Simulated Lidar Signals for Wake-Vortex Detection ahead of the Aircraft

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Aircraft moves towards wake vortex.

Goal:

Evasive Action

or

Encounter with Gust Load Alleviation
# Airborne Lidar measurements ahead of the Aircraft

- **Wetter & Fliegen**: Properties of on-board sensors
- Determination of full 3D wind vectors in clear air
- Feed-Forward-controller (active control)

## Requirements for feed-forward controller

<table>
<thead>
<tr>
<th>Measurement property</th>
<th>landing approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range (distance)</td>
<td>30 – 150 m (120 – 600 m)</td>
</tr>
<tr>
<td>Measurement points (per slab)</td>
<td>min. 20 full 3D wind vectors</td>
</tr>
<tr>
<td>Error (standard deviation)</td>
<td>max. 2.5 m/s</td>
</tr>
<tr>
<td>Frequency (slabs per second)</td>
<td>min. 10 Hz</td>
</tr>
<tr>
<td>Volume (depth of each slab)</td>
<td>max. 3 – 15 m (12 – 60 m)</td>
</tr>
</tbody>
</table>

values for cruising speed in brackets!
1. Simulations of Doppler Wind Lidar (DWL)

Principle of wind velocity and direction measurement by onboard-DWL

Measure the particle movement in air

Doppler-shift-formula

\[ v_{LOS} = -\frac{\Delta \lambda}{2 \lambda_0} C \]
Forward simulation: Simulated FPI-diagrams of a Fringe-Imaging DWL
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Interferograms (ICCD) of Onboard-measurements: AWIATOR, Nov./Dez. 2006

- Reference signal
- Backscattering in dense clouds
- Backscattering in 3600 m altitude
- Backscattering in 11900 m altitude

- Image 1
- Image 2
- Image 3
- Image 4

Mixture of Mie and Rayleigh
Better visible Rayleigh-scattering

Jenaro Rabadan et al., Journal of Aircraft (2010)
Backward simulation: Calculation of radii

![Graph showing ring radii, ring cut from center, and averaging via CA method.](image)
Results of DWL studies

⇒ Error of peak radius or ring center of only $1/40$ of a pixel with side length of 10 $\mu$m means already an error of 1 m/s at a wavelength of 355 nm!

⇒ for exactly known FP ring center at a distance of 56 m and depth of 10 m 20 ring diagrams are sufficient for a bias and standard deviation $< 2$ m/s of $v_{\text{LOS}}$

⇒ for determination of center at the same conditions as above bias of 7 m/s and a standard deviation of 3 m/s for $v_{\text{LOS}}$

⇒ Evaluation needs too much time

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2. Simulations of a Backscatter Lidar for wind measurements
2. Simulations of a Backscatter Lidar for wind measurements

\[ s_2 = s_1 - V_{AIC} \Delta t \]

\( s_2 \) the distance to the plane center

\( \Delta t = t_2 - t_1 \)
Wake Vortex Extinction profiles from Large Eddy Simulations

extinction slab for A340 generated wake vortices, $t^*=40$ s, $\varepsilon^* = 0.01$, $N^* = 0.35$
Wake Vortex Extinction profiles from Large Eddy Simulations

extinction at $t_2 = t_1 + \Delta t$
Wake Vortex Extinction profiles from Large Eddy Simulations

optimal Lamb-Oseen-vortices
Wake Vortex Extinction profiles from Large Eddy Simulations

retrieved wind field via cross-correlation

extinction [1/km]

0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8

y-axis position [m]

z-axis position [m]

-40 -20 0 20 40
Backscatter profiles of Monte-Carlo simulations

Backscatter profile at $t_1$
Backscatter profiles of Monte-Carlo simulations

backscatter profile at $t_2$
Backscatter profiles of Monte-Carlo simulations retrieved wind field via cross-correlation

normalized backscatter intensity

y-axis position [m]

z-axis position [m]

-40 -20 0 20 40
Backscatter profiles of Monte-Carlo simulations

without outliers
Relative deviations between wind field of extinction profiles and wind field of backscatter profiles via cross-correlation

Relative errors for the lengths of the wind vectors

velocity magnitudes in m/s

velocity deviations in m/s
Relative deviations between wind field of extinction profiles and wind field of backscatter profiles via cross-correlation.

Relative errors for the direction of the wind vectors.

Wind directions in rad

Angle deviations in rad

z-axis position [m]

y-axis position [m]
Benefits and results of the simulated BL

- feasibility of detecting rotational features of vortices shown
- sufficient number of v- and w-components of wind vectors per slab and more slabs per second
- relatively low errors for wind velocities and directions, i.e. more precision for y- and z-components (transversal to aircraft’s propagation axis x; crucial to flight stability) => very erroneous for DWL!
- much faster signal processing

Conclusion from the simulations

- From the DWL and BL simulations it turns out to be advisable to combine a FI-DWL for the x- with a BL for the y- and z-wind components
- BL may be sufficient for flight control

M.C. Hirschberger, T. Misaka, F. Holzäpfel, C. Horn, „Simulated Lidar Signals for Wake Vortex Detection ahead of the Aircraft“, this project’s final report, pp.130-143.
Outlook

- Principle of BL also useful to measure wakes behind wind power stations or to optimize their orientation to the wind direction.
- Further BL simulations useful (angles of encounter and vortex ages, wavelength).

Challenges for building a BL device for wind measurements:
- Distribution of thousands of pulses (or split parts of pulses) at the same moment of time.
- Adaptation of measurement angles according to flight speed.
- BL must be able to detect the backscattered photons from different directions at the same time plus to distinguish between the directions of backscattered photons.
- Design and build a working lidar instrument for flight control.
Thank you for your attention!