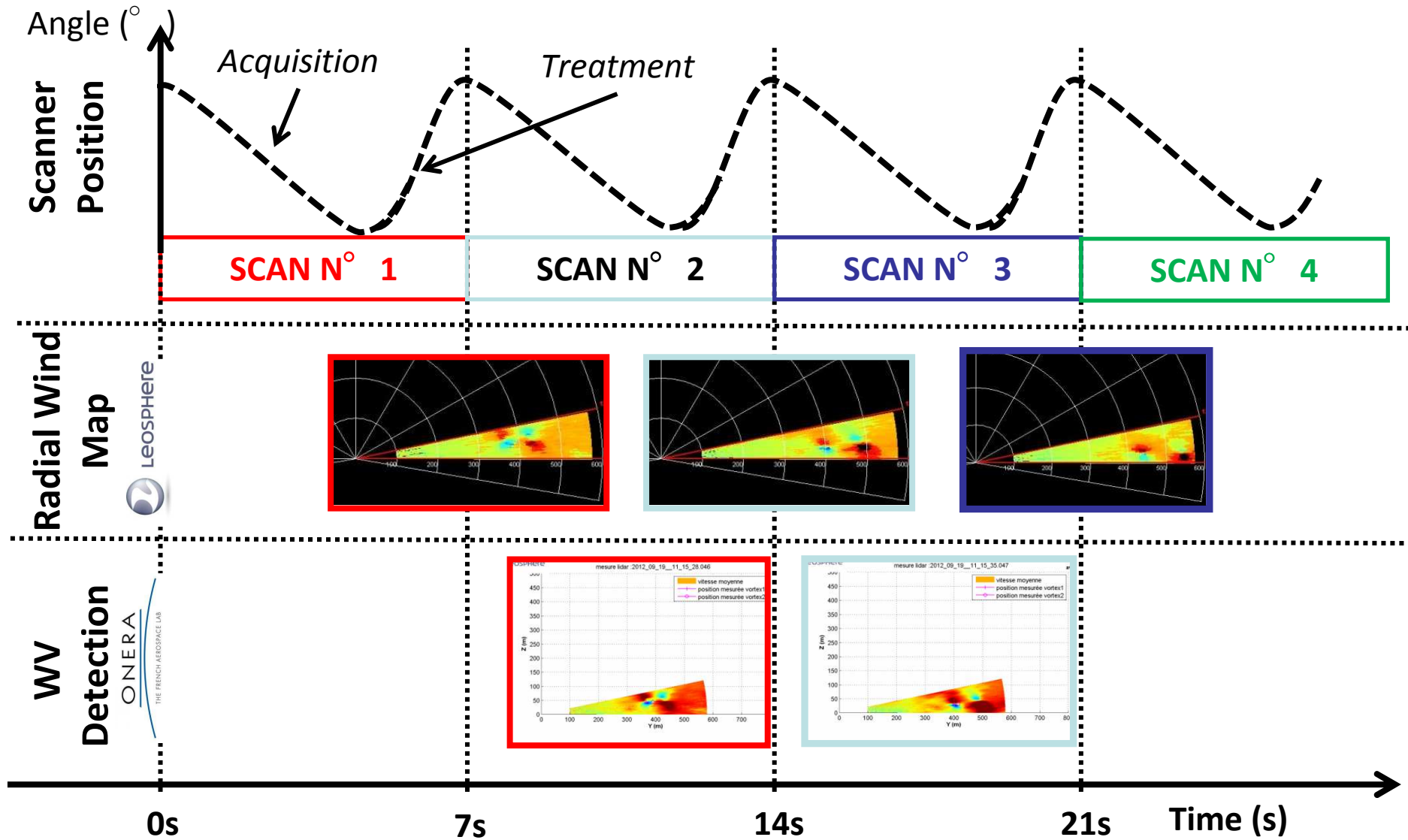
Take into account cross-winds

to quickly detect the WV knowing a previous position

Take into account "turbulence level"

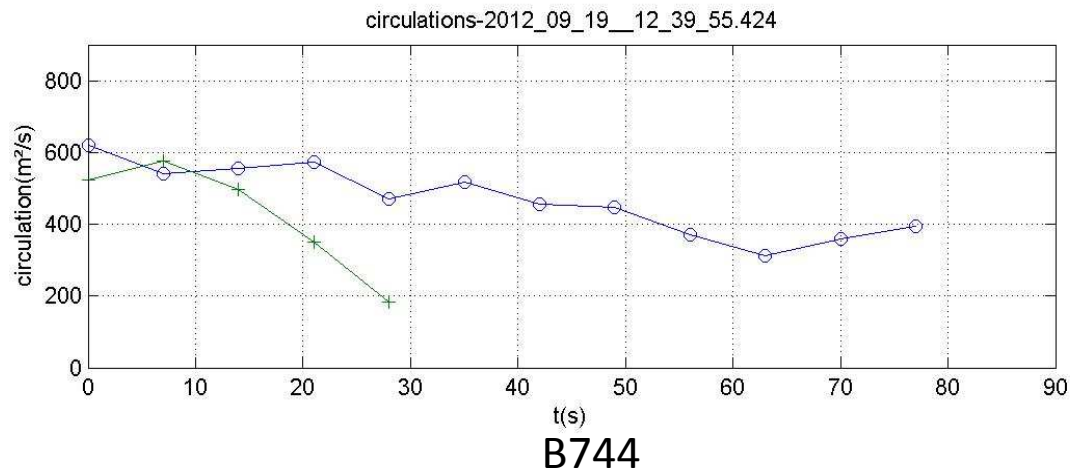
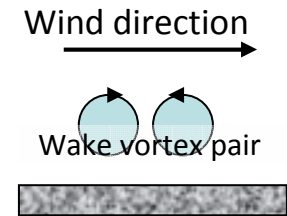
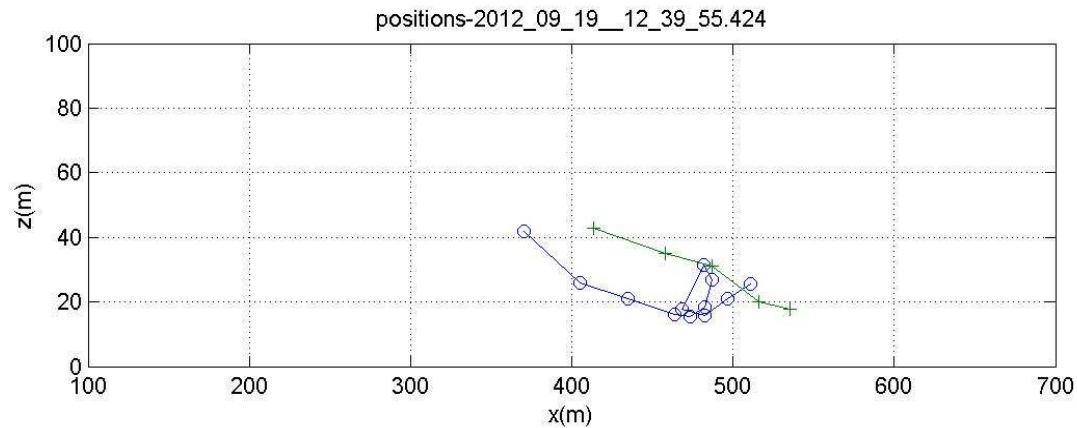
to adjust detection thresholds

# Development and process of the real-time WV algorithm

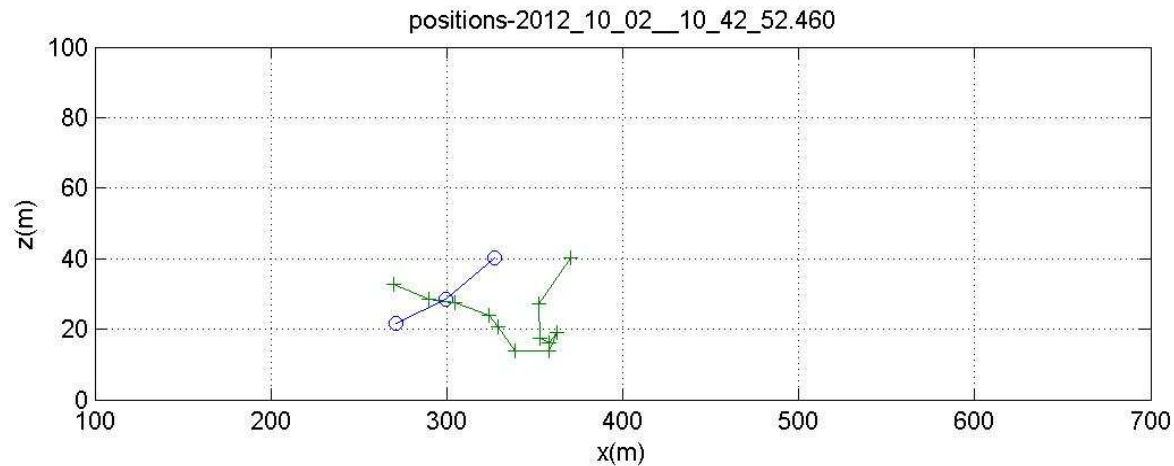




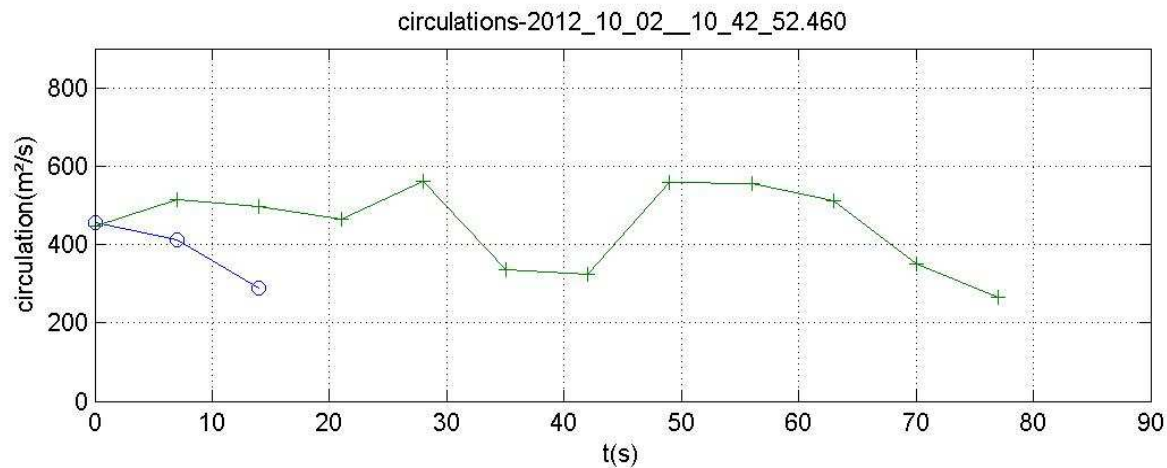
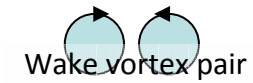
# On ground effect illustration (2/3)



# On ground effect illustration (3/3)



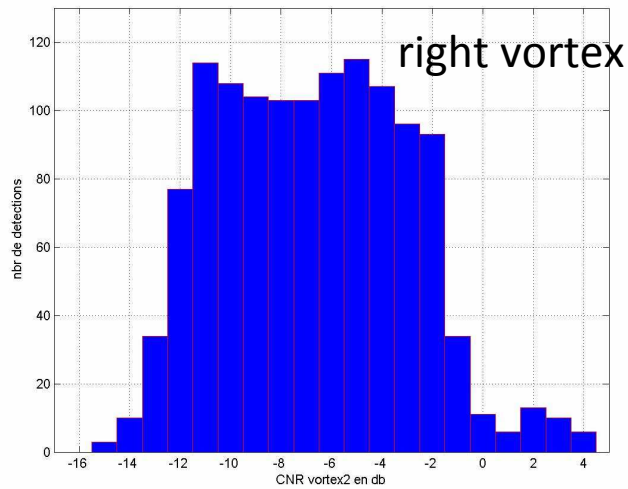
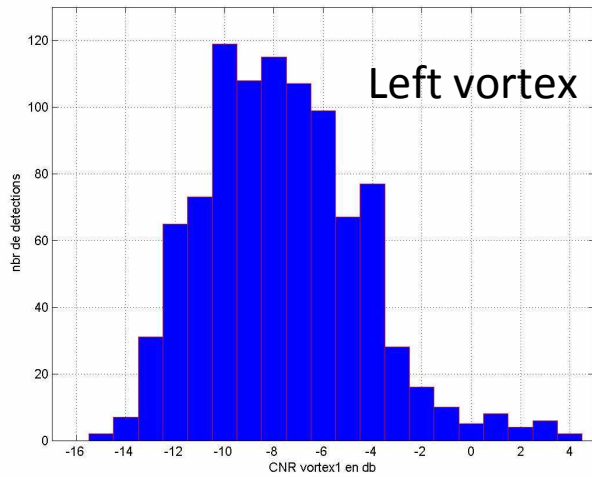
Wind direction



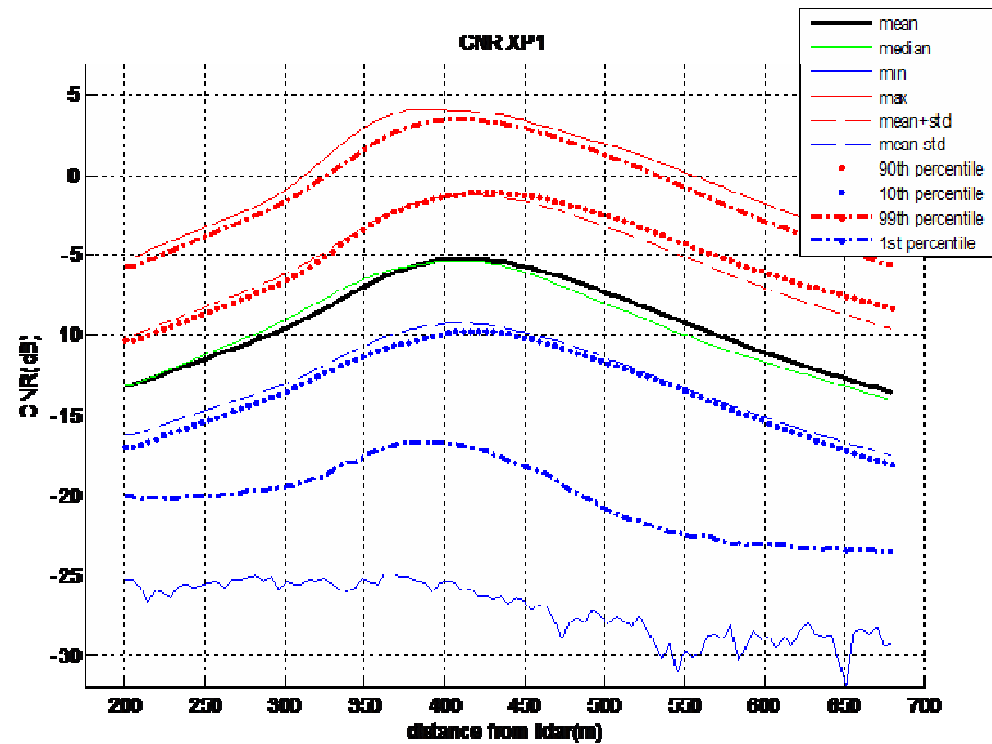
B772

# Statistical analysis of XP1 lidar measurements (2/ 4)

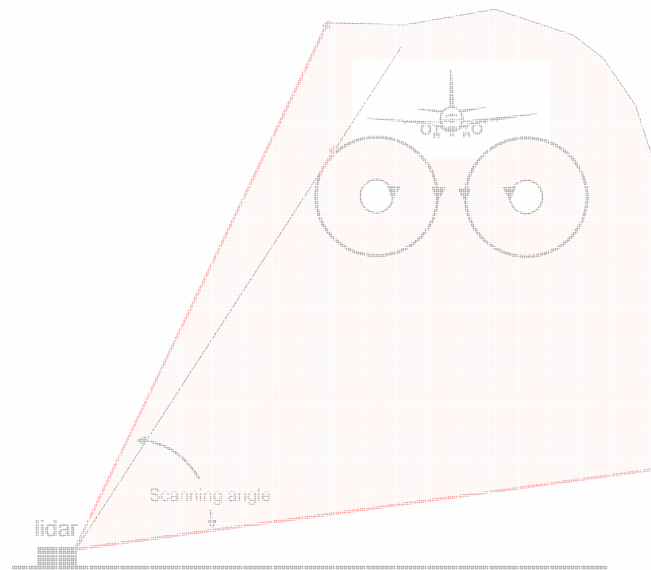
## CNR values when vortex detection



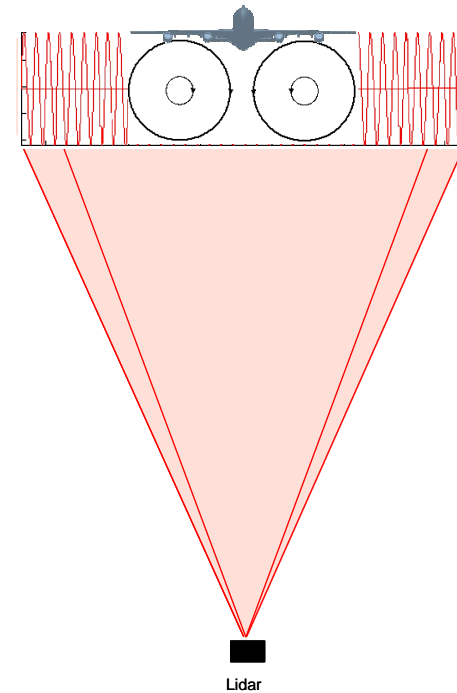
Histogramme of CNR values when vortex detection  
Current wake vortex detection algorithm effective from -15 dB



# Mesure des « wake vortex » par lidar

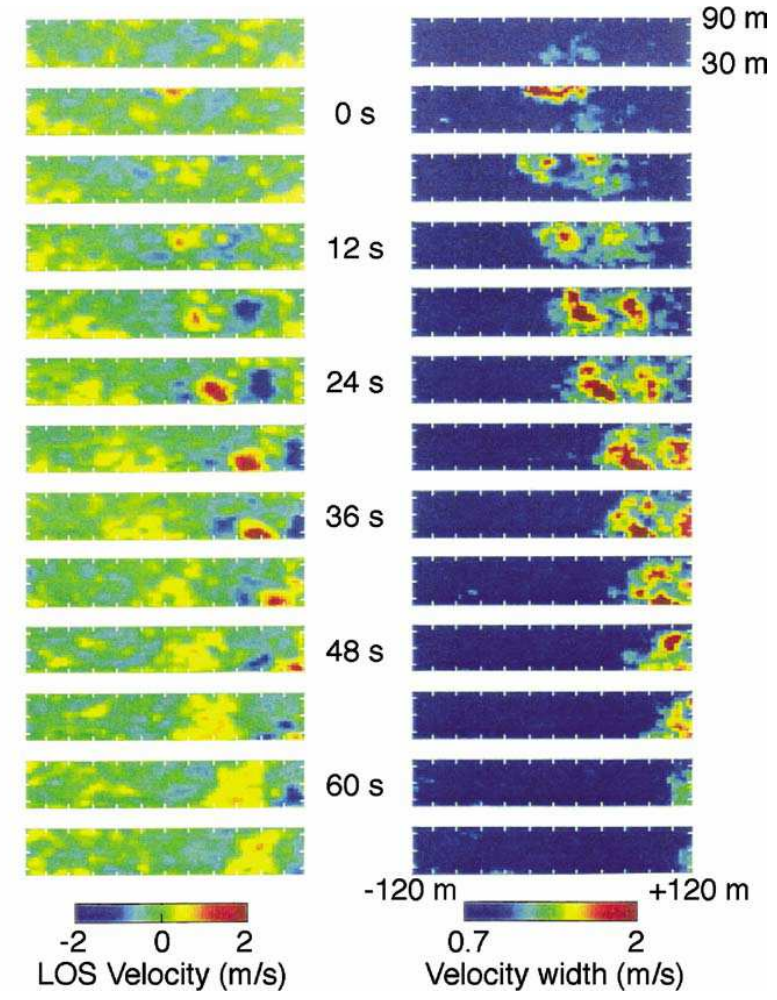
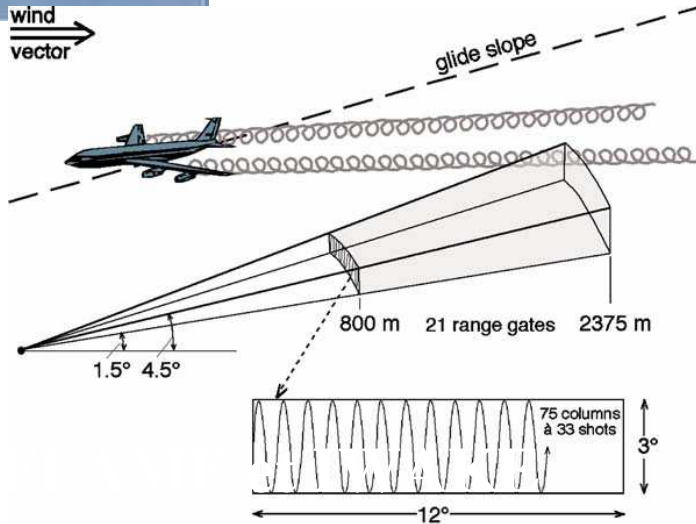


Détection transversale  
sol



Détection axiale  
Embarquée ou sol

# Détection axiale des wake vortex



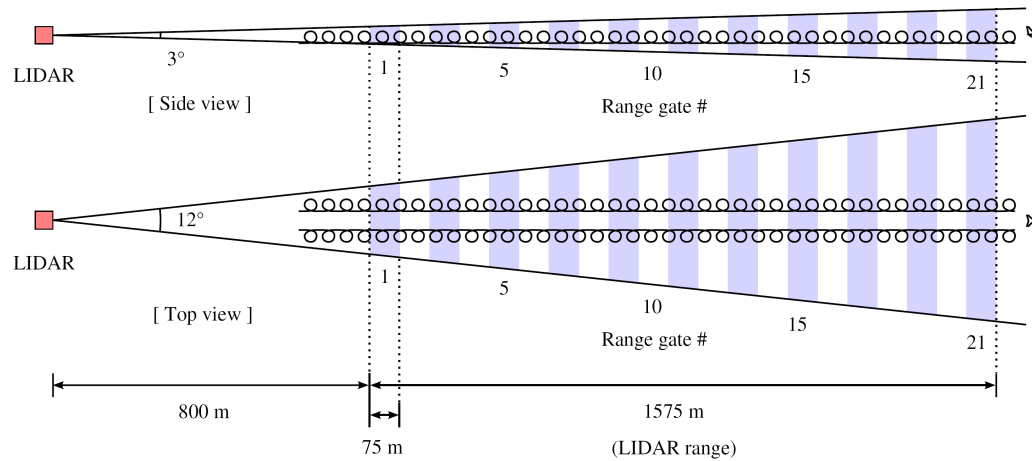
- Faisabilité de la détection axiale démontrée dans projets MFLAME and IWAKE

Projets européens ( Thales, DLR, UCL ...)

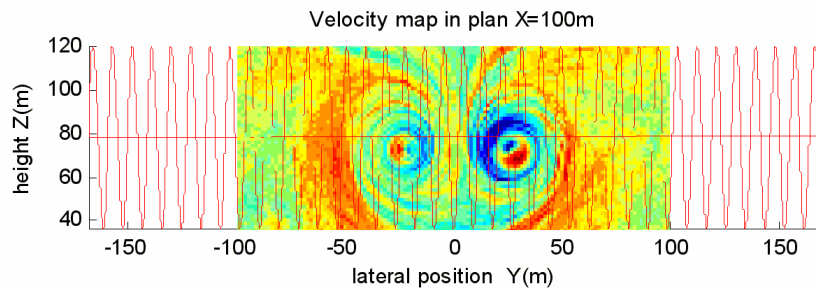
Source laser solide 2  $\mu\text{m}$  , 5mJ , 500 Hz

# Detection axiale des tourbillons de sillage

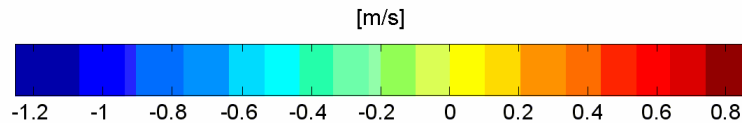
## Geometrie de detection



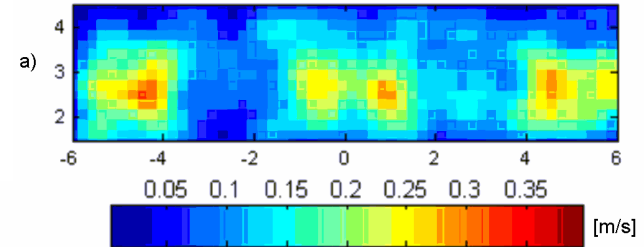
Projet FIDELIO  
simulation lidar + tourbillon



Modélisation du tourbillon projeté sur l'axe lidar

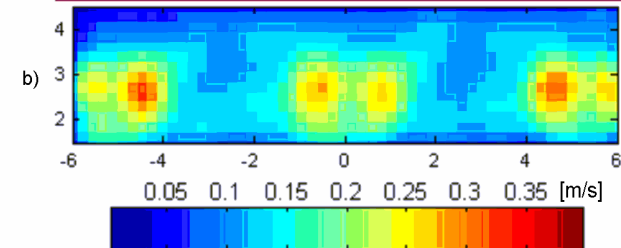


Lidar simulations: Radial velocities dispersion. MLE.  $X=2120$

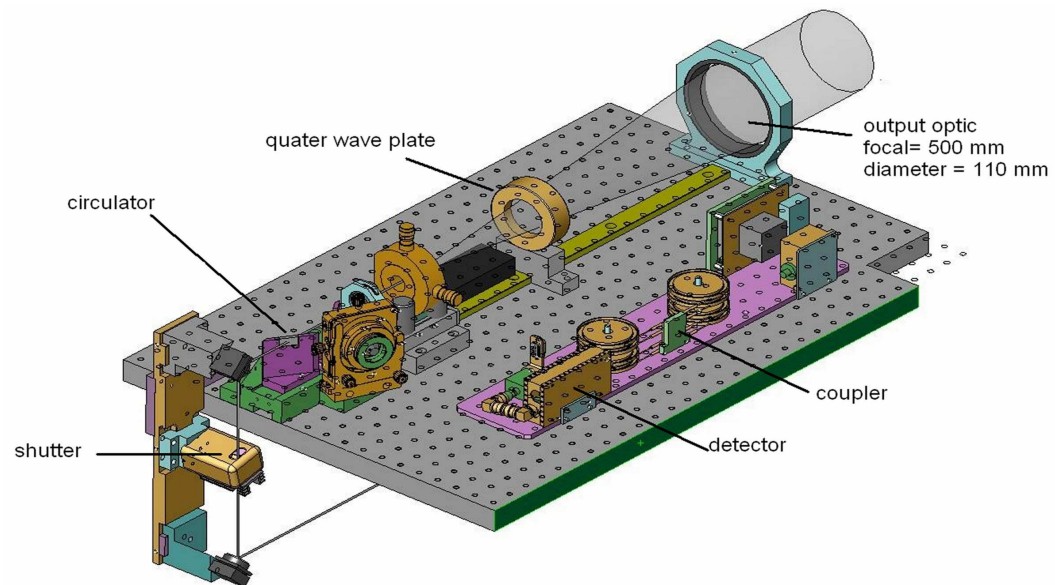


CC=0.74 laser energy :0.001; pulse duration:8e-007  
PRF:4000; Beta :1e-007; overlap:0Nbf=0Cn2=1e-014

Theoretical Radial velocities dispersion ... $X=2118.75$



# FIDELIO : architecture lidar

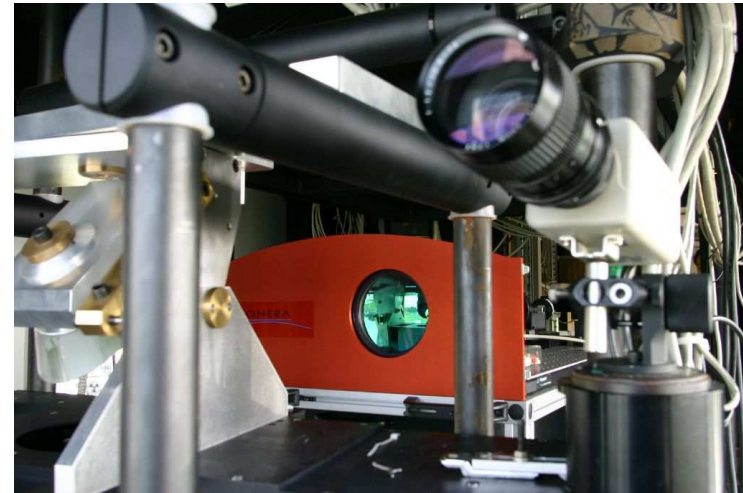


## Caractéristiques du lidar

- Longueur d'onde: **1.55  $\mu\text{m}$**
- Energie laser: **0.1 mJ**
- Durée pulse laser: **800ns**
- Cadence laser: **10kHz**
- M2=1.3
- Maintien de polarisation
  
- Portée : **0.5 à 1.6 km**
- résolution : **: 1 m/s**
- Cadence image : **0.2Hz**

Acquisition and  
real time display

# FIDELIO :Field tests



2008-05-07 17:41:30.52 UTC - MARK 02 - FIDELIO Ground Tests

Estimated parameters:

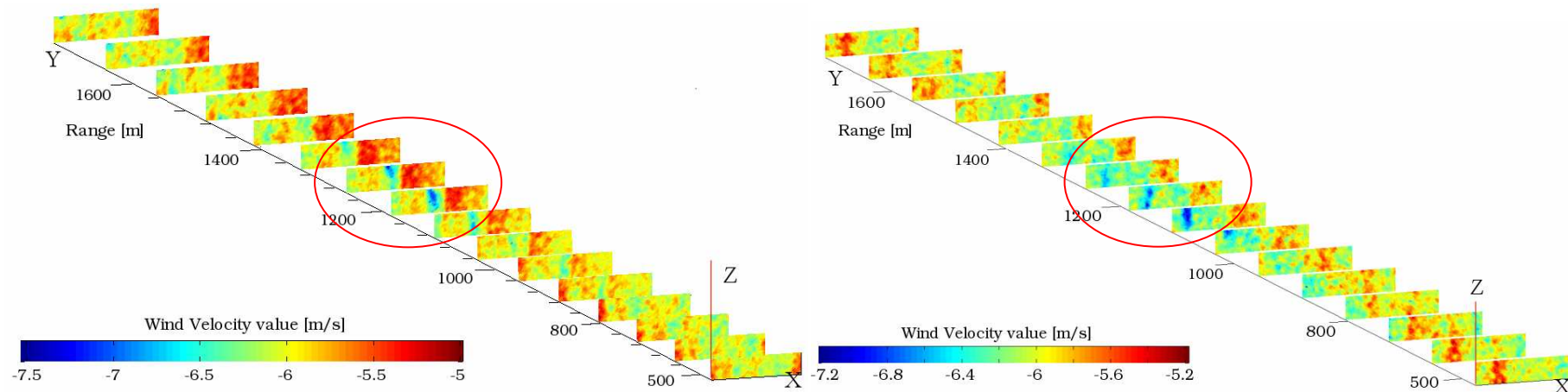
Aircraft type: A319  
Distance: 799,0 m  
Roll: 0,0 deg

(c) 2008 S. Lugan - UCL TELE





# FIDELIO :Field tests



- 3D representation of wake vortex detection
- two successive scans a few seconds after a B747 landing.
- each rectangle corresponds to a range gate



- **Au sol**
  - Ⓢ Turbulence de sillage /wake vortex
  - Ⓢ Cisaillement / rafale (Wind hazard)
- **Embarqués**
  - Ⓢ Turbulence de sillage /wake vortex
  - Ⓢ **Turbulence en air clair**
  - Ⓢ **Cisaillement / rafale (Wind hazard)**

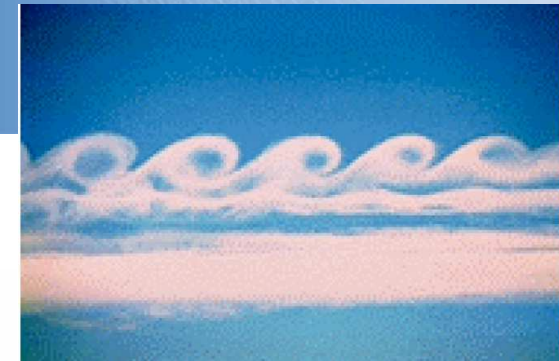
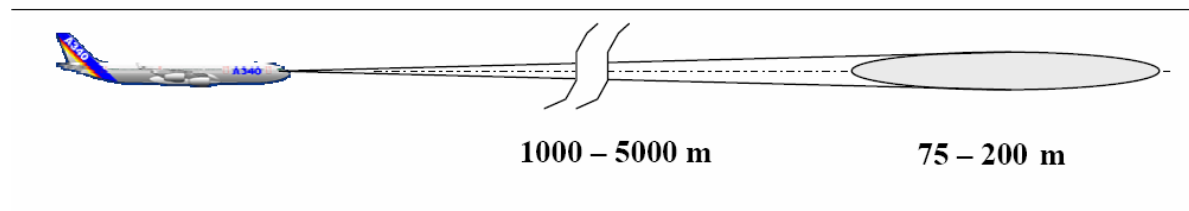
## Detection des TAC

[Detecting Clear Air Turbulence Research Deveropment on Airborne Doppler LIDAR\\_hd720.mp4](#)

# Senseur d'alerte : turbulence en air Clair

Détection longue portée : > 10 km

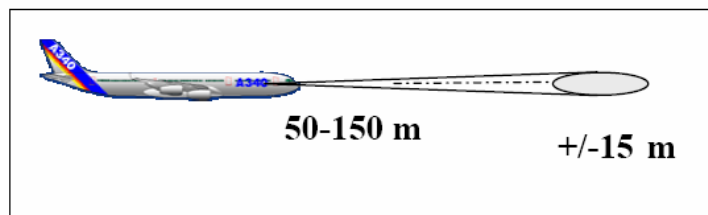
Mid-range WARNING systems



lidar DELICAT  
lidar Rayleigh densité

Detection courte portée : 50 à 100 m

Shorter range systems with high depth resolution suitable for CONTROL (feed-back into flight control)



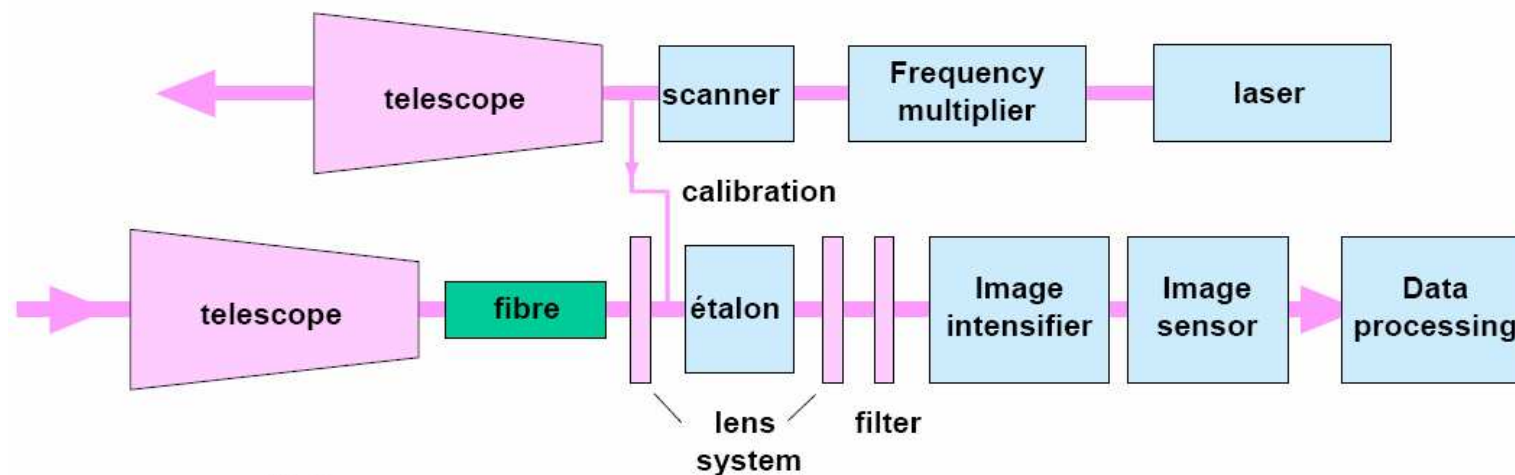
lidar Rayleigh doppler  
**Method of AWIATOR**

*Illustrations extraites de la présentation à CLRC 2009 de N.Schmitt EADS*

# AWIATOR Lidar



AWIATOR turbulence sensor layout (UV, direct detection):



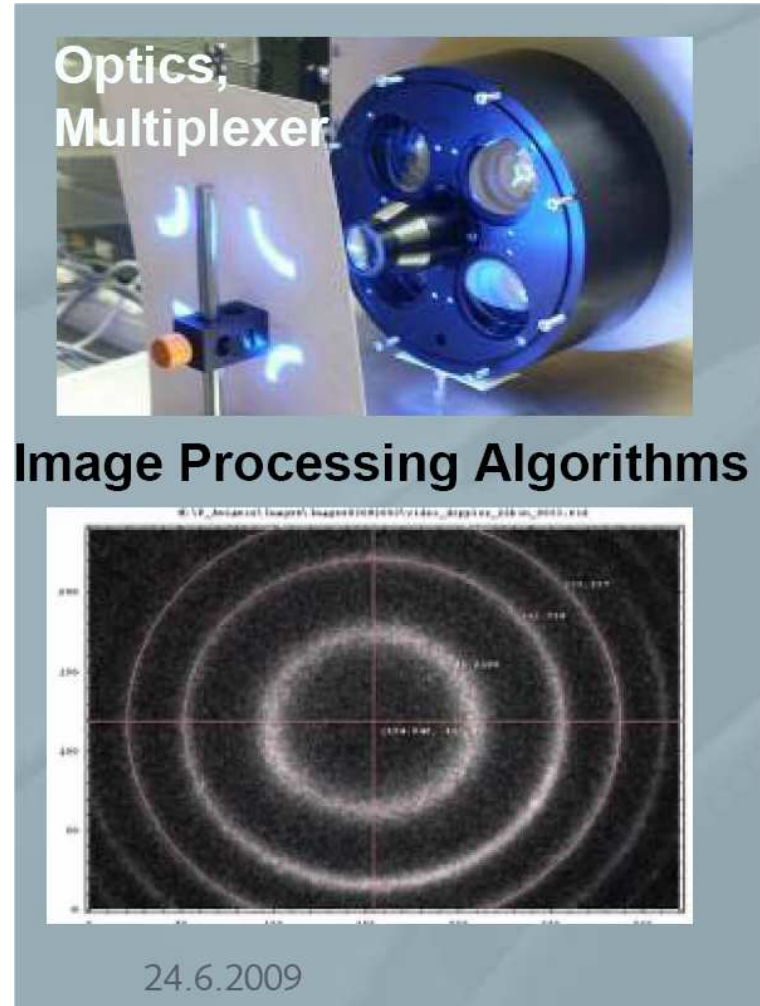
Using

- UV, micropulse lidar (355 nm, ~ 10 ns, 20 kHz, 150  $\mu$ J, 3W av.)
- direct detection, fringe imaging technique (60 Hz)

# Lidar AWIATOR



**Forward looking turbulence/gust UV  
LIDAR beneath A340-300 cockpit**



*Illustrations extraites de la présentation à CLRC 2009 de N.Schmitt EADS*

# CLEAR AIR TURBULENCE DETECTION AND CHARACTERISATION IN THE DELICAT AIRBORNE LIDAR PROJECT

## CAT detection with lidar

Relationship between vertical wind speed  $w$  and air density  $r$ :

$$\frac{\Delta\rho}{\rho} = -\frac{\Delta T}{T} = w\frac{N}{g}$$

$N$ : Brunt-Väisälä-frequency (stratification stability), measured in-situ

Outer scale of turbulence (largest eddy size): some hundred meters

Characteristic rotation time (given by  $N$ ): 5 to 10 minutes

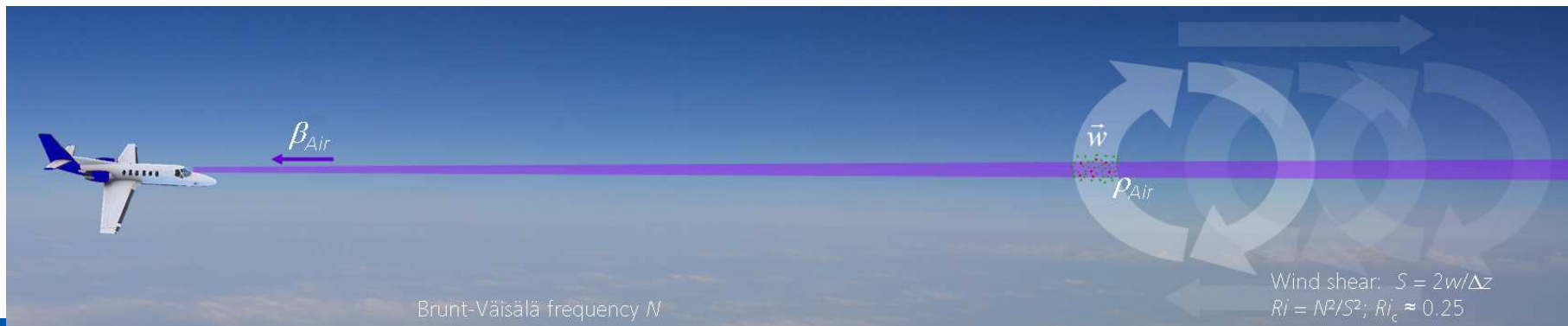
Measurement of air density  $r$  by molecular backscatter coefficient  $\beta_{\text{mol}}$

Separation from spurious aerosol contribution by spectral filter

Need to measure  $\Delta\rho/\rho$  on 1% level, thus need high SNR

Airborne, front looking lidar: Measurement integration along line of sight

→ Averaging to achieve needed SNR



# CLEAR AIR TURBULENCE DETECTION AND CHARACTERISATION IN THE DELICAT AIRBORNE LIDAR PROJECT

## Principle / Experiment

NLR Cessna Citation II research aircraft  
equipped with  
DELICAT lidar  
Front looking fairing  
5-probe nose boom for in-situ  
measurement of turbulence

Flight campaign in 2013

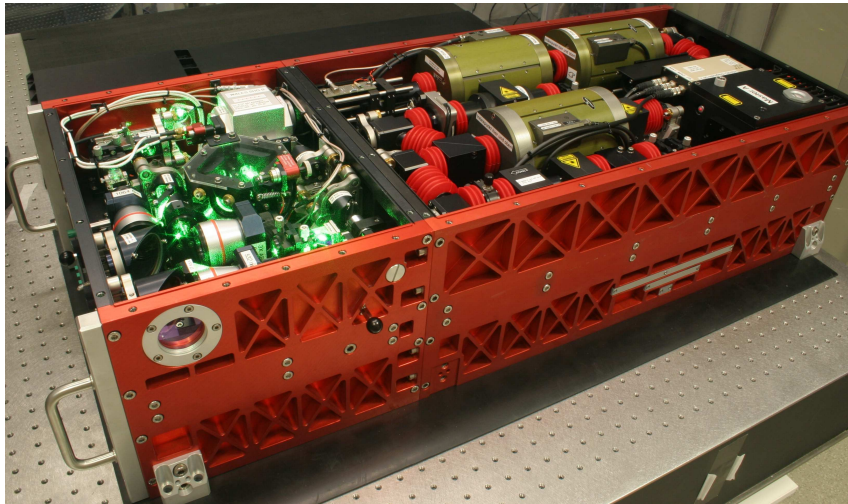




# CLEAR AIR TURBULENCE DETECTION AND CHARACTERISATION IN THE DELICAT AIRBORNE LIDAR PROJECT

## Transmitter

Nd:YAG passively Q-switched MOPA laser,  
7 ns FWHM,  $f_{rep} = 100$  Hz,  $E = 400$  mJ (IR)  
Intrinsically single mode, stabilised to I2  
Third harmonic generation,  $E \approx 100$  mJ (UV)



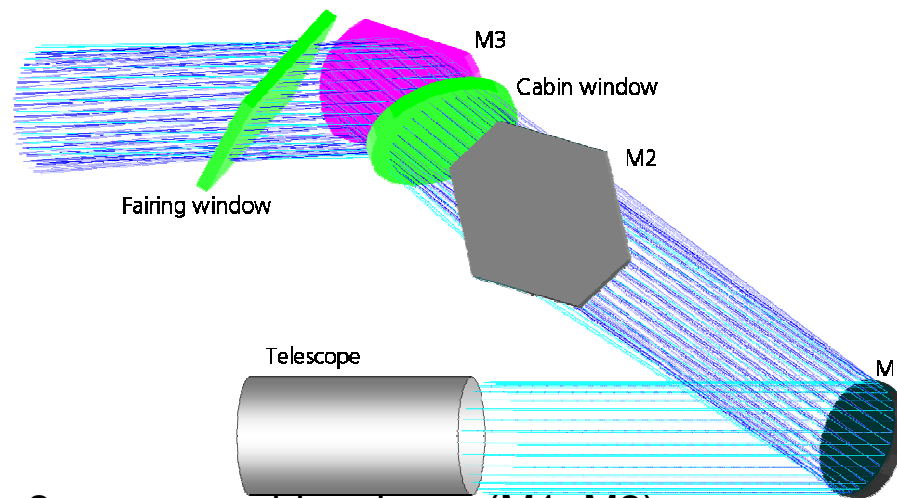
Coaxial transmission (w/ receiver telescope)  
Proven system (based on DLR WALES DIAL)

# CLEAR AIR TURBULENCE DETECTION AND CHARACTERISATION IN THE DELICAT AIRBORNE LIDAR PROJECT

## Beam steering

Insuring continuous tracking of  
aircraft horizontal flight path

Compensation of change in angle-of-attack  
and attitude fluctuations due to turbulence



Two 2-axes movable mirrors (M1, M2)

Beam invariant at centre of fairing window  
(no truncation due to beam tilt)

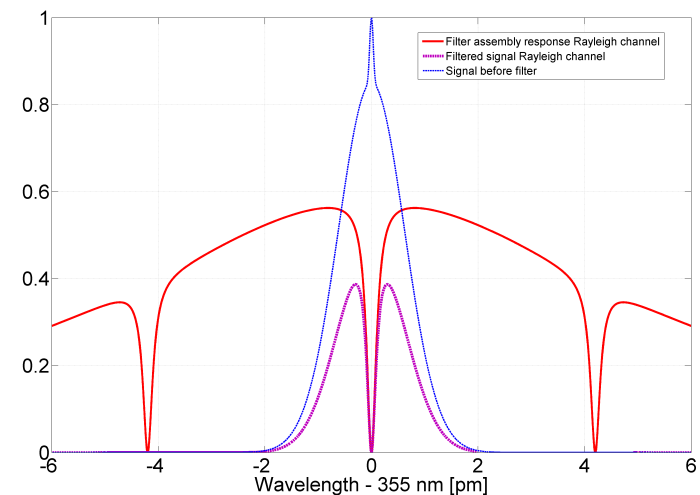
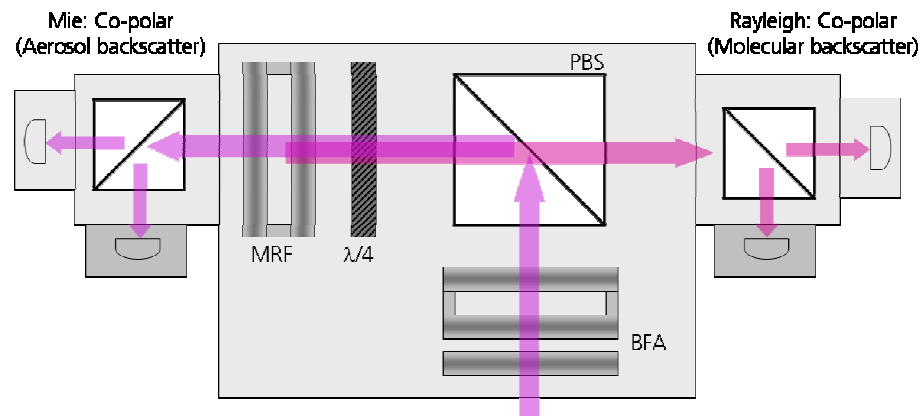
# CLEAR AIR TURBULENCE DETECTION AND CHARACTERISATION IN THE DELICAT AIRBORNE LIDAR PROJECT

## Receiver system

Ø 140 mm telescope

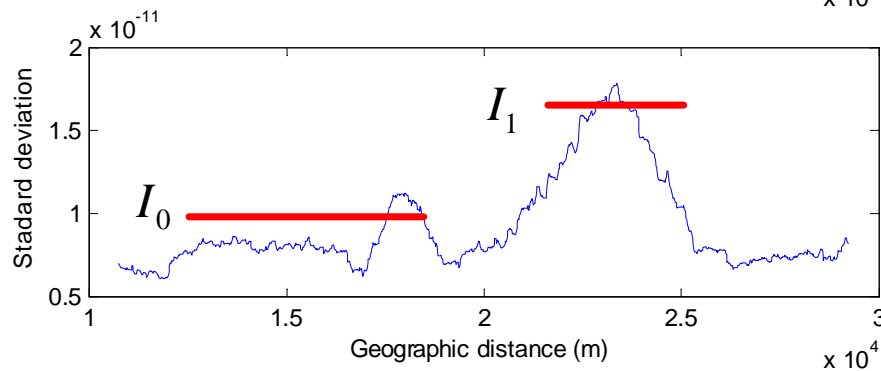
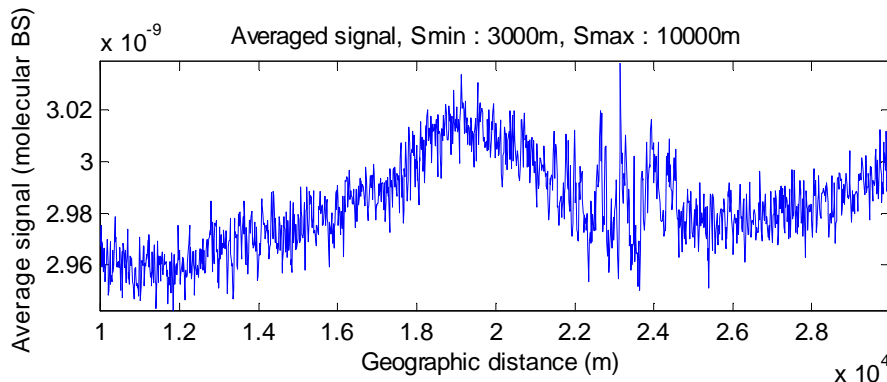
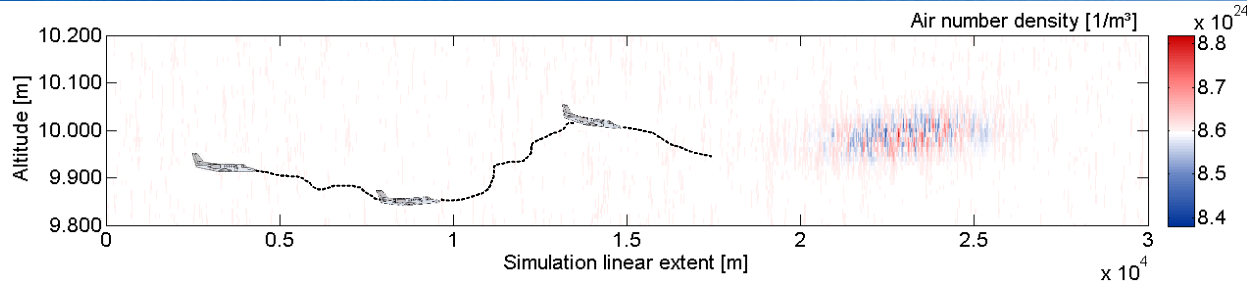
EOM for detector protection during laser shot

Etalon filter assembly for Mie-Rayleigh  
backscatter spectrum separation (HSRL)



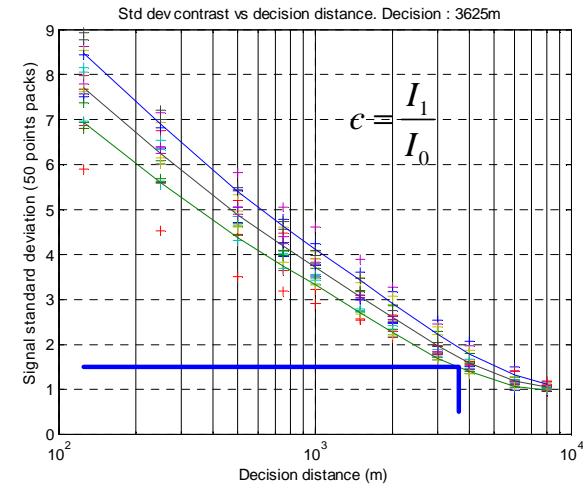
Analogue and photon counting detection on  
Rayleigh (air density) and Mie (aerosols)  
channels

# CLEAR AIR TURBULENCE DETECTION AND CHARACTERISATION IN THE DELICAT AIRBORNE LIDAR PROJECT



## Expected performance - Simulations

- 3-D atmospheric parameters including turbulence
- Aircraft position and lidar line of sight angle
- Atmospheric parameters projection
- Signal processing for turbulence signal recovery

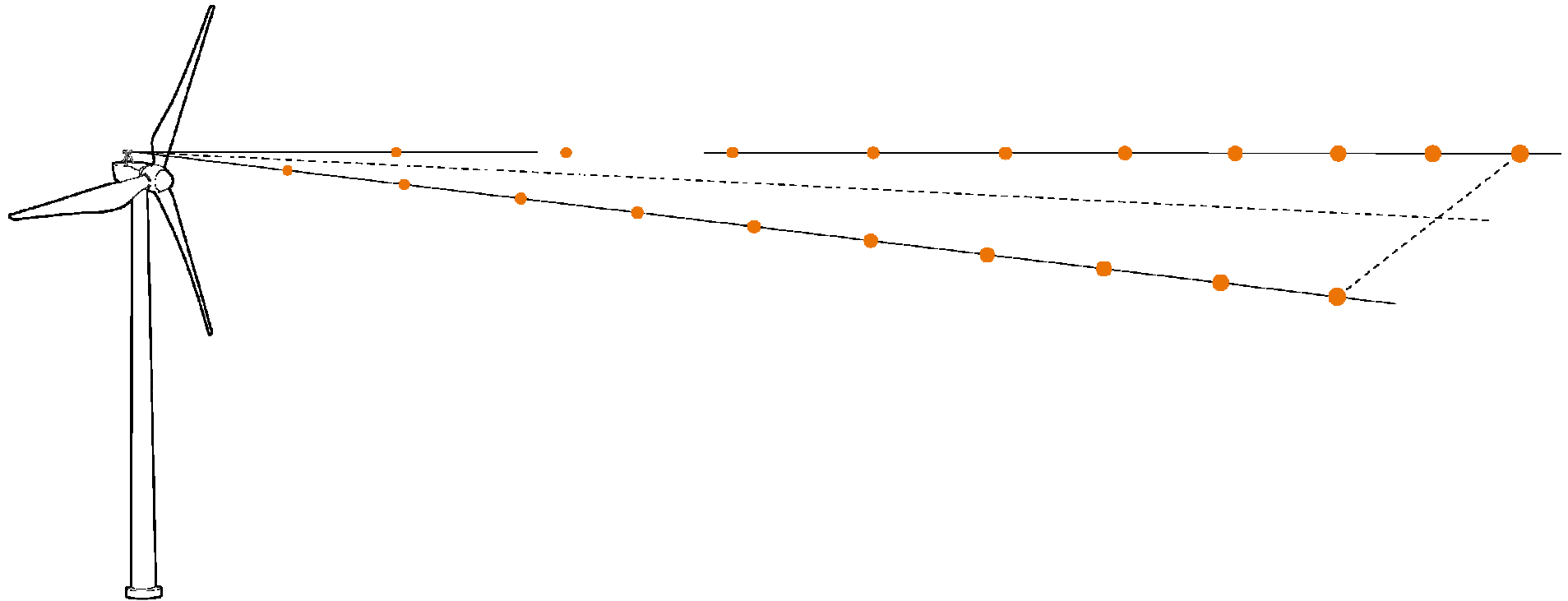


# Lidar Doppler pour l'éolien

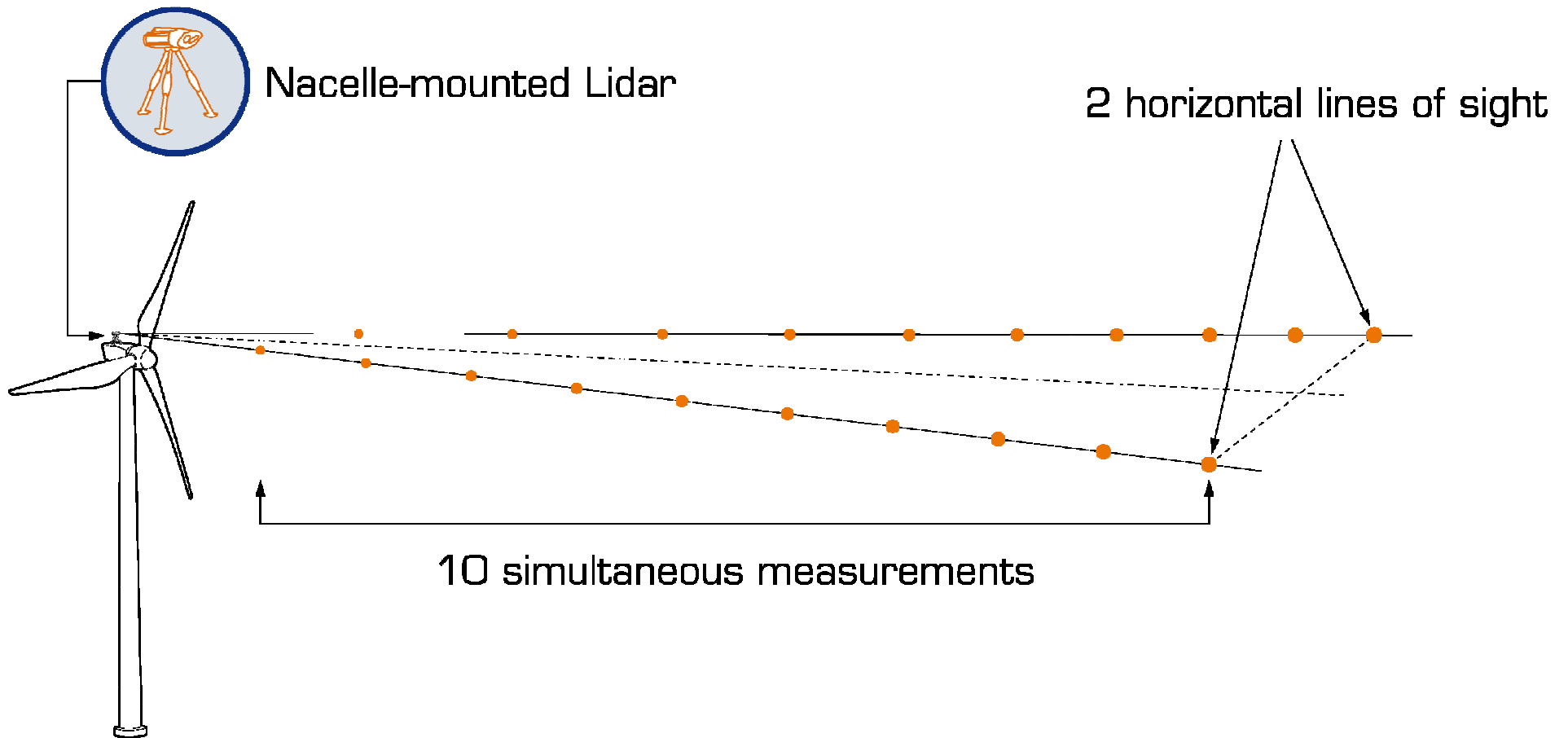
Besoins :

- Mesure des turbulences (fluctuations rapides de vitesse) pour estimer la charge sur les pales
- Vérification de la courbe de puissance, en fonction de la vitesse du vent.

# Lidar Doppler pour l'éolien



# Lidar Doppler pour l'éolien



# Lidar Doppler pour l'éolien

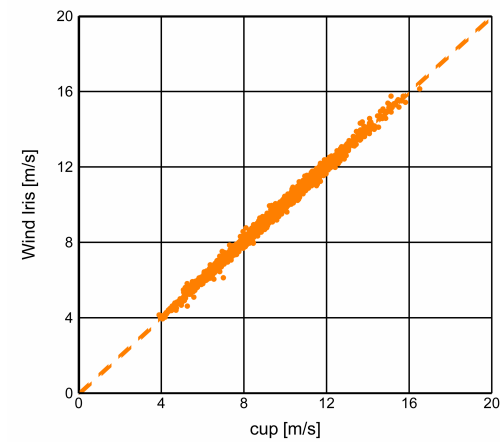
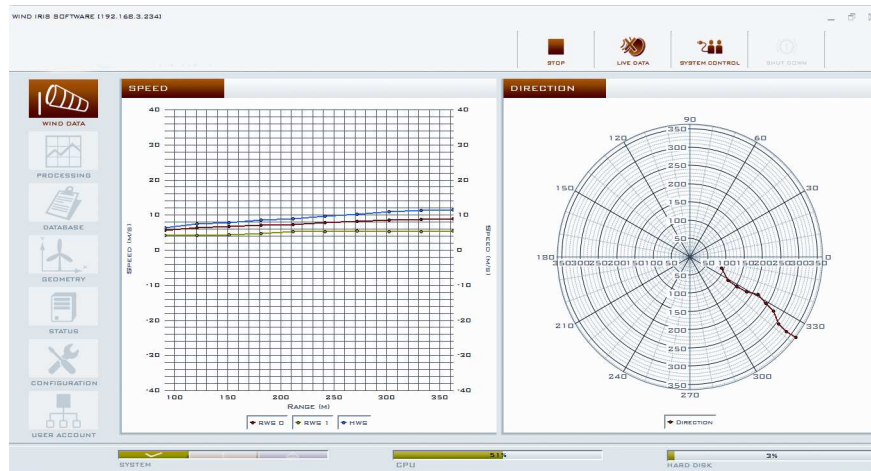




# Lidar Doppler pour l'éolien



Lidar avent



## Résumé : Senseurs lidar pour les applications aéronautiques (1)

<i>Type de senseurs</i>	<i>Type de mesure</i>	<i>Principe de la mesure</i>	<i>Type de lidar</i>	<i>exemple</i>
<b>Senseurs de navigation :</b> mesure la vitesse vraie de l'avion Étalonnage des sondes pitots / mesure primaire				
	1 point , 3 composantes Quelques mètres à une 50 mètres devant l'avion	Doppler Mie multiparticules	Hétérodyne continu ou pulsé 10.6 $\mu\text{m}$ , 1.5 $\mu\text{m}$	ALEV DALHEC DALEV
	1 point , 3 composantes Quelques centimètres/mètres devant l'avion	Doppler Mie monoparticule	continu Hétérodyne 1.5 $\mu\text{m}$ 1.06 $\mu\text{m}$	DALAS Boeing Doppler lidar
	1 point , 3 composantes Quelques mètres à une 50 mètres devant l'avion	Doppler Rayleigh	pulsé détection directe 266 nm	MOADS

## Résumé : Senseurs lidar pour les applications aeronautiques (2)

Type de senseurs	Type de mesure	Principe de la mesure	Type de lidar	Exemple
<b>Senseurs d'alerte</b> d'évènements dangereux				
Turbulence de sillage Wake vortex	Cartographie vitesses projetées (2D transverse / 3D axial)	Doppler Mie  (Rayleigh directe)	Pulsé hétérodyne 1.5 $\mu\text{m}$ , 2 $\mu\text{m}$  Pulsé directe 355 nm	CREDOS, FIDELIO MFLAME/ IWAKE Greenwake (nouveau projet )
Cisaillement / turbulence	Multipoint différentiel 50 /150 m devant l'avion	Doppler Rayleigh  Doppler Mie heterodyne	Pulsé directe 355 nm  Pulsé hétérodyne	AWIATOR
Turbulence en air clair	Le long de l'axe 10 km devant l'avion	Rayleigh densité	Détection directe Pulsé , 355 nm	DELICAT (nouveau projet)

Merci de votre attention