Wake Vortex Tracker for Radar/Lidar Sensors

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WAKENET-3 Europe / GREENWAKE Dedicated Workshop,
THALES Palaiseau, 30.03.2010

Outline

- background and context of wake vortex tracking
- why collaboration between sensors and models?
- how can collaboration be implemented?
- what have we already achieved?
  - examples for the current system status
- what can be achieved in the future?
- conclusions

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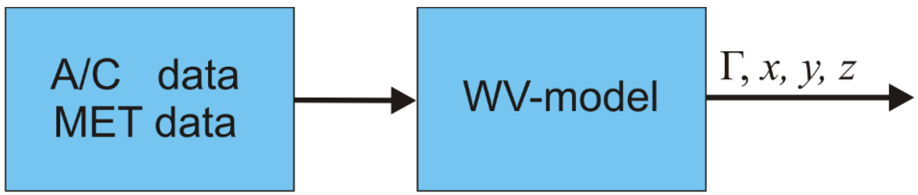
Need for reliable continuous wake vortex monitoring

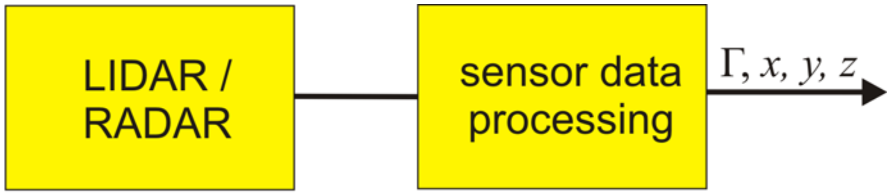
- SESAR: from Airspace to Trajectory Management
  - medium-long-term: trajectory based operations
    - ➔ delegate more separation authority AND responsibility to airspace users
- WV strength & position are subject to
  - changing MET conditions
  - uncertainties in movement/configuration of generator a/c
  - ➔ need for a real-time monitoring and detection at the airport and on-board aircraft

Current situation: two individual approaches

- two approaches:
  - propagation by model



  - detection and monitoring by sensors



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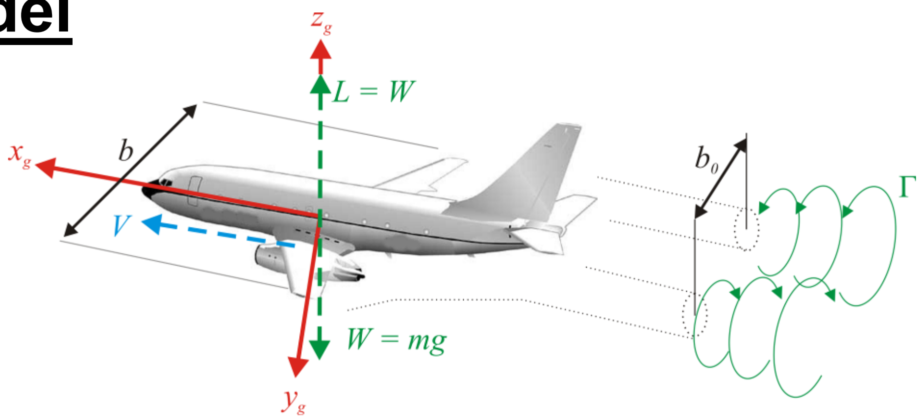
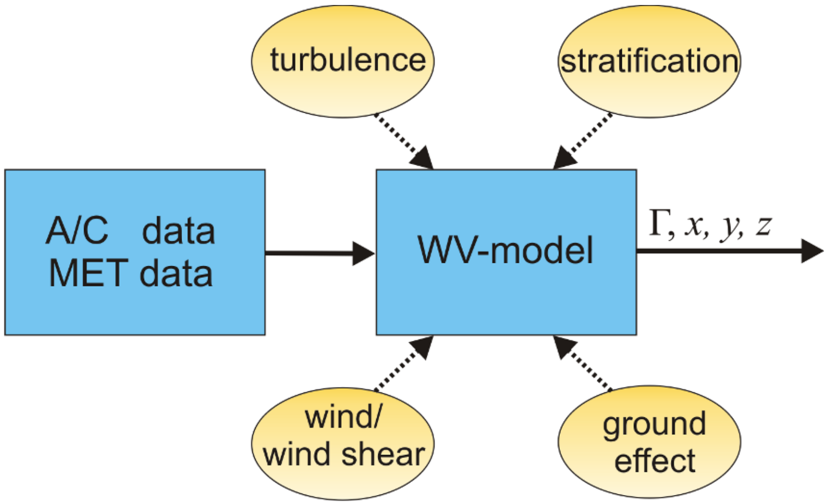
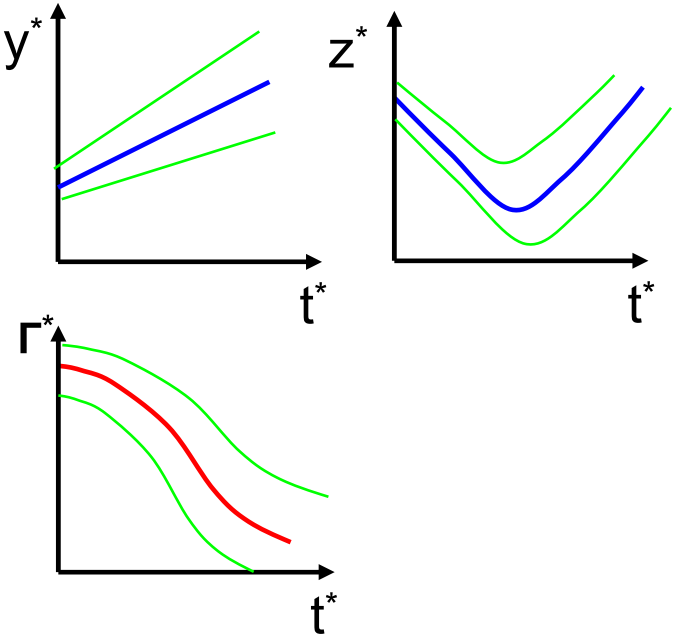
model



z_g
$L = W$
x_g
b
V
$W = mg$
y_g
b_0
Γ



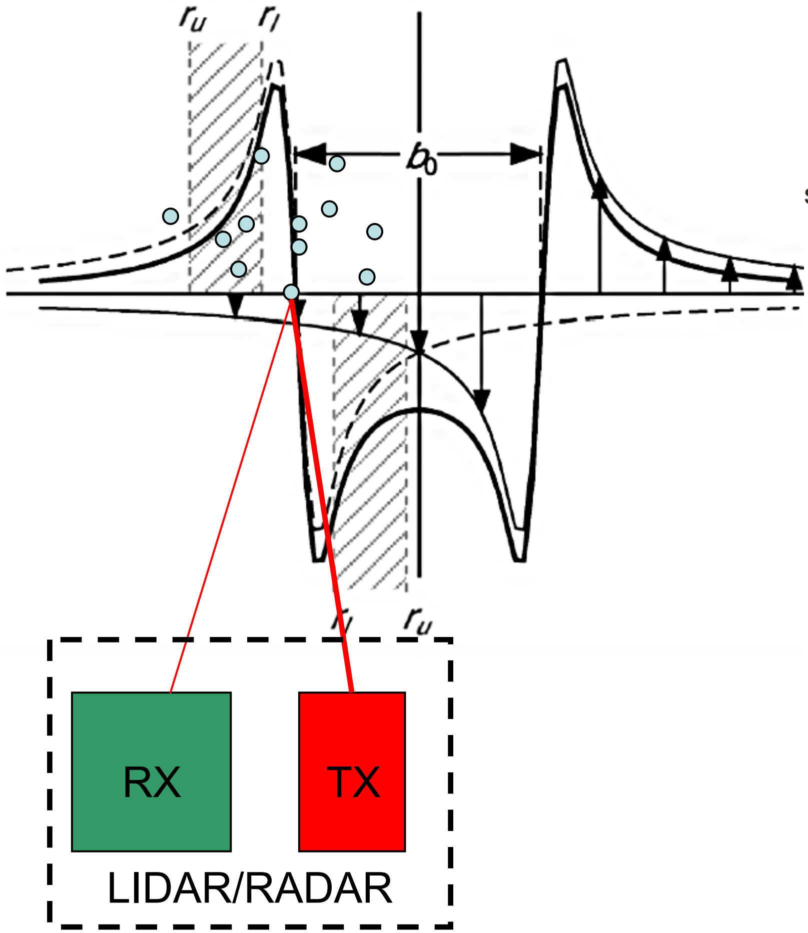
turbulence
stratification
A/C data
MET data
WV-model
Γ, x, y, z
wind/
wind shear
ground
effect

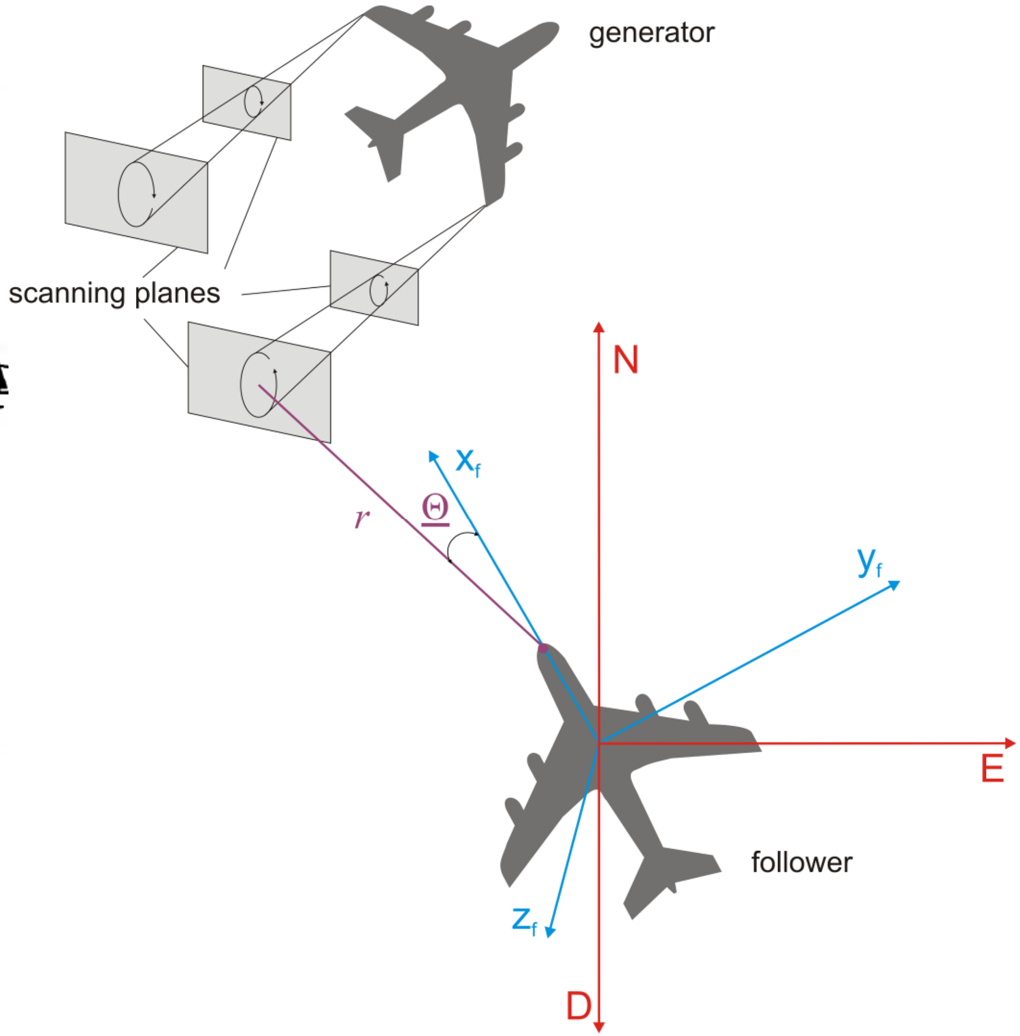


y^*
t^*
z^*
t^*
Γ^*
t^*

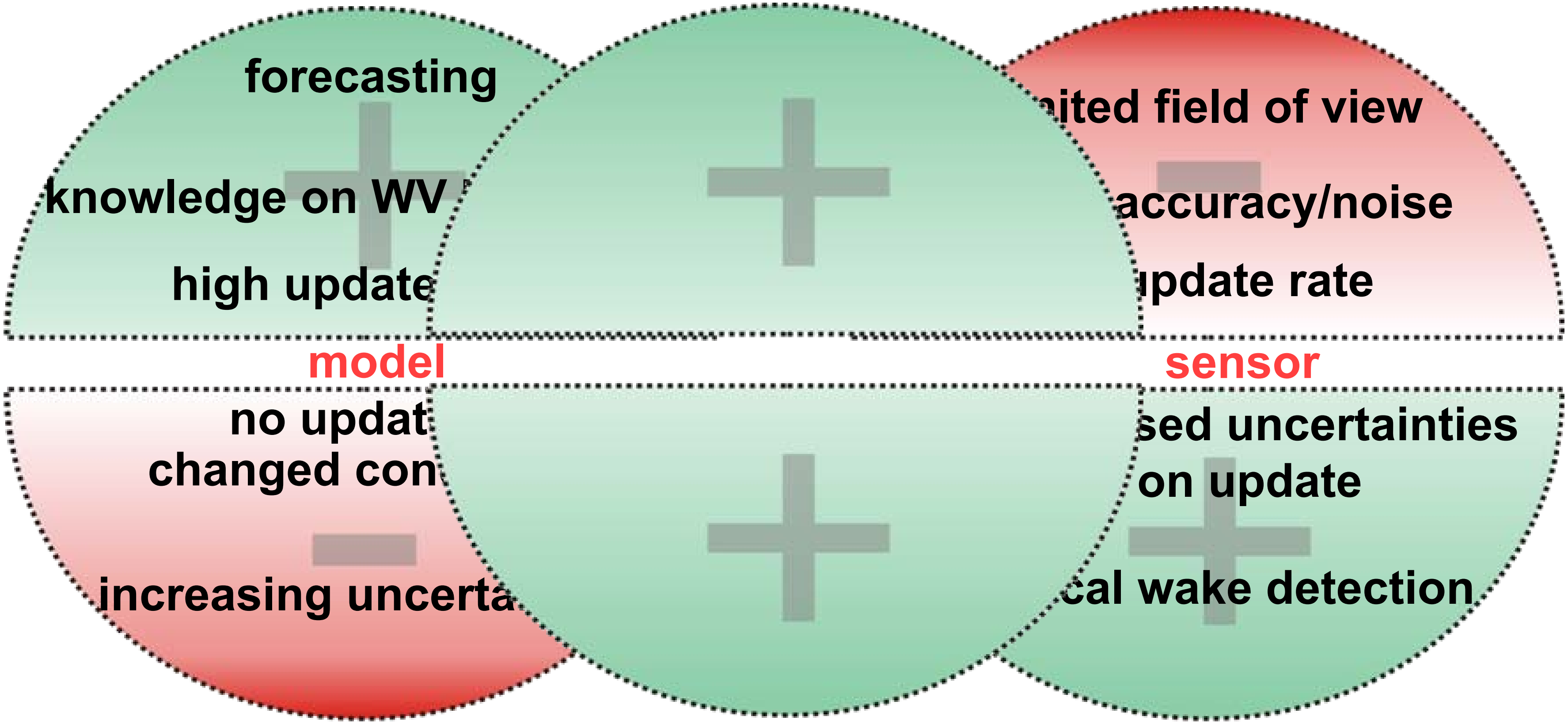
State-of-the-art approaches - detection

sensor





Typical example of two complementary systems



➔ Taking advantage by using only the positive characteristics of each system

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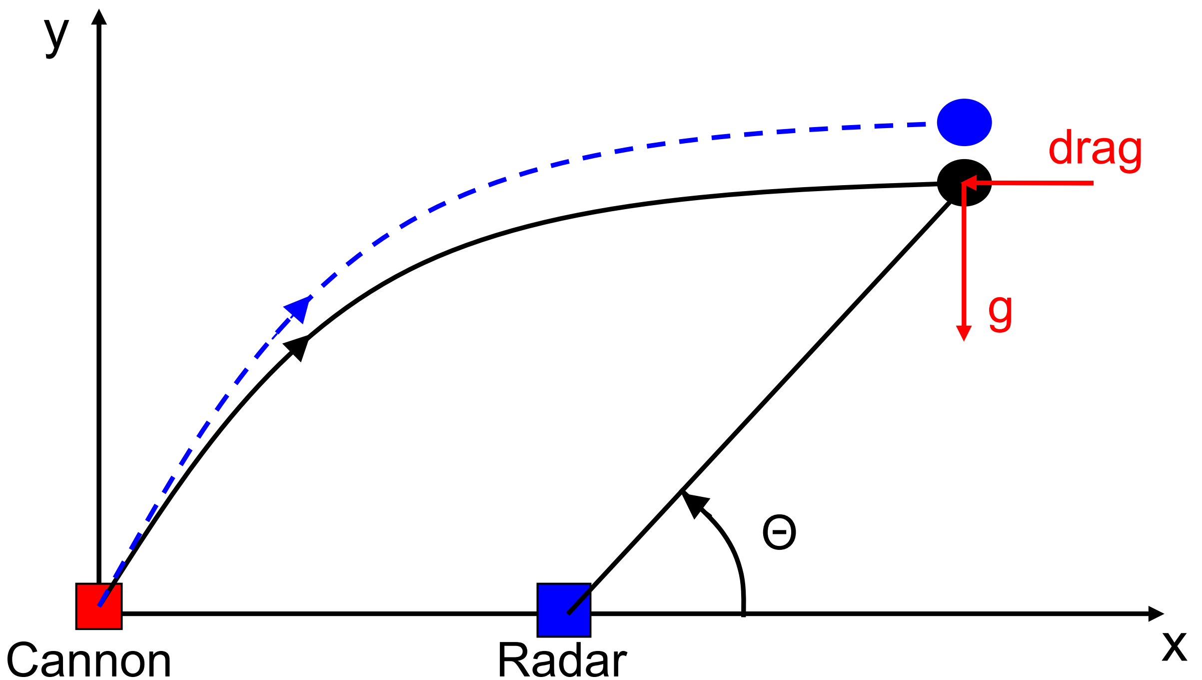
The tracking problem

- typical tracking application
  - model of movement exists (e.g. gravity, drag)
    ➔high frequent prediction
  - low frequent measurement updates model



Fusion Filter algorithms: using the Kalman Filter

state (WV trajectory error, circulation error)

state transition (error propagation)

error/uncertainty-feedback

time-update

$$\underline{\hat{x}}_{k+1}^{-} = \underline{\underline{\Phi}}\,\underline{\hat{x}}_k + \underline{\underline{\Gamma}}\,\underline{u}_k$$

$$\underline{\underline{P}}_{k+1}^{-} = \underline{\underline{\Phi}}\,\underline{\underline{P}}_k\,\underline{\underline{\Phi}}^T + Q_k$$

x_0, P_0

measurement-update

$$\underline{\underline{K}}_k = \underline{\underline{P}}_k^{-}\,\underline{\underline{H}}^T\left(\underline{\underline{H}}\,\underline{\underline{P}}_k^{-}\,\underline{\underline{H}}^T + R_k\right)^{-1}$$

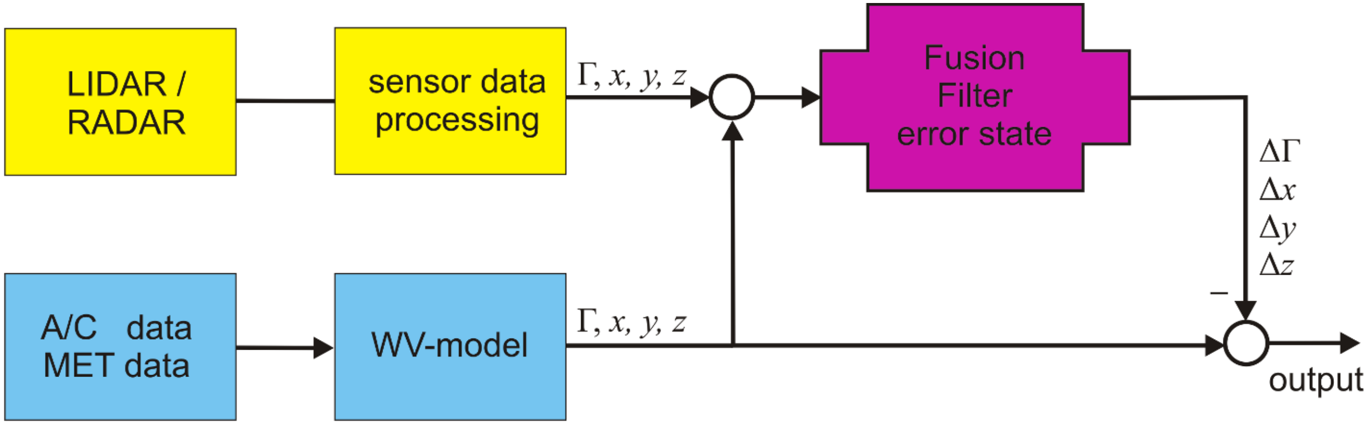
$$\underline{\hat{x}}_k = \underline{\hat{x}}_k^{-} + \underline{\underline{K}}_k\left(\underline{z}_k - \underline{\underline{H}}\,\underline{\hat{x}}_k^{-}\right)$$

$$\underline{\underline{P}}_k^{+} = \left(\underline{\underline{I}} - \underline{\underline{K}}_k\,\underline{\underline{H}}\right)\underline{\underline{P}}_k^{-}$$

Covariance (analogous to uncertainty bound in current models, but decreased by measurement)

measured quantities (WV circulation, position)

System layouts for wake vortex tracking

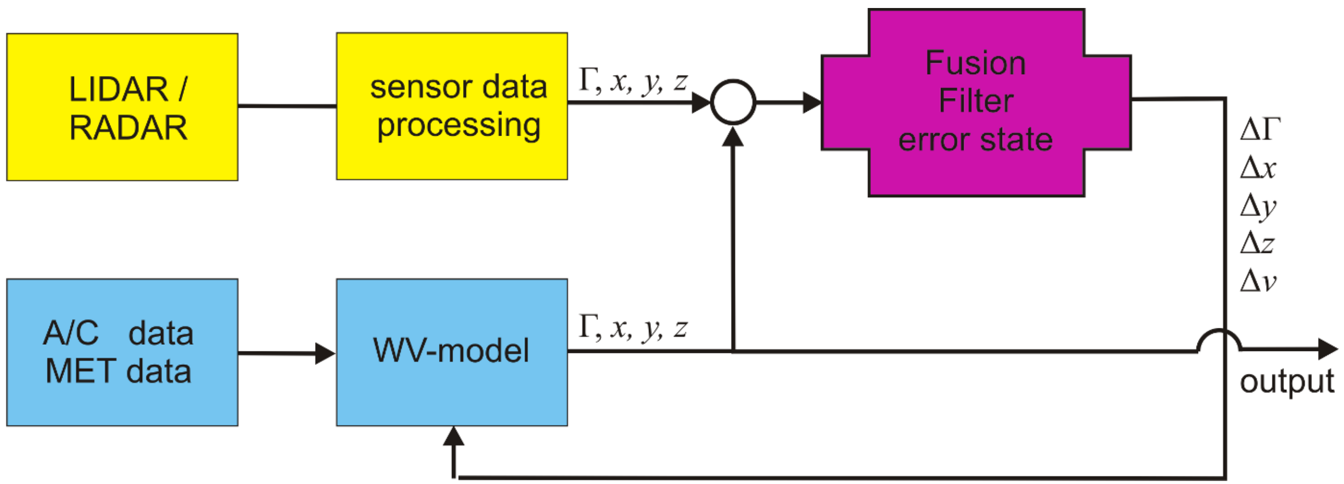


$$\Gamma^{*+}_{output,k} = \Gamma^{*-}_{prediction,k} - \Delta\Gamma^{*+}_{k}$$

$$y^{*+}_{output,k} = y^{*-}_{prediction,k} - \Delta y^{*+}_{k}$$

$$z^{*+}_{output,k} = z^{*-}_{prediction,k} - \Delta z^{*+}_{k}$$

System layouts for wake vortex tracking



$$\Gamma^{*+}_{prediction,k} = \Gamma^{*-}_{prediction,k} - \Delta\Gamma^{*+}_{k}$$

$$y^{*+}_{prediction,k} = y^{*-}_{prediction,k} - \Delta y^{*+}_{k}$$

$$z^{*+}_{prediction,k} = z^{*-}_{prediction,k} - \Delta z^{*+}_{k}$$

$$v^{*+}_{k} = v^{*-}_{k} - \Delta v^{*}_{k}$$

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Error propagation

- formulation of errors: $\underline{\dot{x}} = \underline{\underline{F}}\,\underline{x}$

- simplified example:

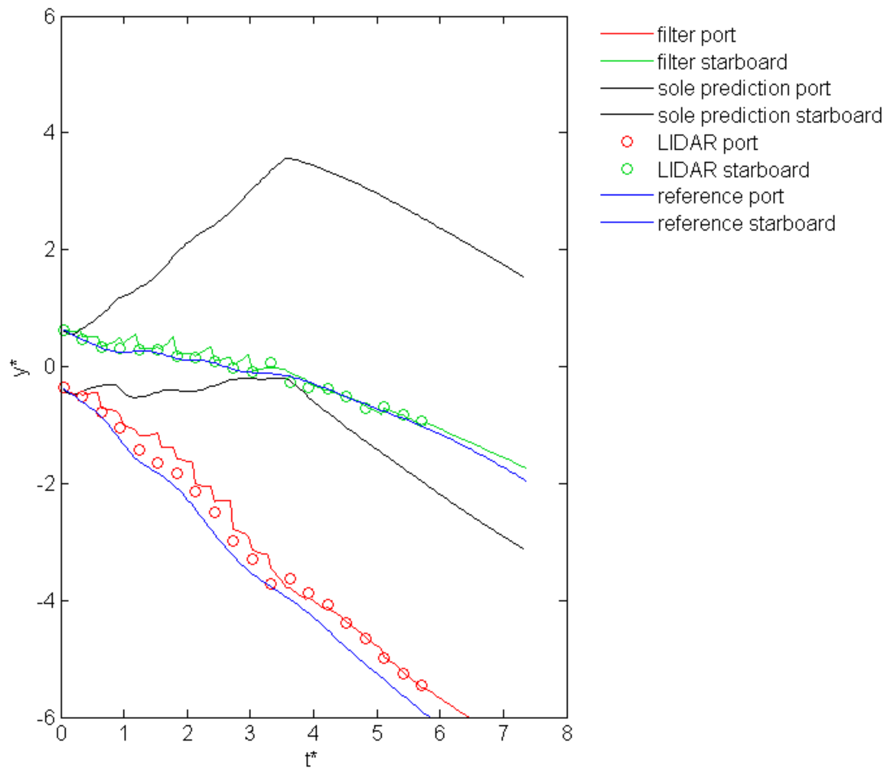
  circulation errors depending on:
  - actual circulation error
  - circulation decay error
  - error in initial circulation

$$\underline{x} = \begin{bmatrix} \Delta\Gamma^* \\ \Delta\dot{\Gamma}^* \\ \Delta\Gamma_0 \\ \Delta y^* \\ \Delta\dot{y}^* \\ \Delta z^* \\ \Delta\dot{z}^* \\ \Delta v^* \end{bmatrix}$$

$$\Delta\dot{\Gamma}^* = \frac{\partial\Delta\dot{\Gamma}^*}{\partial\Delta\Gamma^*}\cdot\Delta\Gamma^* + \frac{\partial\Delta\dot{\Gamma}^*}{\partial\Delta\dot{\Gamma}^*}\cdot\Delta\dot{\Gamma}^* + \frac{\partial\Delta\dot{\Gamma}^*}{\partial\Delta\Gamma_0}\cdot\Delta\Gamma_0$$

Result example

- sudden crosswind error
- prediction-only gives misleading information
- fused system more reliable



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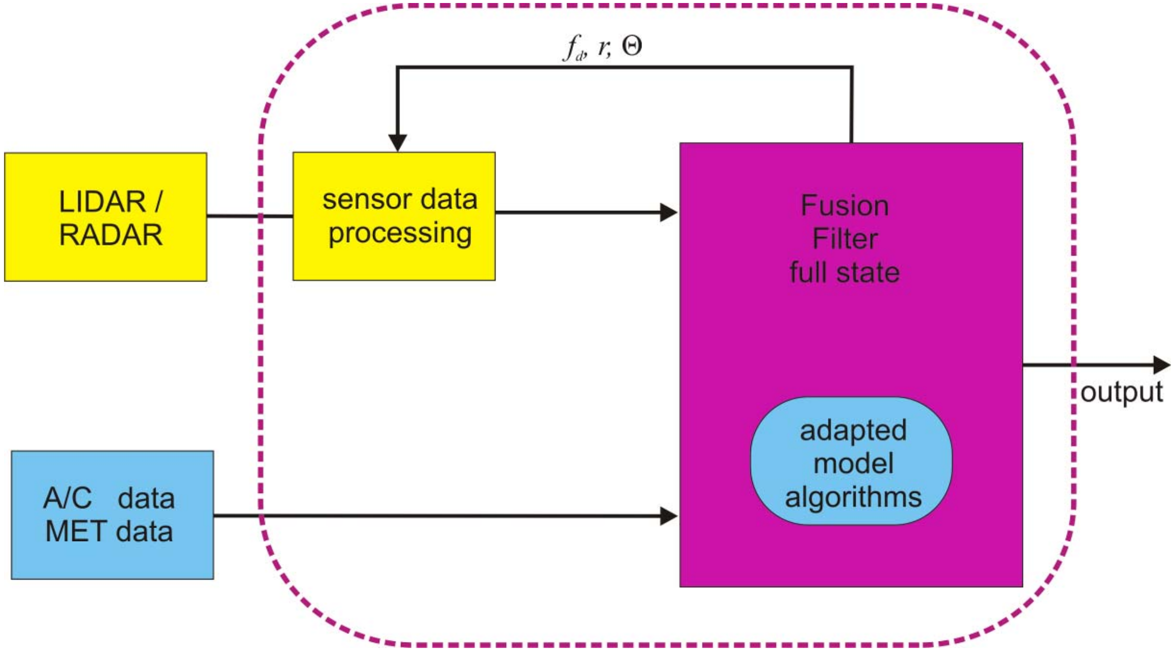
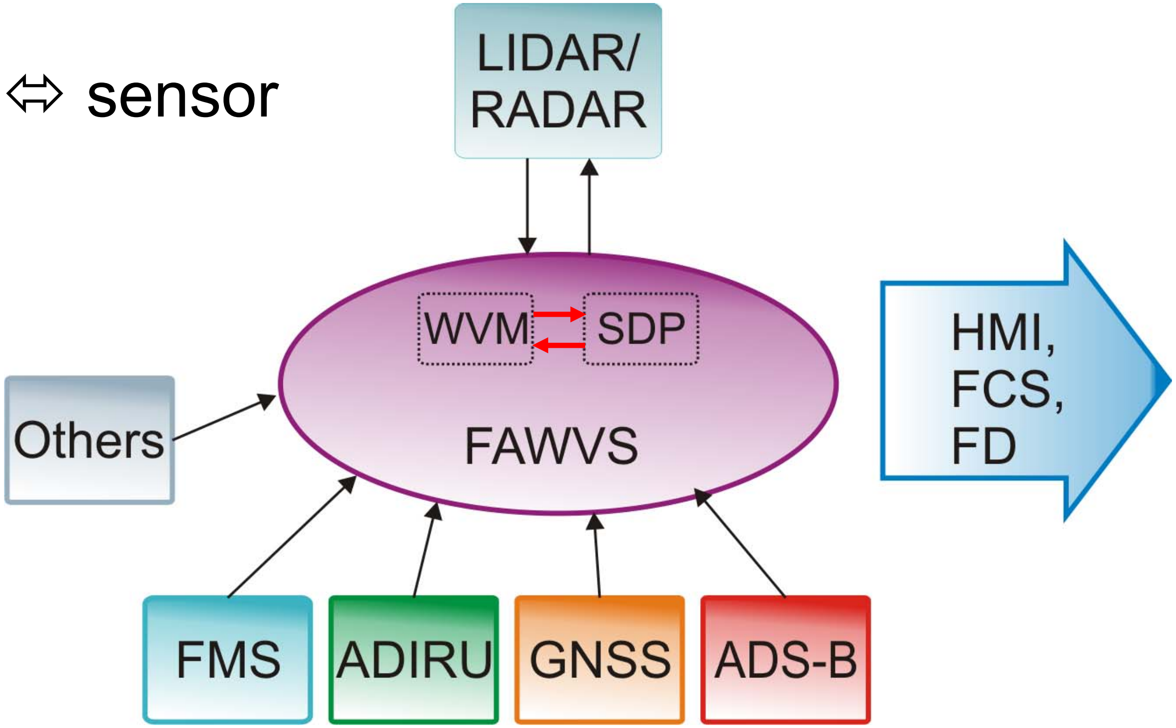
Recommended fusion principle: Fully collaborative system



- most favorable in terms of
  - accuracy
  - reduced uncertainty
  - model/sensor interaction

Fused Airborne Wake Vortex Surveillance

- interfaces to on-board avionics
  - one-way
- interface model ⇔ sensor



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Conclusions

- wake vortex tracking via fusion of two complementary approaches: prediction and detection
- possible collaboration approach presented
- first implementation results show compatibility with existing elements

  ➔ fusion approach improves accuracy **AND** reduces uncertainty
- future wake vortex tracking sensors can benefit from collaborative approach
  – better a priori information
- on-board application for the long-term

Outlook – further steps still to go – ongoing research

- further development and constant improvement of fusion algorithm
  - short-term: better error propagation models
  - longer-term: implementation of wake vortex model algorithms and sensor data processes as part of filter

- interfaces to sensors and models
  - two-ways: provide input to filter ←→ accept information from filter

Acknowledgement

This work has been co-financed by the European Organisation for the Safety of Air Navigation (EUROCONTROL) under its Research Grant scheme.

The content of the work does not necessarily reflect the official position of EUROCONTROL on the matter.

Thank you for your attention!

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Error propagation

- only first decay phase:

$$\Gamma^* = A - e^{-\frac{C}{\nu_1^*\left(t^* - T_1^*\right)}}$$

$$\dot{\Gamma}^* = \frac{C}{\nu_1^*\left(t^* - T_1^*\right)^2}\left(-e^{-\frac{C}{\nu_1^*\left(t^* - T_1^*\right)}}\right) = k \cdot \left(\Gamma^* - A\right)$$

$$\dot{\Gamma} = \Gamma_0 \cdot k \cdot \left(\Gamma^* - A\right)$$

$$\dot{\Gamma} + \Delta\dot{\Gamma} = \left(\Gamma_0 + \Delta\Gamma_0\right) \cdot k \cdot \left(\Gamma^* + \Delta\Gamma^* - A\right)$$

$$\underline{x} = \begin{bmatrix} \Delta\Gamma^* \\ \Delta\dot{\Gamma}^* \\ \Delta\Gamma_0 \\ \Delta y^* \\ \Delta\dot{y}^* \\ \Delta z^* \\ \Delta\dot{z}^* \\ \Delta v^* \end{bmatrix}$$

Error propagation

- only first decay phase:

$$\dot{\Gamma}^* + \Delta\dot{\Gamma}^* = \frac{(\Gamma_0 + \Delta\Gamma_0)}{\Gamma_0} \cdot k \cdot (\Gamma^* + \Delta\Gamma^* - A)$$

$$\Delta\dot{\Gamma}^* = \frac{(\Gamma_0 + \Delta\Gamma_0)}{\Gamma_0} \cdot k \cdot (\Gamma^* + \Delta\Gamma^* - A) - k \cdot (\Gamma^* - A)$$

$$\Delta\dot{\Gamma}^* = k \cdot (\Gamma^* + \Delta\Gamma^* - A) + \frac{\Delta\Gamma_0}{\Gamma_0} \cdot k \cdot (\Gamma^* + \Delta\Gamma^* - A) - k \cdot (\Gamma^* - A)$$

$$\Delta\dot{\Gamma}^* = k \cdot \Delta\Gamma^* + \frac{\Delta\Gamma_0}{\Gamma_0} \cdot k \cdot (\Gamma^* + \Delta\Gamma^* - A)$$

$$\underline{x} = \begin{bmatrix} \Delta\Gamma^* \\ \Delta\dot{\Gamma}^* \\ \Delta\Gamma_0 \\ \Delta y^* \\ \Delta\dot{y}^* \\ \Delta z^* \\ \Delta\dot{z}^* \\ \Delta v^* \end{bmatrix}$$