Methods to establish probabilistic wake vortex models

WakeNet3-Europe
A network on Aircraft Wake Turbulence

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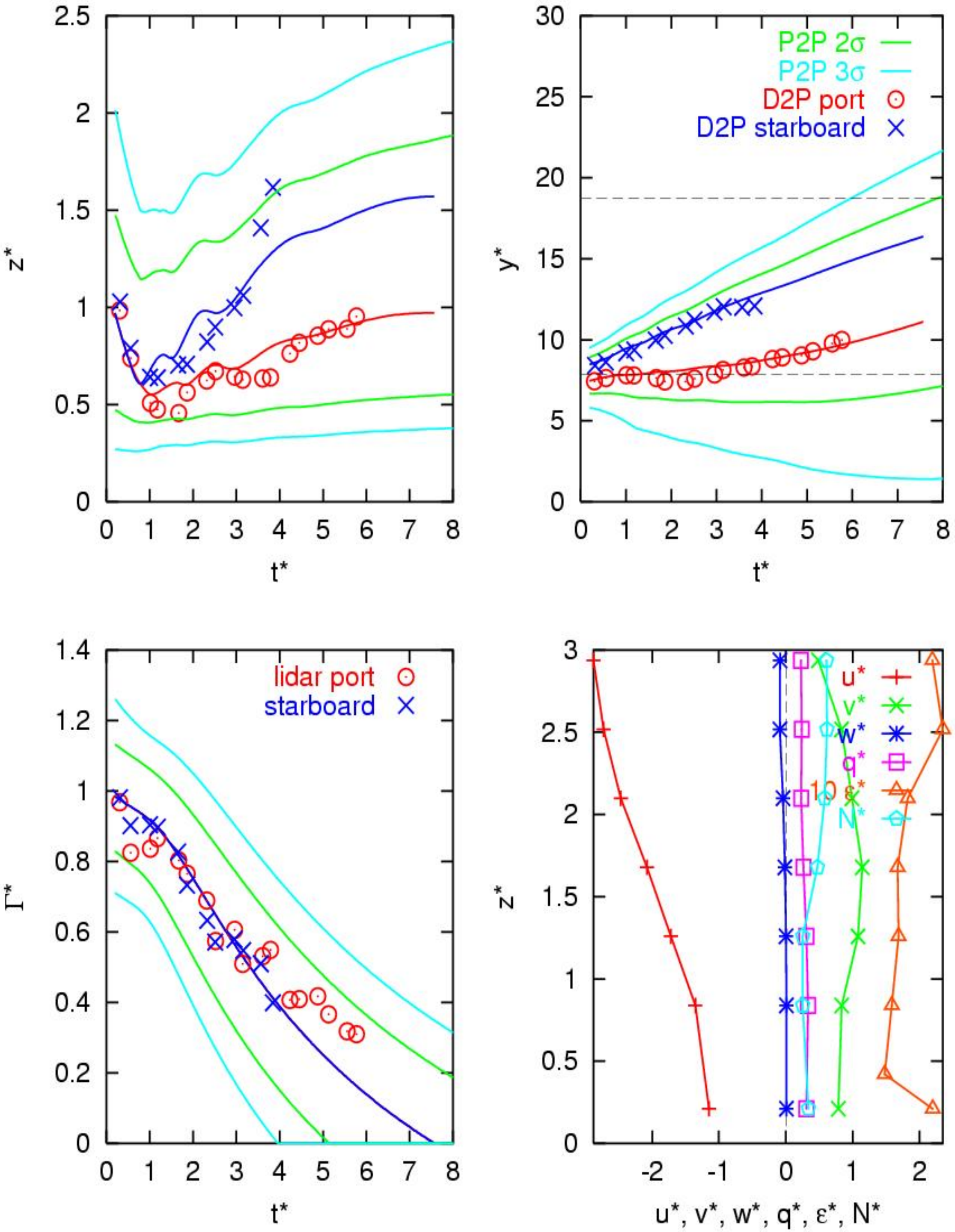
- sources of uncertainty
  - initial conditions
  - environmental conditions
  - reference data
  - intrinsic variability of wake vortex data
- relevance of crosswind
- probabilistic methods
  - systematic - Monte Carlo simulation
  - empirical hybrid methods

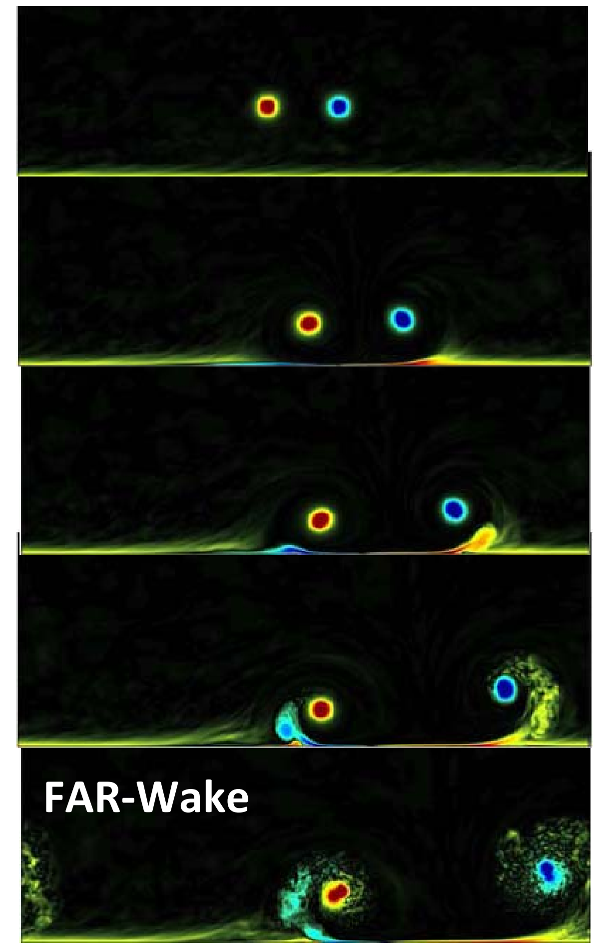
Idaho Falls
courtesy NOAA/FAA

example for probabilistic WV prediction

asymmetric rebound in ground proximity



Holzäpfel & Steen, AIAA J. **45** 2007



Uncertainties – Initial Conditions

Using a/c parameters

$$b_0 = s\,b \qquad \Gamma_0 = \frac{C_L\, bV}{2s\, AR}$$

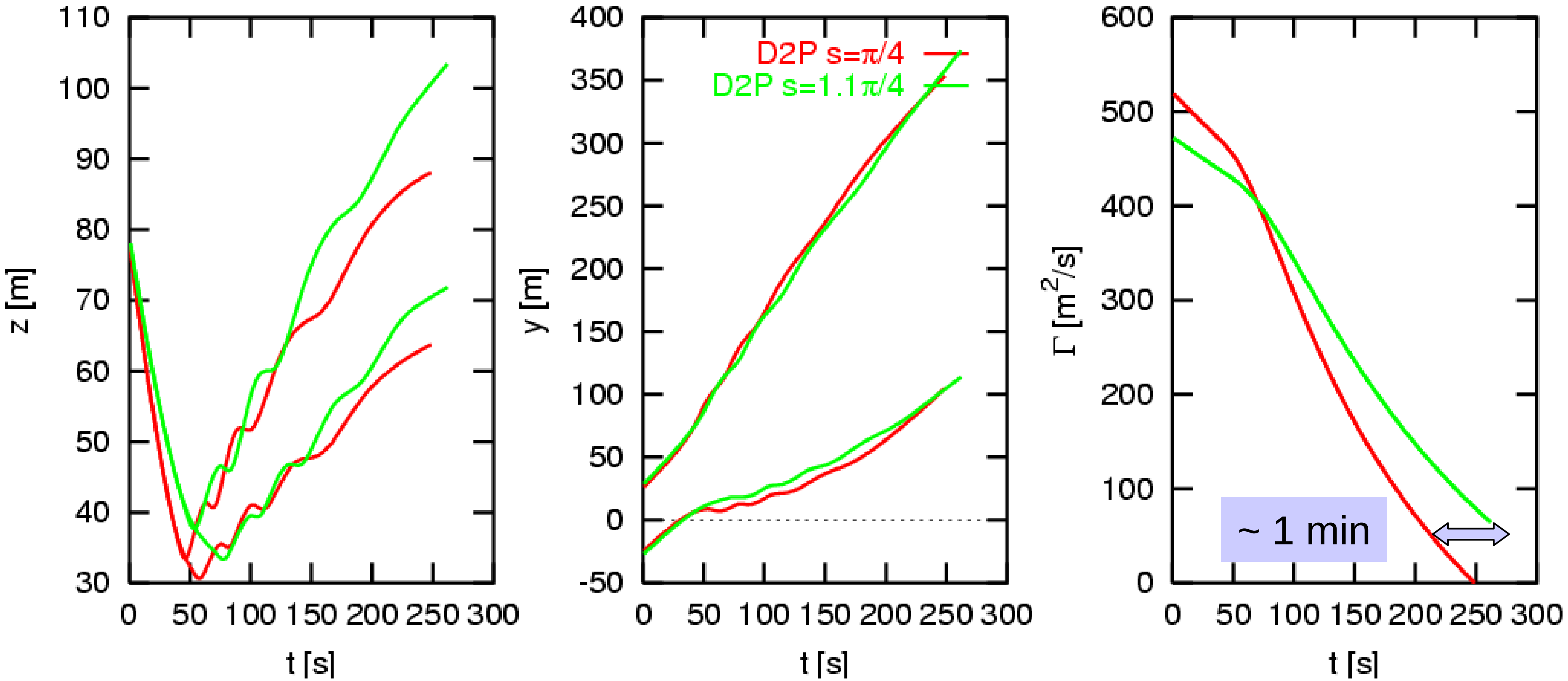
$$t_0 = \frac{b_0}{w_0} = \frac{2\pi\, b_0^2}{\Gamma_0} = \frac{4\pi\, s^3 b\, AR}{C_L\, V}$$

uncertainty of **spanwise load factor s** of 10%

$\Rightarrow$ uncertainty of t_0 (vortex lifetime) of 30%

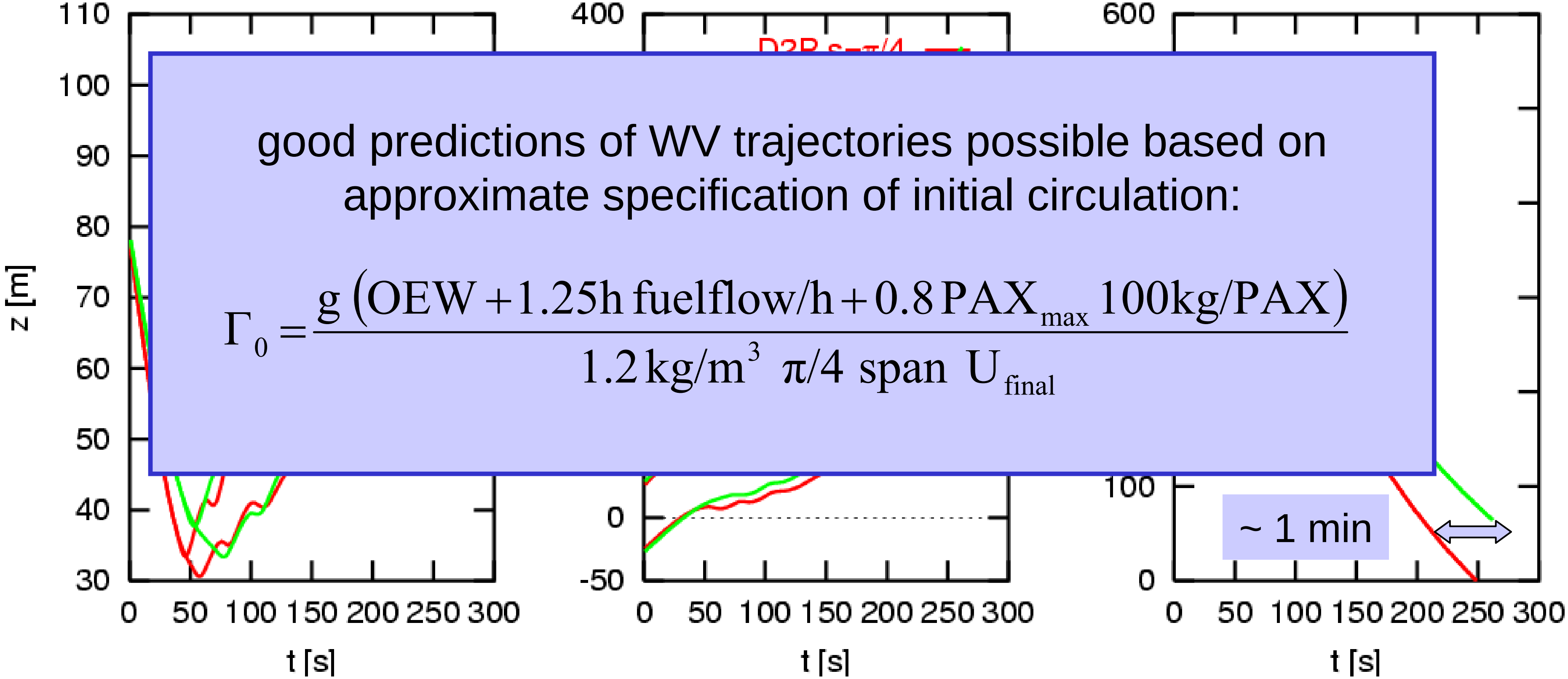
Uncertainties – Initial Conditions

using a/c parameters



Uncertainties – Initial Conditions

using a/c parameters

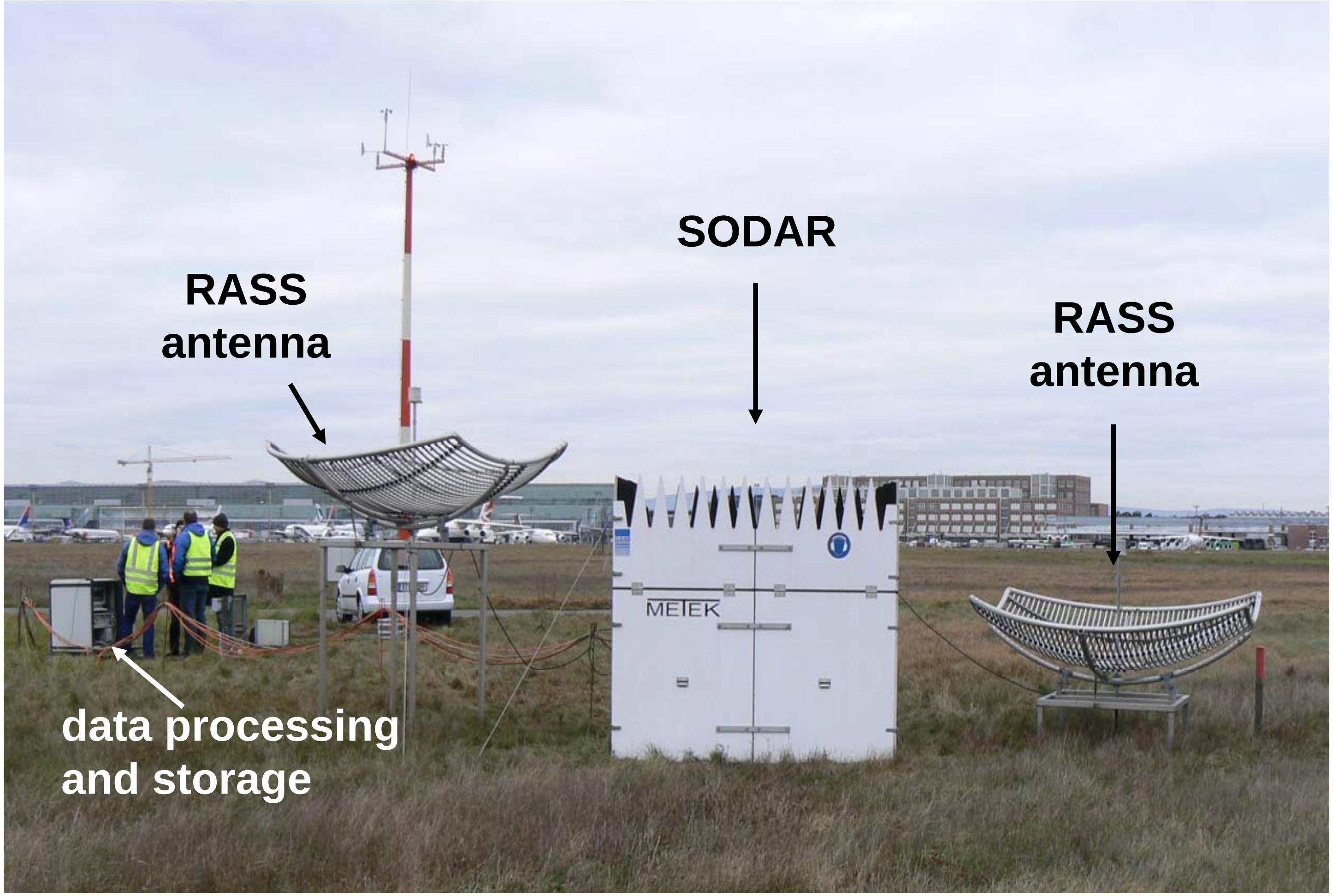


good predictions of WV trajectories possible based on approximate specification of initial circulation:

$$\Gamma_0 = \frac{g\left(\mathrm{OEW} + 1.25\mathrm{h}\ \mathrm{fuelflow/h} + 0.8\,\mathrm{PAX}_{max}\ 100\mathrm{kg/PAX}\right)}{1.2\,\mathrm{kg/m}^3\ \ \pi/4\ \mathrm{span}\ \ U_{final}}$$

Uncertainties – Environmental Parameters

example: accuracy of wind measurements



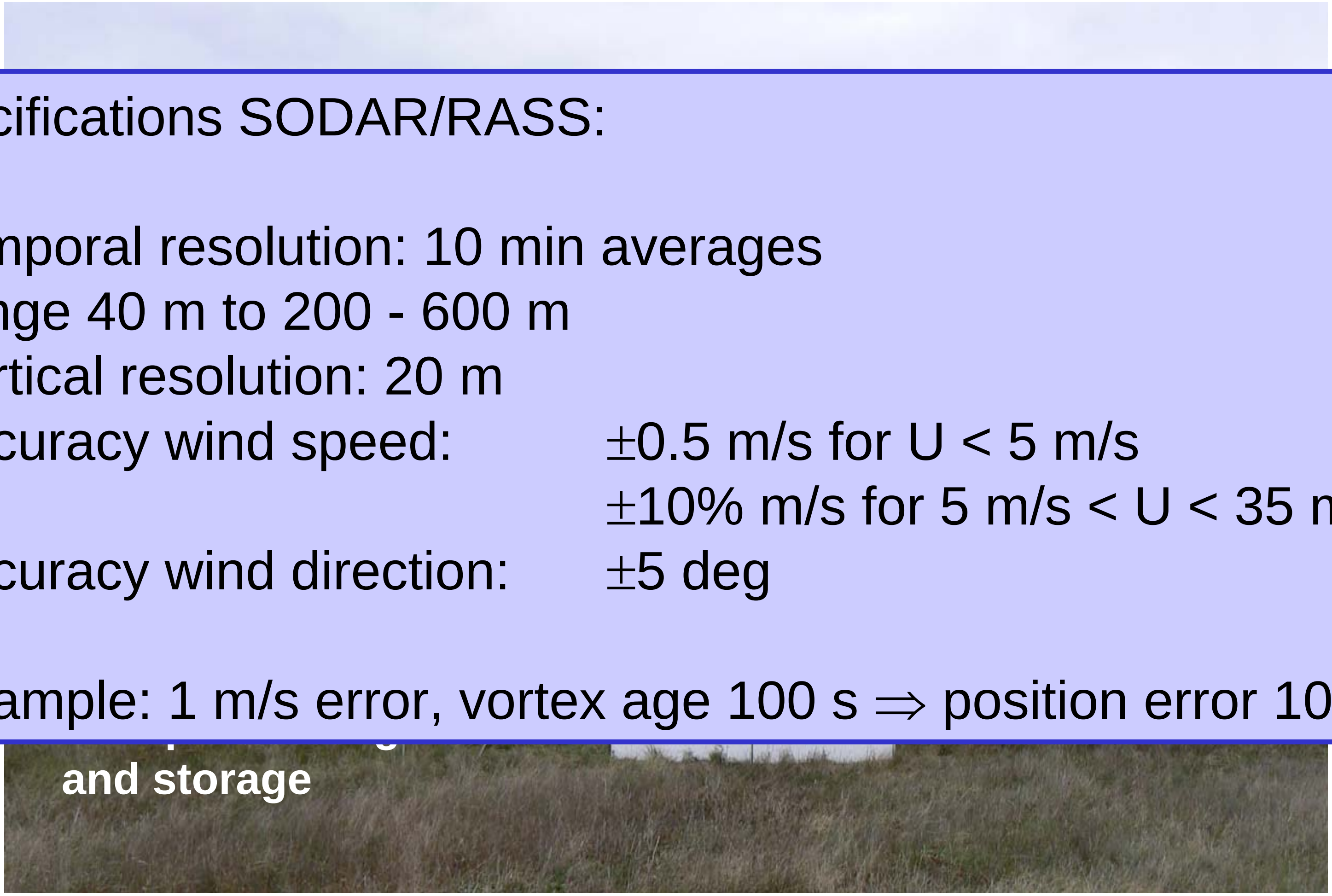
Uncertainties – Environmental Parameters

example: accuracy of wind measurements

specifications SODAR/RASS:

- temporal resolution: 10 min averages
- range 40 m to 200 - 600 m
- vertical resolution: 20 m
- accuracy wind speed: ±0.5 m/s for U < 5 m/s
  ±10% m/s for 5 m/s < U < 35 m/s
- accuracy wind direction: ±5 deg

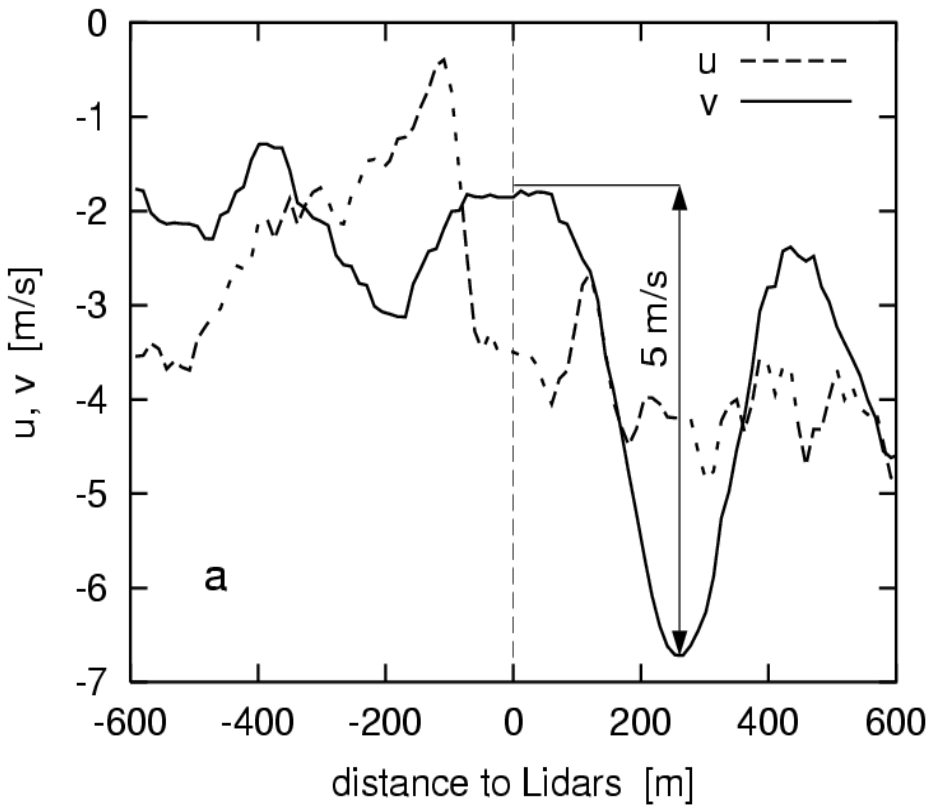
- example: 1 m/s error, vortex age 100 s ⇒ position error 100 m



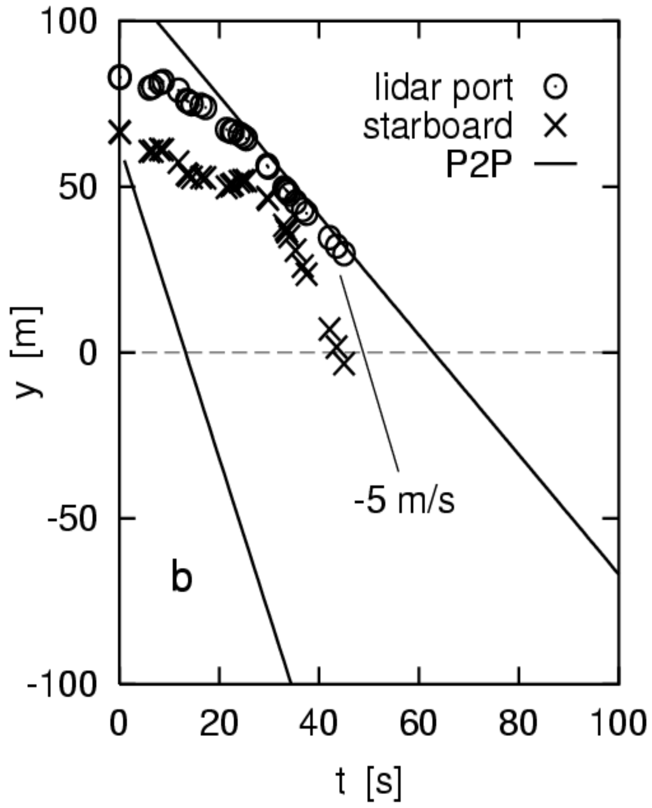
Uncertainties – Environmental Parameters

example: spatio/temporal variability of crosswind

ATTAS wind data



P2P — Lidar

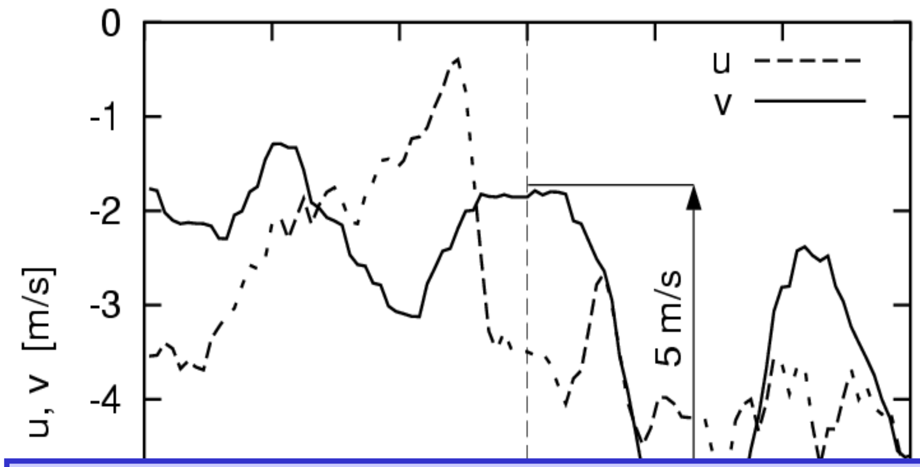


Holzäpfel & Robins, Journal of Aircraft **41** 2004

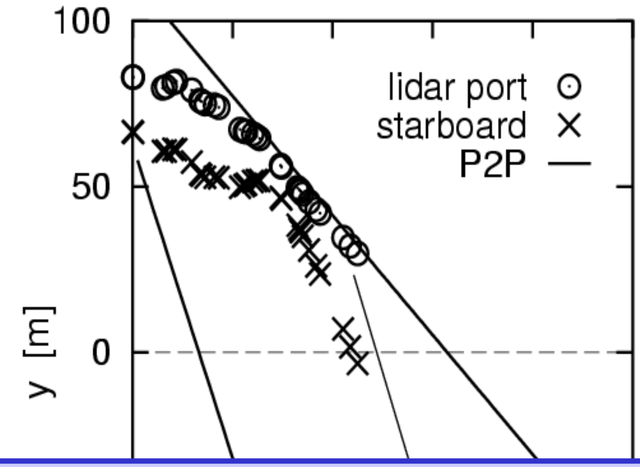
Uncertainties – Environmental Parameters

example: variability of crosswind

ATTAS wind data



P2P — Lidar

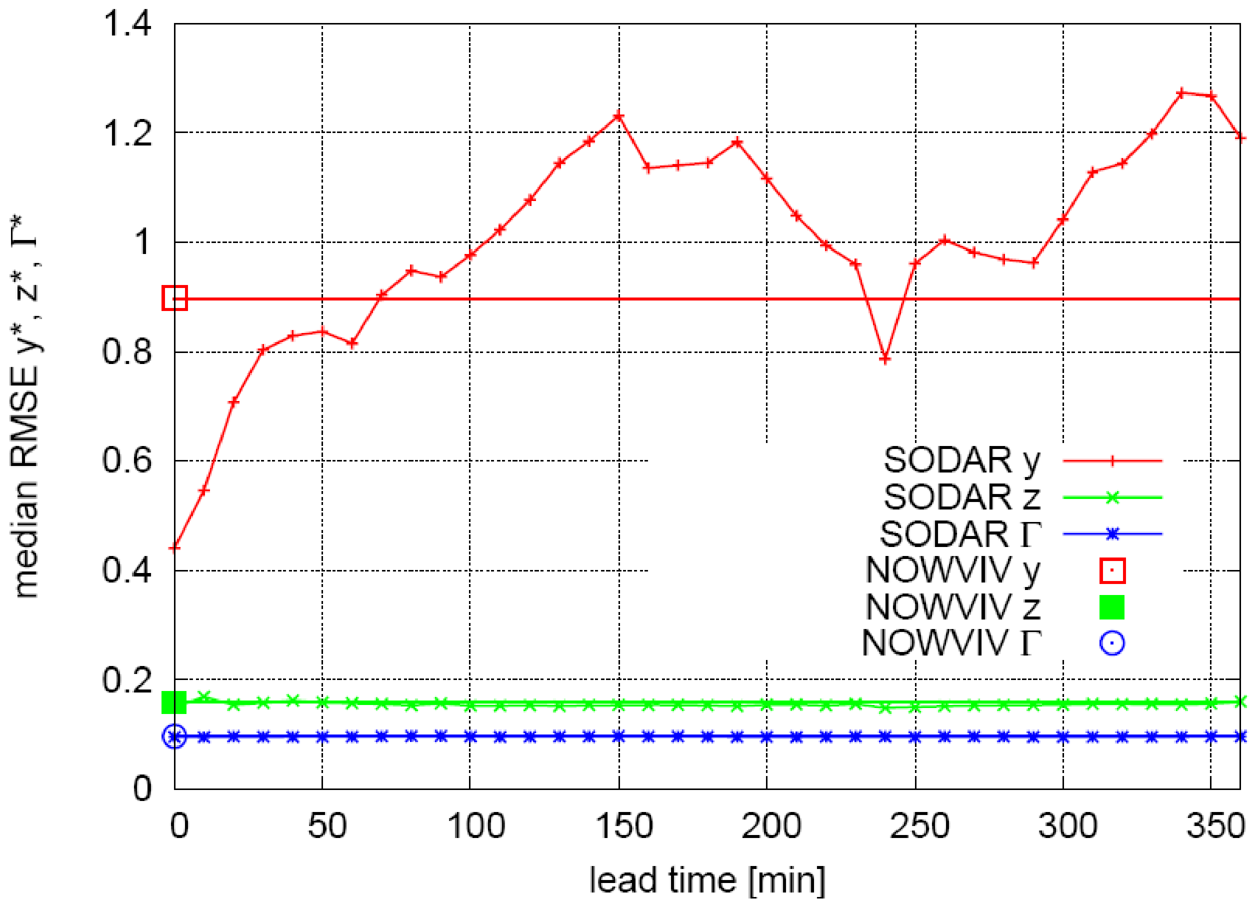


how can we handle this?

⇒ minimize distance between wind & vortex measurement/pred.
⇒ consider spatio/temporal wind variations as turbulence
⇒ probabilistic predictions

Nowcasting (Persistence) versus Numerical Weather Prediction

wake-vortex prediction skill IGE



Frech M., Holzäpfel F., Skill of an Aircraft Wake-Vortex Model Using Weather Prediction and Observation, J. Aircraft **45** 2008. andere Bilder

Nowcasting (Persistence) versus Numerical Weather Prediction

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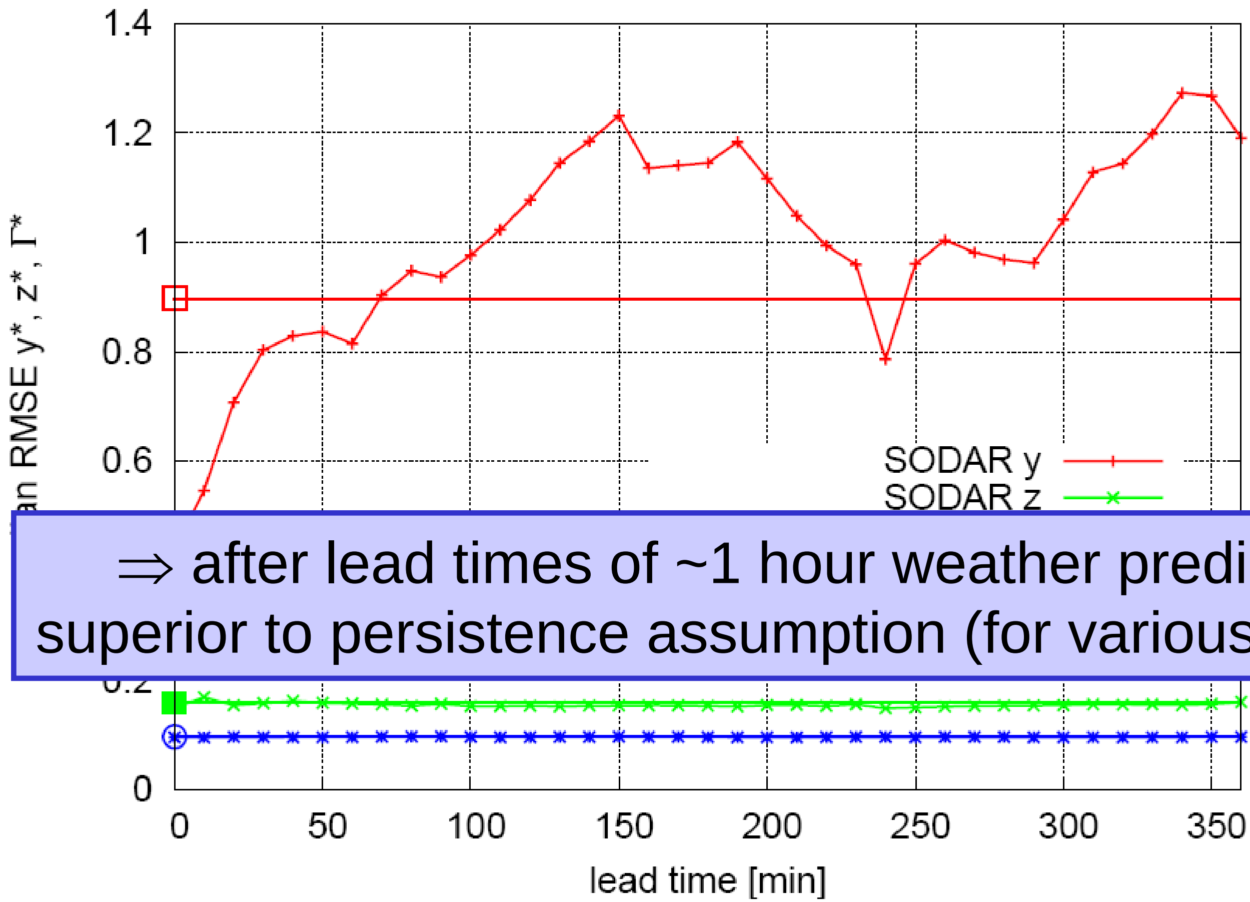
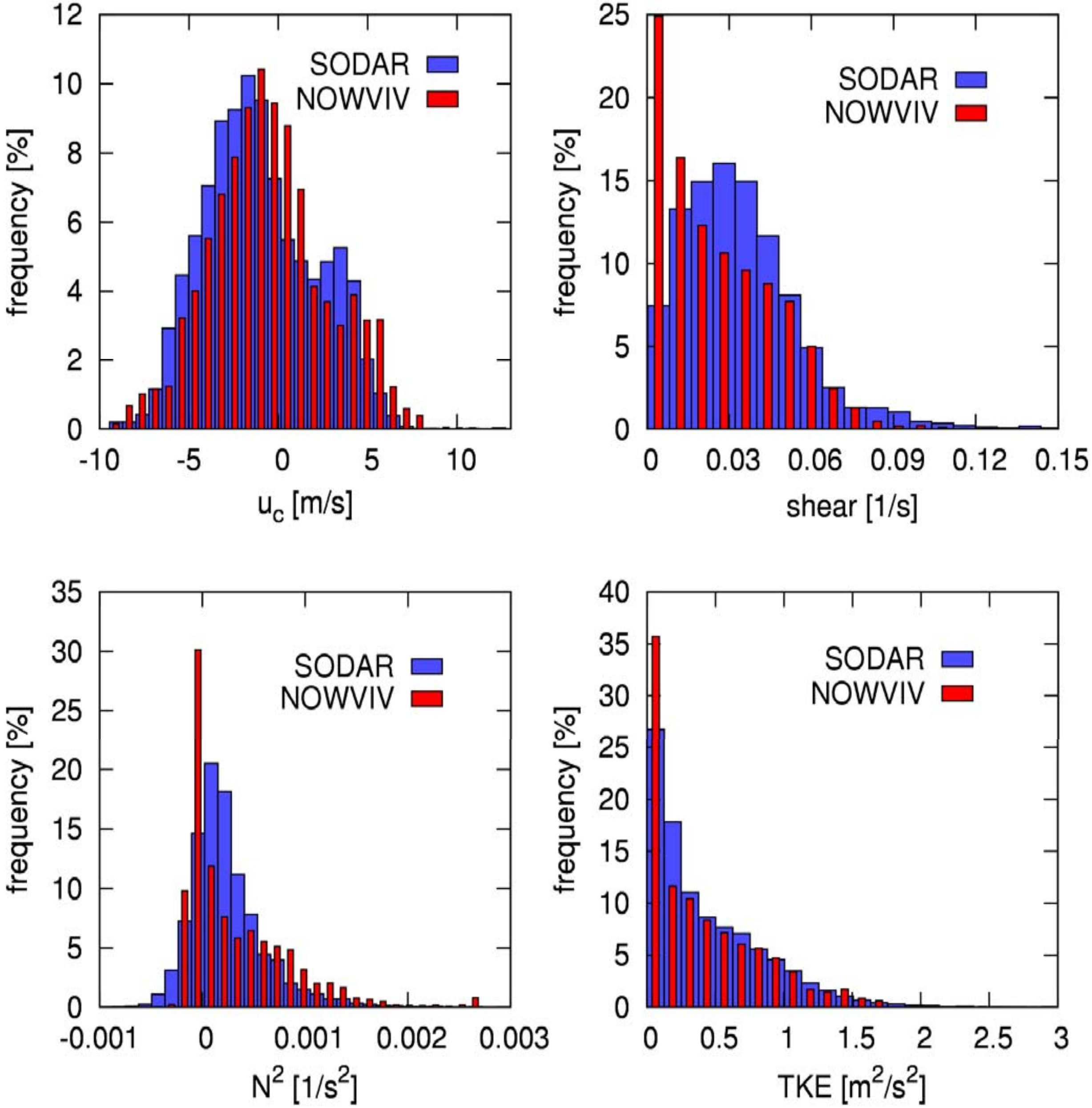


⇒ after lead times of ~1 hour weather prediction superior to persistence assumption (for various criteria)

Frech M., Holzäpfel F., Skill of an Aircraft Wake-Vortex Model Using Weather Prediction and Observation, J. Aircraft **45** 2008. andere Bilder

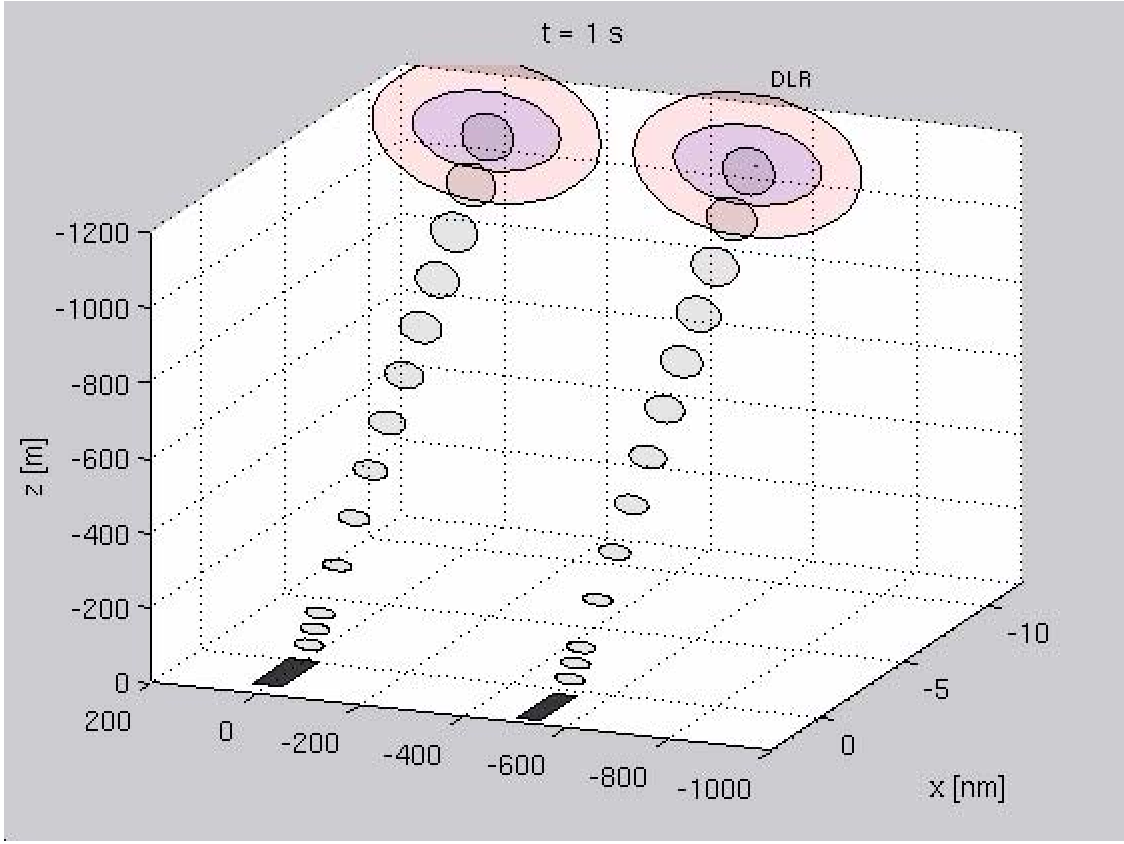
Accuracy of Numerical Weather Predictions



40 days
z = 100 m

Relevance of Crosswind

WSVBS - Wake Vortex Prediction and Monitoring System

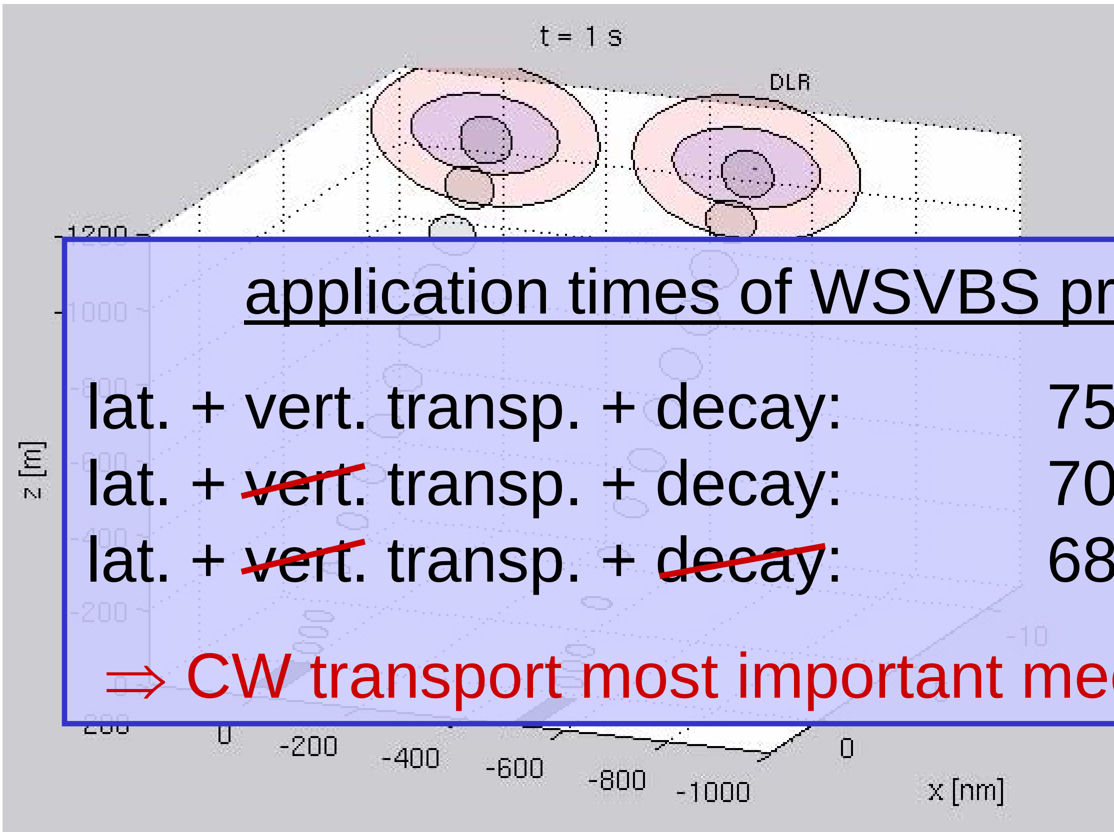


- 2004/09/10 19:10

- modified staggered left
- reduced sep. single rwy

Relevance of Crosswind

WSVBS - Wake Vortex Prediction and Monitoring System



<u>application times of WSVBS procedures:</u>

lat. + vert. transp. + decay: 75%

lat. + ~~vert.~~ transp. + decay: 70%

lat. + ~~vert.~~ transp. + ~~decay~~: 68%

⇒ CW transport most important mechanism (90%)

- 2004/09/10 19:10

- modified staggered left
- reduced sep. single rwy

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Prediction Skill

deterministic scoring results

lateral transport: most important, easy to model, largest uncertainty

	RMS $\Delta\Gamma_{5-15} / \Gamma_0$	RMS $\Delta z / b_0$	RMS $\Delta y / b_0$
best median	0.128	0.118	0.402
		factor 2 - 4	
worst median	0.240	0.452	0.968

worst median	86 m²/s	17 m	34 m

Uncertainties – Reference Data

accuracy of lidar data

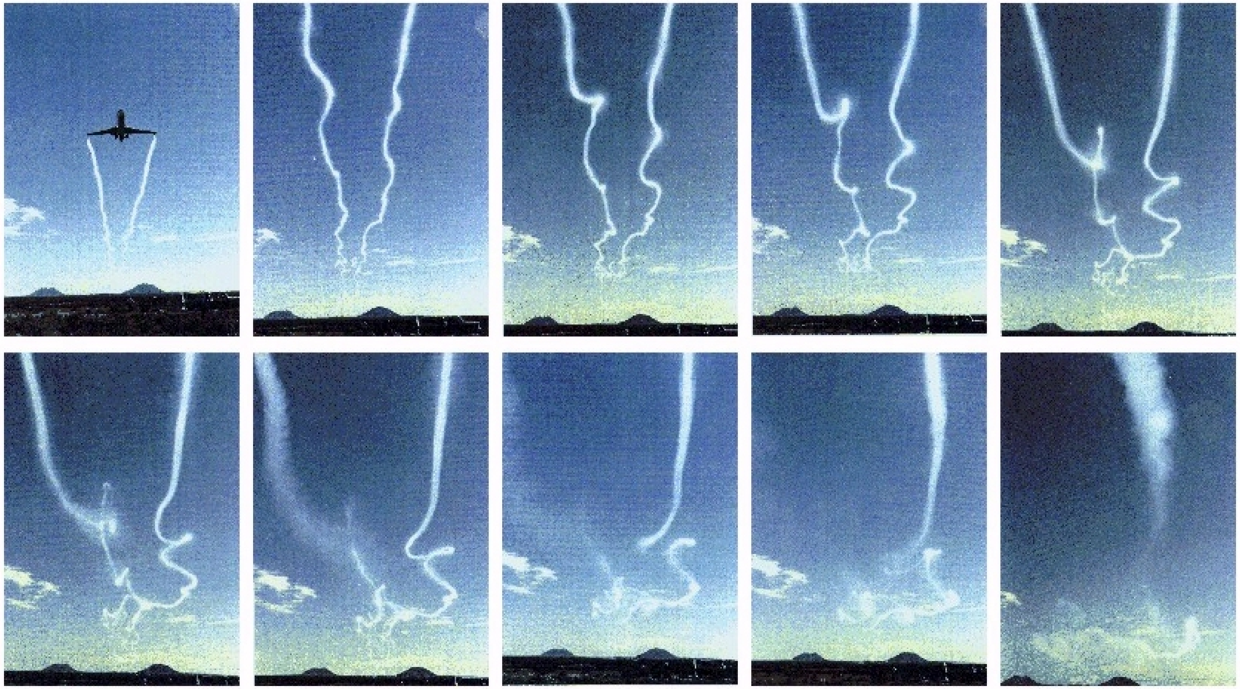
estimates from triangulation of lidars from ONERA, Qinetiq, DLR

$\sigma_y < 6.5$ m
$\sigma_z < 4.5$ m
$\sigma_\Gamma \approx 13$ m²/s

Köpp et al., J. Aircraft 42, 2005

Uncertainties – Reference Data

what about variability ?



Idaho Falls
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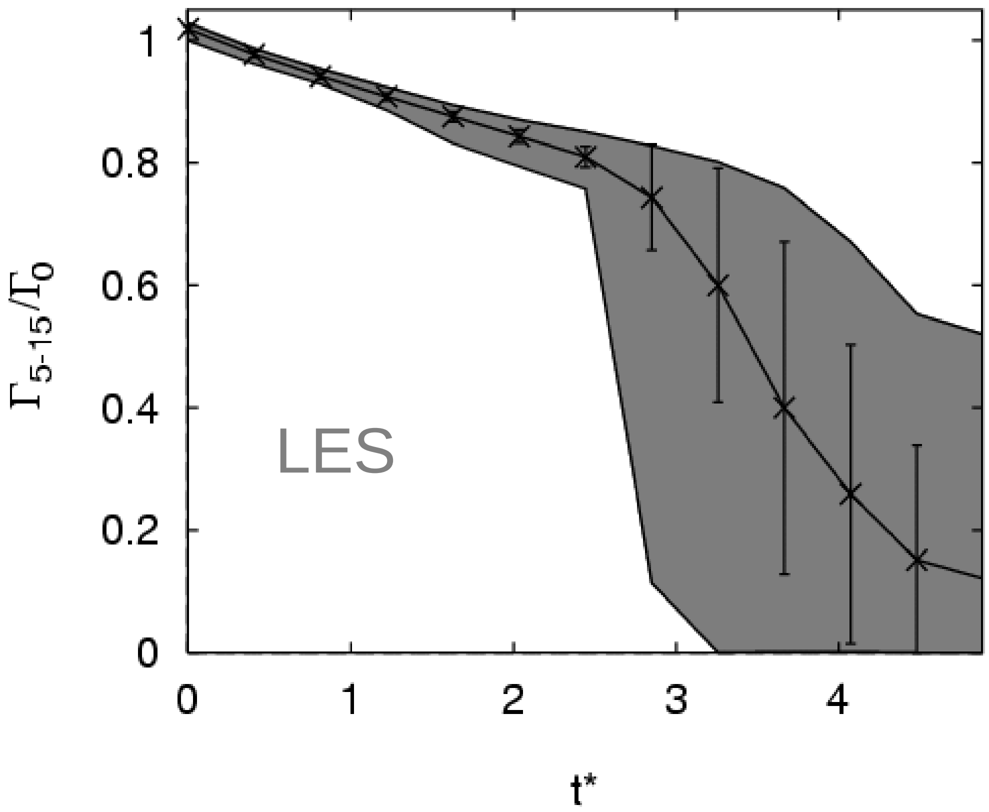
Uncertainties – Reference Data

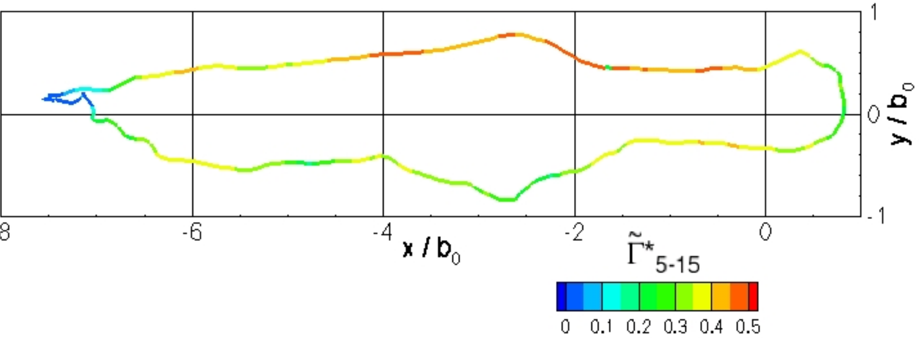
what about variability ?

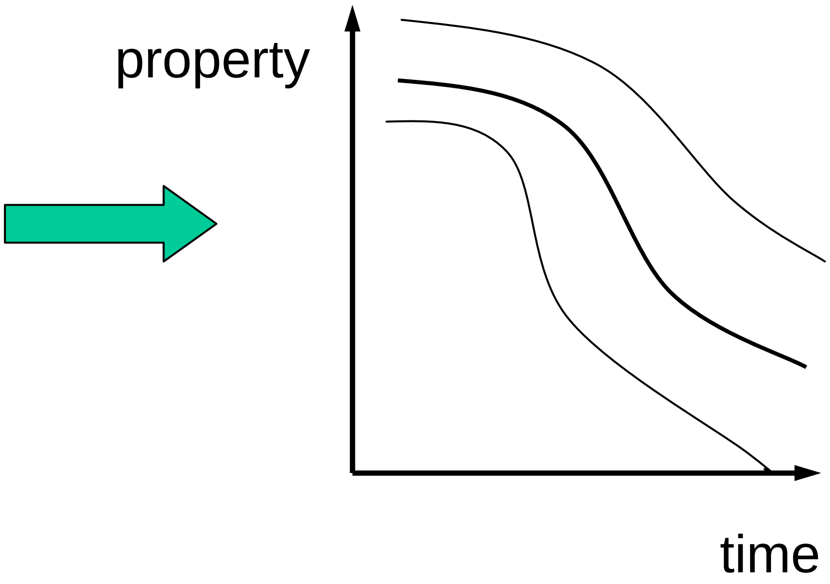


Holzäpfel, J. Aircraft **43** 2006

Difficulty – Stochastic Phenomenon

how can we handle this ?





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Probabilistic Methods - Systematic

Monte Carlo Simulation

consider uncertainties of initial, environmental, (model) parameters:

$$x_0 \pm \sigma_{x_0}, y_0 \pm \sigma_{y_0}, z_0 \pm \sigma_{z_0}, b_0 \pm \sigma_{b_0}, \Gamma_0 \pm \sigma_{\Gamma_0}, \ldots$$

$$u(z) \pm \sigma_{u(z)}, v(z) \pm \sigma_{v(z)}, w(z) \pm \sigma_{w(z)}, \mathrm{TKE}(z) \pm \sigma_{\mathrm{TKE}(z)}, \varepsilon(z) \pm \sigma_{\varepsilon(z)}, \theta(z) \pm \sigma_{\theta(z)}$$

difficulties:
- specification of uncertainties
- computation times
- intrinsic wake vortex variability / deformation

Probabilistic Methods - Hybrid (empirical)

Probabilistic Two-Phase Wake Vortex Model – P2P

fixed uncertainties:

- variation of decay parameters $(\upsilon^*_{2,u}, 0.8T^*_2); (\upsilon^*_{2,l}, 1.2T^*_2)$
- uncertainty allowances $\pm b_0, \quad \pm 0.2\Gamma_0$

dynamic uncertainties:

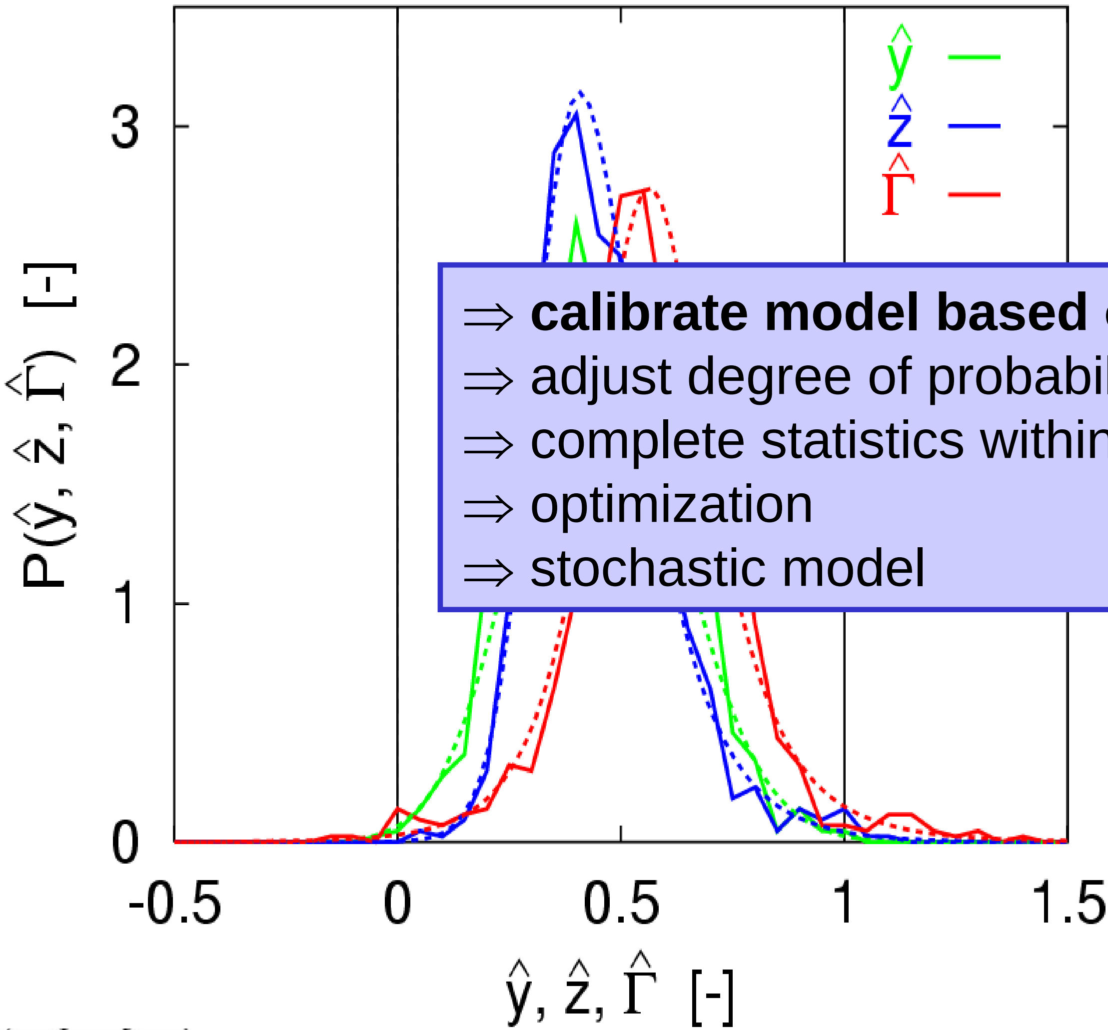
- uncertainty allowances $y^*_{u(l)}, z^*_{u(l)} = y^*, z^* + (-) \int \sqrt{\left(C_q q^*\right)^2 + \left(C_{sh} v^*_{sh}\right)^2}\, dt^*$

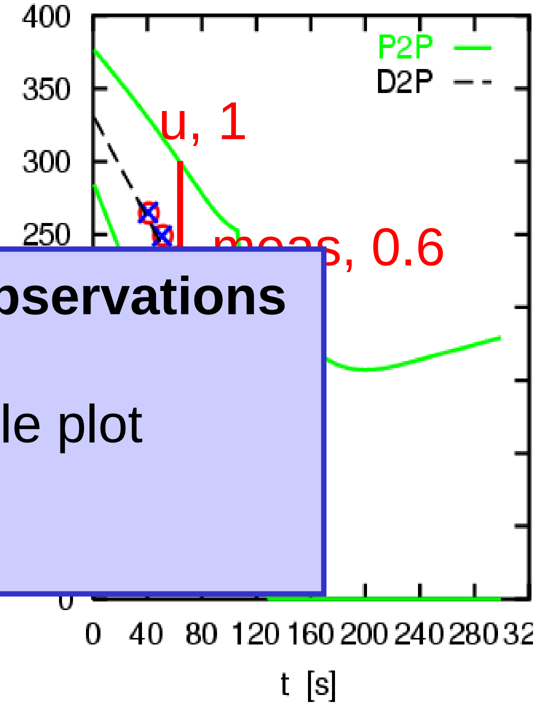
model calibration with measurement data:

- uncertainty allowances (see next slide)

Model Calibration with Measurement Data

prediction of envelopes with defined probabilities





⇒ **calibrate model based on observations**

⇒ adjust degree of probability

⇒ complete statistics within single plot

⇒ optimization

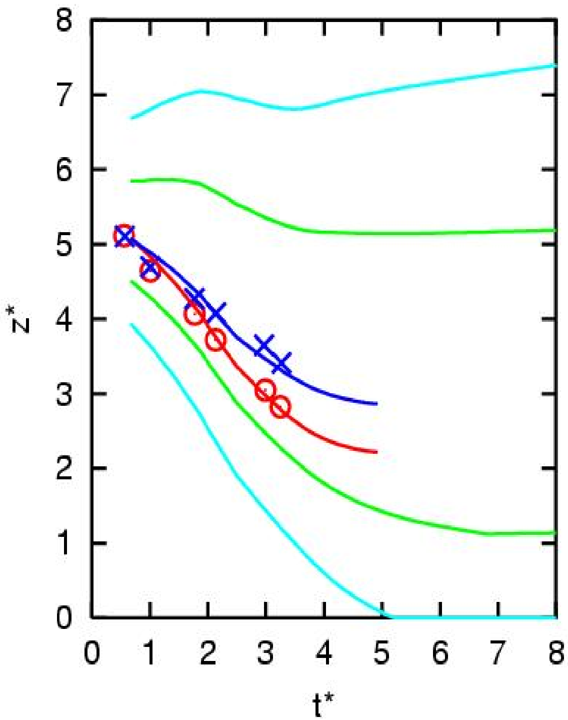
⇒ stochastic model

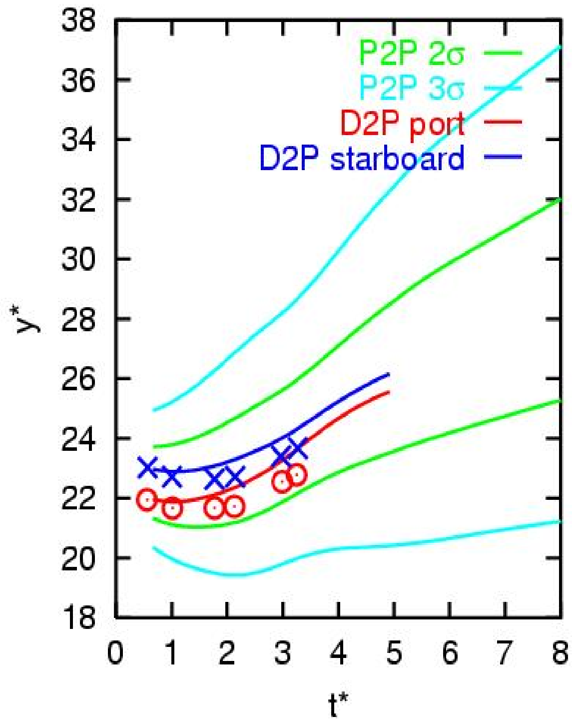
$$\hat{z} = \frac{z_{meas} - z_l}{z_u - z_l}$$

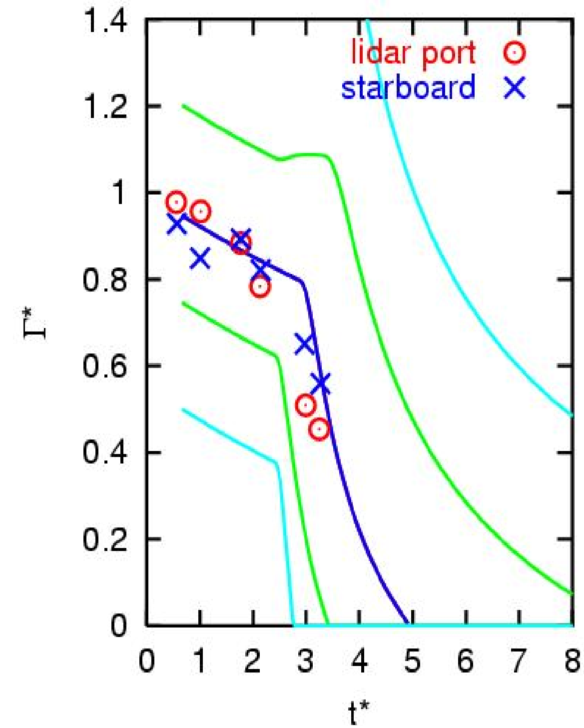
Holzäpfel, J. Aircraft **43** 2006

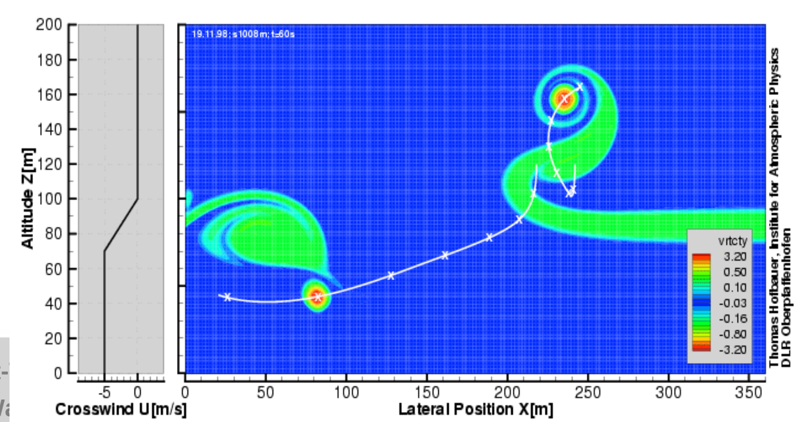
Examples

crosswind shear



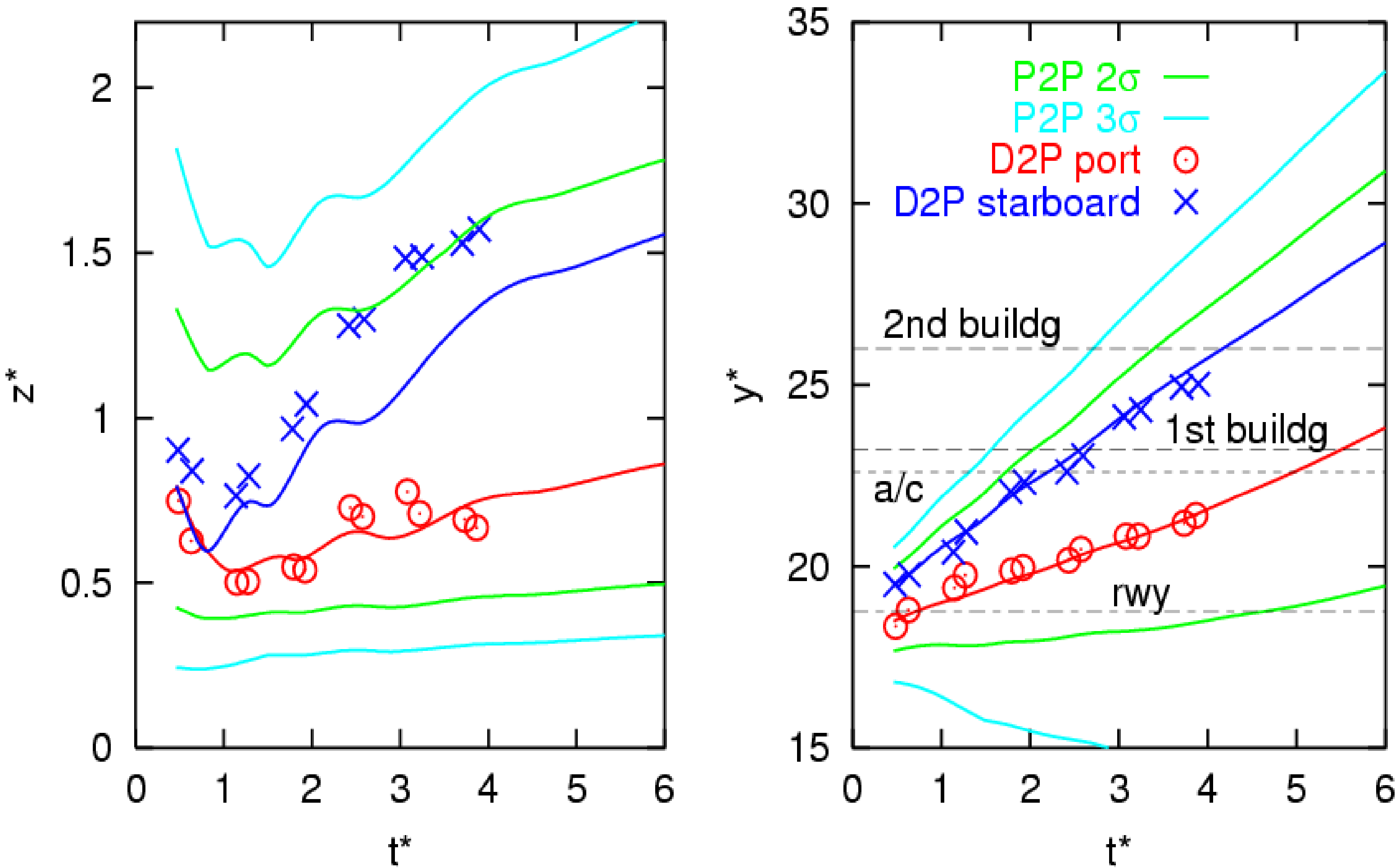






Examples

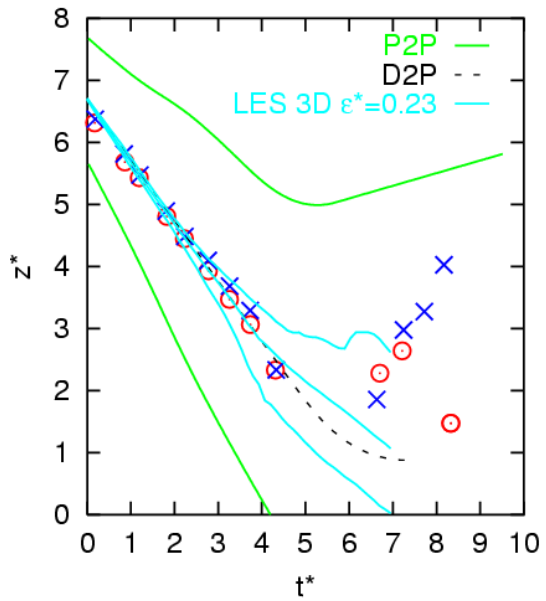
effect of obstacles

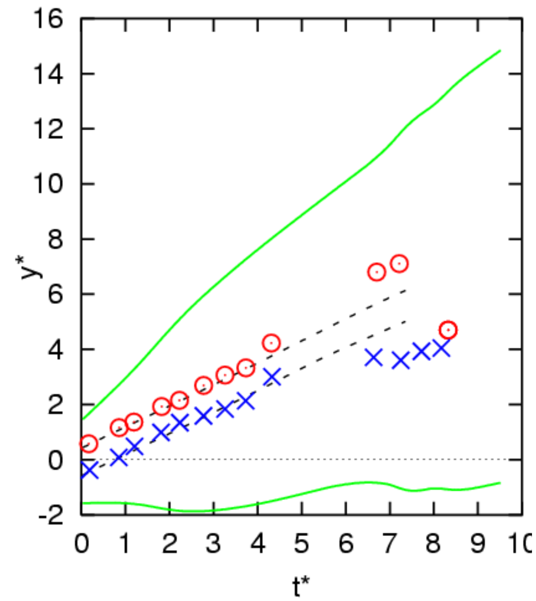


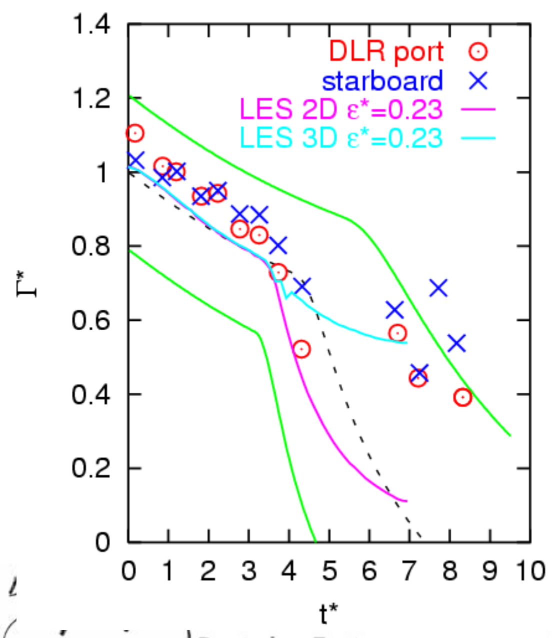
Holzäpfel & Steen, AIAA J. **45** 2007

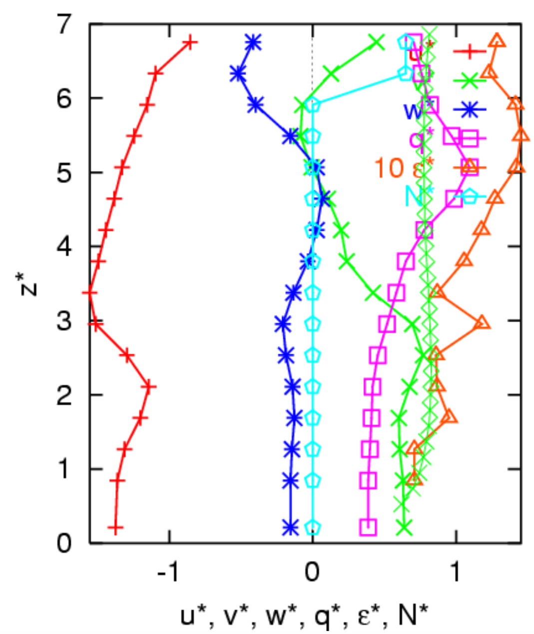
Examples

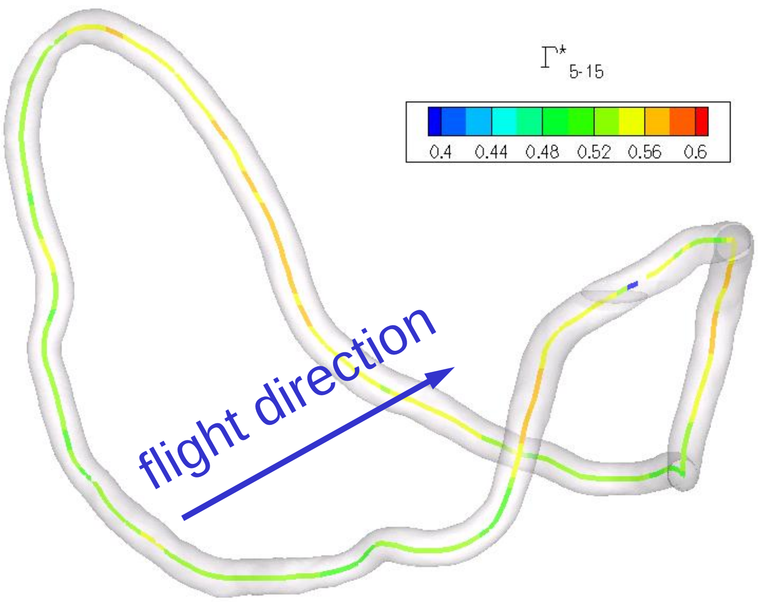
long-lived vortex rings











Hennemann & Holzäpfel, 5th Int. Symp. Turbulence & Shear Flow Phenomena, TU Munich 2007

conclusions

- considerable uncertainties arise from
  - initial conditions
  - environmental conditions
  - reference data
  - intrinsic variability of wake vortex data
- crosswind transport is most important / robust mechanism for WVAS
- crosswind variability / uncertainty introduces the largest uncertainties
- num. weather prediction superior to persistence assumption after ~1 hour
- probabilistic methods:
  - systematic - Monte Carlo simulation
  - empirical hybrid methods
  - others ?

scientific questions - priorities for future research

- what is the spatial and temporal correlation of the required meteo parameters?
- which is the most effective weather prediction method for different lead times?
- (how) can we quantify the predictability of particular weather scenarios for short-term predictions?
- how to introduce disturbances to ensemble prediction methods for short-term predictions?
- which probabilistic nowcasting methods are available / appropriate?

- how to use meteo uncertainty information optimally by the WV predictors?
- how to quantify improvements of probabilistic prediction chain?

- quantify effects of uncertainties of input parameters on WV properties!
- compare skills of probabilistic nowcasting with ensemble weather prediction!

P2P validation work - survey

campaign	No. cases	det./prob. scoring	compared to	a/c types	flight phases	documentation
Memphis, TN (1994, 1995)	282 211	X/-	APA	23 hvy/med/li	arrival OGE/IGE	J. Aircraft 2003/2004
Dallas Fort Worth, TX (1997)	191	X/-		16 hvy/med/li	arrival OGE/NGE	J. Aircraft 2004
WakeOP (2001)	41	X/-	APA	ATTAS	level/hi-lift OGE	J. Aircraft 2004
WakeTOUL Tarbes (2002)	32	X/X	APA	A340	lev/arr/cl/hi OGE	J. Aircraft 2006
AWIATOR FT1 Tarbes (2003)	32	X/X	APA	A340	level/take-off/OGE	J. Aircraft 2006
WakeFRA Frankfurt (2004)	282 + 233	X/X	APA / DVM	25 hvy/med	arrival IGE/OGE	AIAA J. 2007
CREDOS EDDF-1 (2007)	137	X/-	DVM	12 heavy	departure OGE	CREDOS D2-3, 2008
CREDOS EDDF-2 (2007)	~ 9,000	X/-	DVM	28 med/hvy	departure IGE/NGE	CREDOS D2-3, 2009
unpublished					cruise/arr. OGE/IGE	