Experimental airborne four channel cw-Laser-Doppler-Anemometer for flight instrumentation

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Towards optical air data sensors

Optical measurement of...
True air-speed, angle-of-attack, angle-of-sideslip
static pressure, static temperature

Increased flight safety
Fuselage-flush mounting possible
Intrinsic self diagnostics and measurement uncertainties
Direct measurement of the wind vector

Reduced calibrational effort
Self-referenced, calibration-free techniques
Probeless remote-sensing outside the aircraft boundary layer
System Layout

1550 nm
4 x 1 W MOPA System
80 MHz
Er-DFB Laser
AOF
+1
Opt. Switch

Interferometers

RX/TX Channels

LDA Signal

16 GBit/s
Full-dump channel
< 150 MBit/s
Preprocessed data

Central measurement and control system
(x86)

Python Client
Storage

Command, Control, Process
USB
HID
GigE
PCIe

16 GBit/s
Full-dump channel
< 150 MBit/s
Preprocessed data

Xilinx Zynq 7100 System-on-Chip
PLL

ADC

LVDS

Event detection

2048-FFT

Trigger

Delta T

2048-FFT Interleaving

DDRAM

Linux IIO Daemon

PCIe

GigE

Switch

AD9467
250 MS/s, 16 Bit

AD9517
1.6 GHz VCO

High-speed averager (1024x)
Principle of spectral triggering

**Schematic with simulated signal**

Due to the real temporal signal, half of the complex spectrum holds the full spectral and temporal information!

**Real spectra with non-trivial trigger function**

An interleaved complex spectral stream holds the full temporal information
LDA Transceiver

- Measurement distances: 500 mm, 1000 mm
- 4” windows with IBS-AR-coating
- 4” aspheric lenses for imaging of the fiber end in the ratio 1:2 and 1:4
- 15° elevation angle
- FC/APC fiber to the LDA-Rack
- PTC-Heaters and dry air to avoid icing of the windows
## Campaign planning

<table>
<thead>
<tr>
<th>Parameter under evaluation</th>
<th>Flight situation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle of attack</td>
<td>Different flight speeds at constant height</td>
</tr>
<tr>
<td>Angle of side slip</td>
<td>Usually in curves or during landing, but can be controlled by the pilots</td>
</tr>
<tr>
<td>True air speed</td>
<td>Variation of speed</td>
</tr>
</tbody>
</table>
| Signal rate                | Aerosol concentration dependent:  
  • Flight in different heights  
  • Boundary layer  
  • Marine Aerosol  
  • Urban Aerosol  
  • Saharan Dust ... |

Noseboom with five hole probe

LDA transceiver
Data processing & vector reconstruction

- Two real-time FPGA analysis methods were realized for the 250 MS/s ADC
- **Spectral triggering (2048 points FFT)**
  - Averaged continuous spectrogram (4096 points FFT, 1024 averages \(\rightarrow \sim 60\) Hz spectrogram rate)
- 5 different frequency estimators:
  - Simple: maximum, center of mass, quadratic interpolation
  - Extended: **Gaussian-Fit**, linearized Gaussian-Fit
- 1D-Kalman-Filter (still planned—will improve noise)
- **Weighted least-squares for vector reconstruction**

!(Image of a data processing diagram with labeled components and equations)

\[ f_i \propto k_i \cdot \nu \]
\[ v_i = \frac{\lambda}{2} f_i \]

**(Feasible) Weighted least-squares**

\[ f = (f_1, ..., f_N) \]
\[ \Omega = \text{diag}(\sigma_{f_1}, ..., \sigma_{f_N}) \]
\[ K = (k_1, ..., k_N) \]
\[ v = (K^T \Omega K)^{-1} K^T \Omega f \]
Example: 12.04.2022 – Flight 4
12.04.2022 – Flight 4

- The density of the aerosol during the flight varies
- The aerosol size distribution shows only small variations during the flight
12.04.2022 – Flight 4

- Very clean atmosphere with low particle density
- DWD ceilometer shows Cirrusstratus clouds in approximately 9-10 km
What influences the sensitivity of the spectral trigger? How can it be improved?
12.04.2022 – Flight 4 – Particle rates

• Very low measurement rates outside the clouds of 0.1-1 Hz

• Improvement of the real time processing by optimization of the parameters is possible (red dots) → approximately 1 Hz rate per channel is possible
Conclusion

Flight campaign shows successful LDA operation
- Good correlation with noseboom data, limited by remaining systematic errors
- Robust system performance, independent of mechanical/optical/electrical problems (vibrations, g-shocks, icing, EMI, …)
- Demonstration of self-diagnostics

Way Forward
- 2nd flight campaign with improved FPGA algorithms (Oct 2022)
- Investigation of optimal transceiver divergence → Optimal measurement rate
- Miniaturization of the system
- Combination/Comparison with pulsed coherent wind-lidar systems

Thank you for your attention! Questions!? 