A340 flight test results of a direct detection onboard UV Lidar in forward looking turbulence measurement configuration

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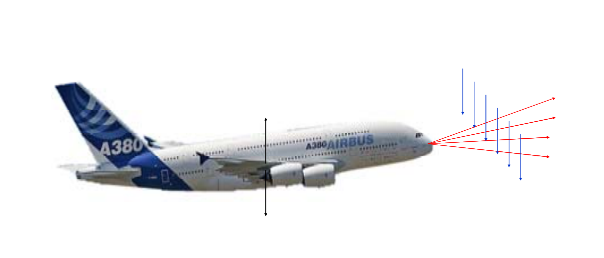

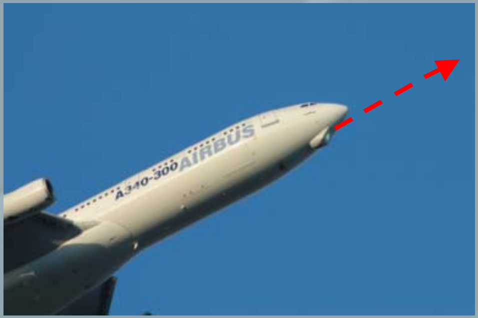

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EADS

Outline:

- The idea of forward looking onboard turbulence measurement
- Description of the LIDAR system developed
- Flight test results
- Outlook / Summary

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Forward looking Doppler LIDAR for turbulence measurement

Main problem: clear air turbulence

- strong gradients in airflow
- mostly at high flight altitude in cloud-free areas
- not detectable by weather radar (no droplets !)
- sudden occurence, up to 30 m/s in z

⇒ negative g dangerous for passengers and crew (seat belt not fastened)

⇒ stress for the aircraft structure

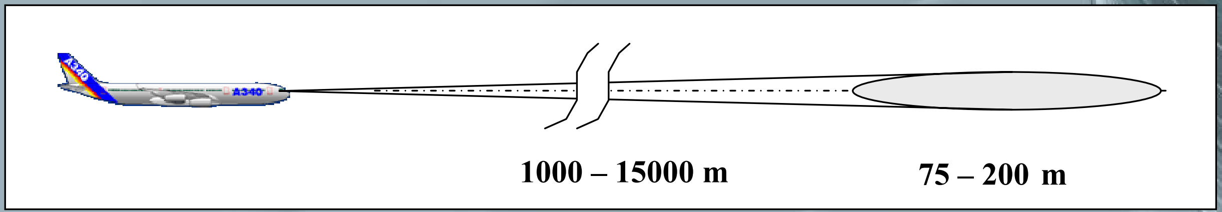
Secondary: Any other kind of turbulence

⇒ passenger comfort

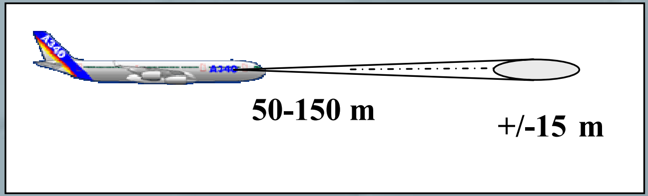
⇒ long term aircraft structure stress

Different methods for remote detection/measurement of turbulences

Mid-range WARNING systems (detection)



b) Shorter range systems with high depth resolution suitable for CONTROL (feed-forward into flight control of exactly measured speed)



Method of AWIATOR project

Forward looking Doppler LIDAR for turbulence measurement

Approach:

- measuring the 3D air flow remotely in front of the aircraft and
- direct feed forward into flight control unit to
- automatically counteract using aircraft control surfaces

Benefits:

- **gust load allevation of the wing loads**
- **passenger safety**
- **passenger comfort**

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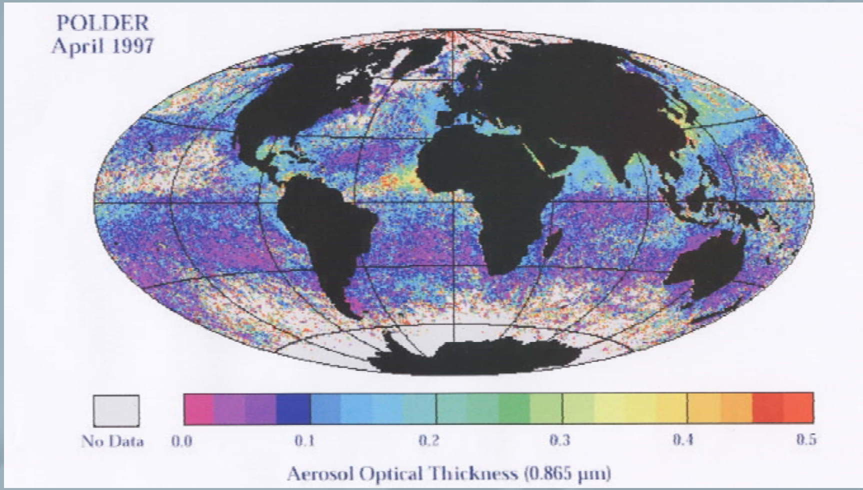
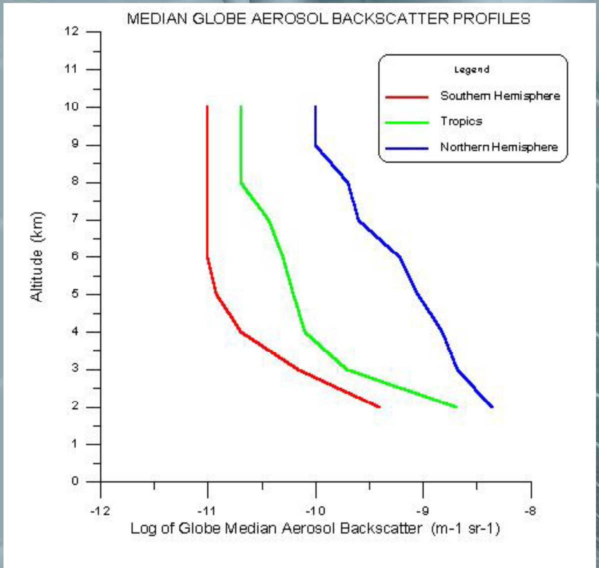
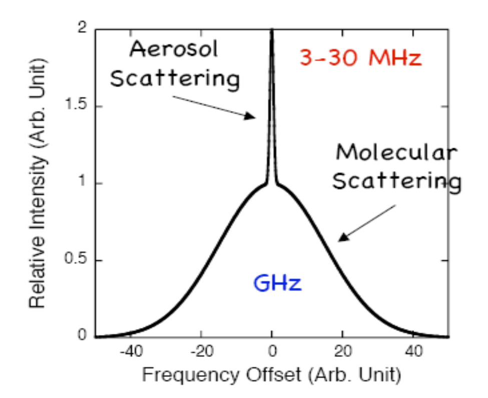
The problem of reliable clear air measurement – aerosol depletion in the upper atmosphere => Rayleigh LIDAR





⇒ **use molecular (Rayleigh) signal (+ Mie if present)**

⇒ **UV wavelength (signal ~ λ^{-4})**

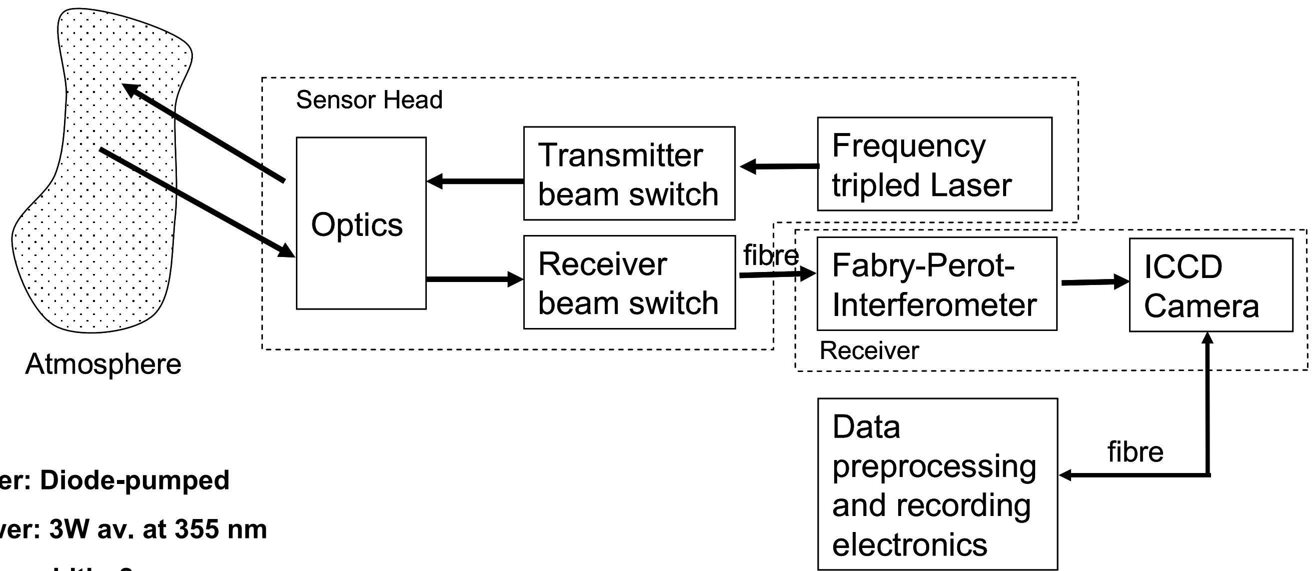


Due to thermal broadening of molecular signal

⇒ **no coherent detection possible**

⇒ **direct detection**

AWIATOR fringe imaging UV Lidar layout:



Laser: Diode-pumped

Power: 3W av. at 355 nm

Pulse width: 8 ns

Line width: about ~150 MHz

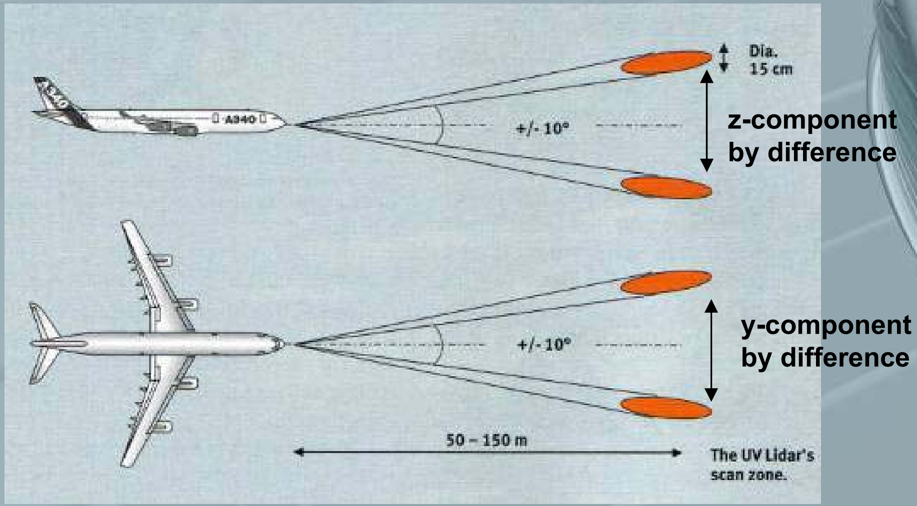
Rep. rate: 18 kHz

Optics diameter: 20 cm

Atm. channels: 4

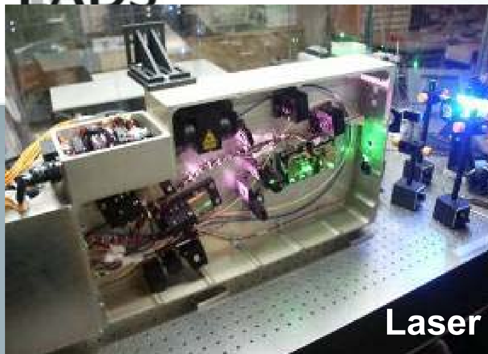
in AWIATOR only online data preprocessing and post-flight speed calculation

Airspeed measurement design specifications:

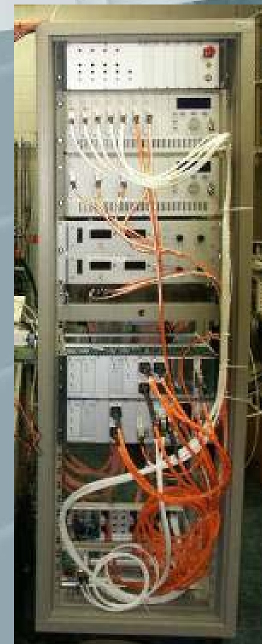


Distance	about 50 m (>70m from wings)
Forward-looking time	0.2 … 0.3 s
Measurement rate	~15 Hz for full vector (~60Hz per LOS)
Longitud. Accuracy	± 15 m
4 atmospheric channels	=> 3 components of air speed
Field of View	+/-10° x +/-10° (or larger in future)
Wind speed standard dev.	~ ± 1 m/s
Rayleigh (+Mie) scatter detection	

Components of the AWIATOR-LIDAR system:


Laser


Inter-
ferometer


Control
Electronics

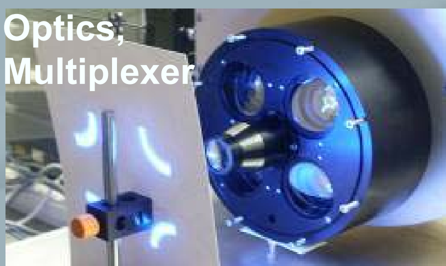

Optics,
Multiplexer

Image Processing Algorithms

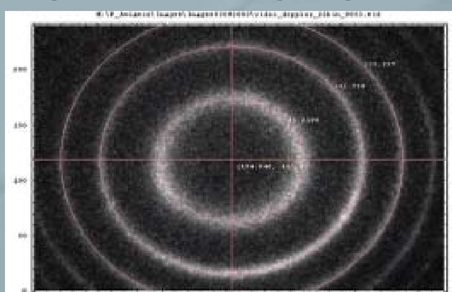
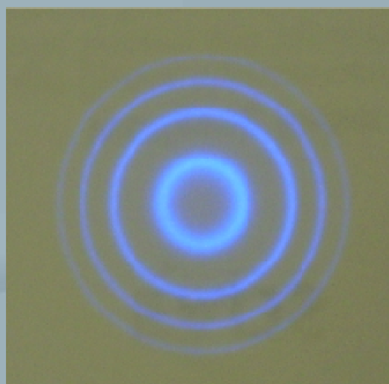


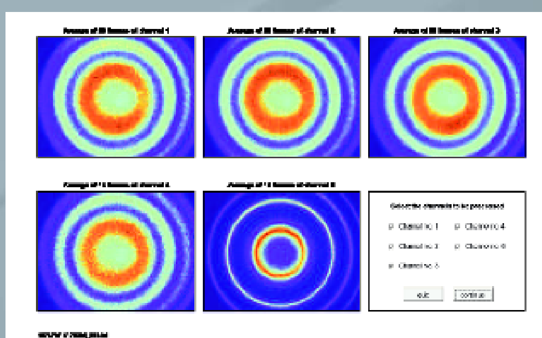

Image
Intensifying
Cameras


Data
Recorder +
RT
Processing
(FPGA)

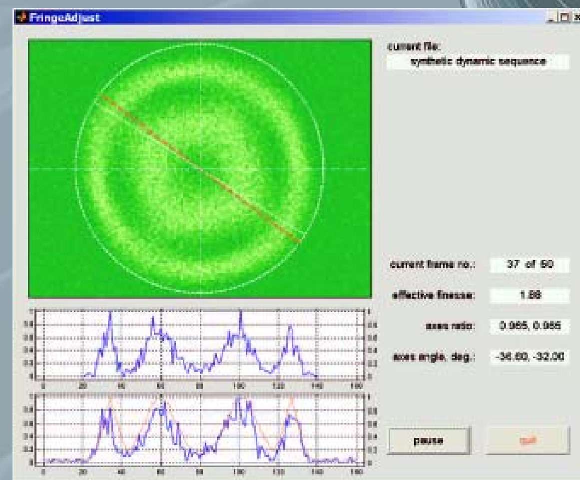
Fringe imaging advantages:

1) Algorithmic correction for fringe asymmetries
2) Algorithmic correction for optical aberrations (e.g. spherical imaging errors)
3) Continuous auto-calibration for fringe centers

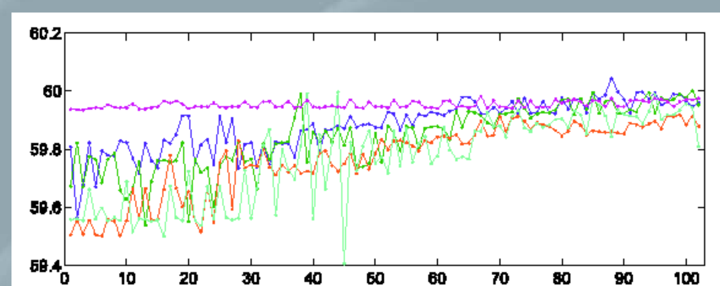




Fringe images (top: Photo of fluorescence down: digitalized)

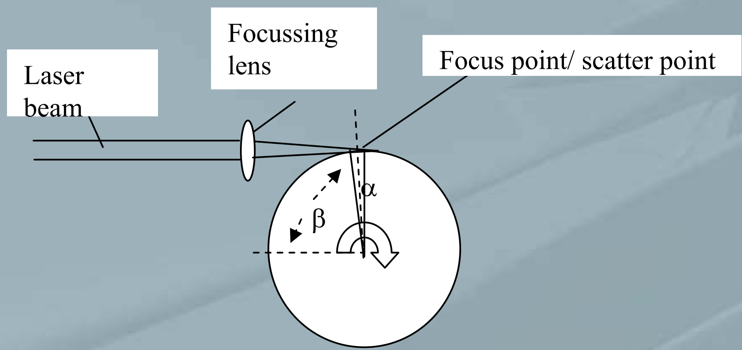


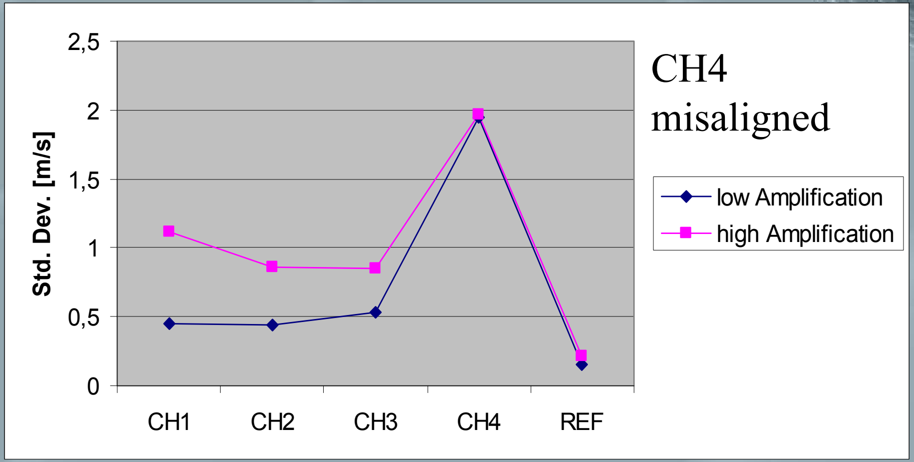
Calibration tool



Fringe centre coordin. vs. time

Atmospheric ground tests with rotating disc: standard deviations for two MCP amplifications

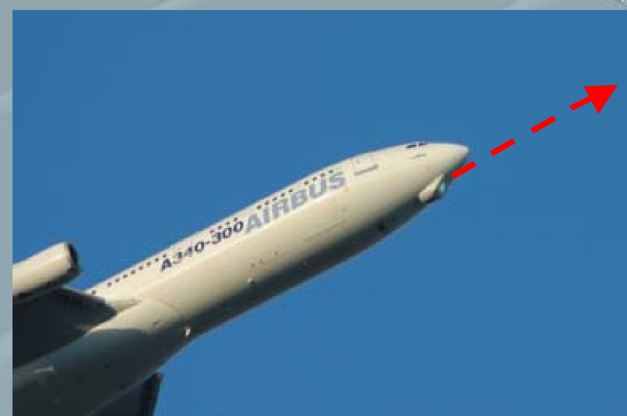




Low Amplification: ~ 0.5 m/s

High Amplification: ~ 1 m/s

Aircraft installation and flight test of the AWIATOR gust sensor with Airbus A340-300



Integration in electronic/avioncs bay

Receiver

Sensor (Laser)

Analogue rack

Digital rack

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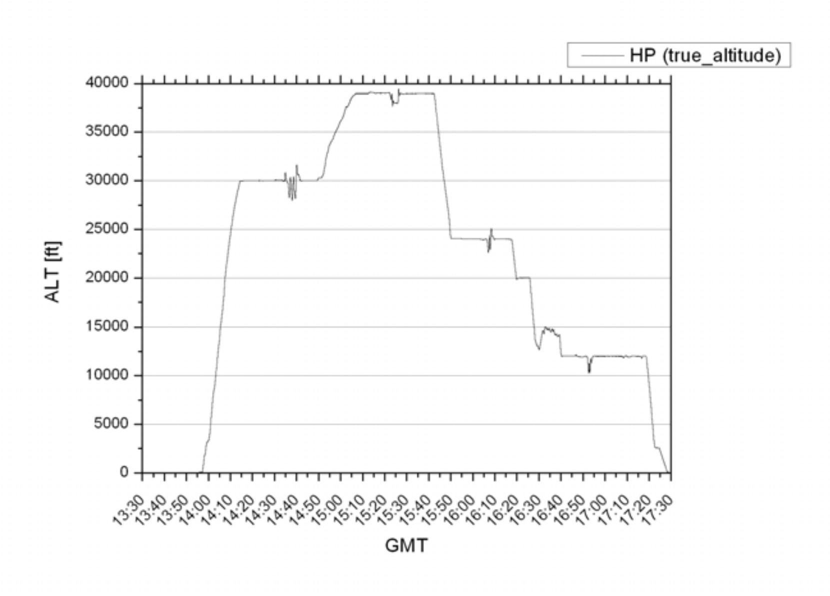
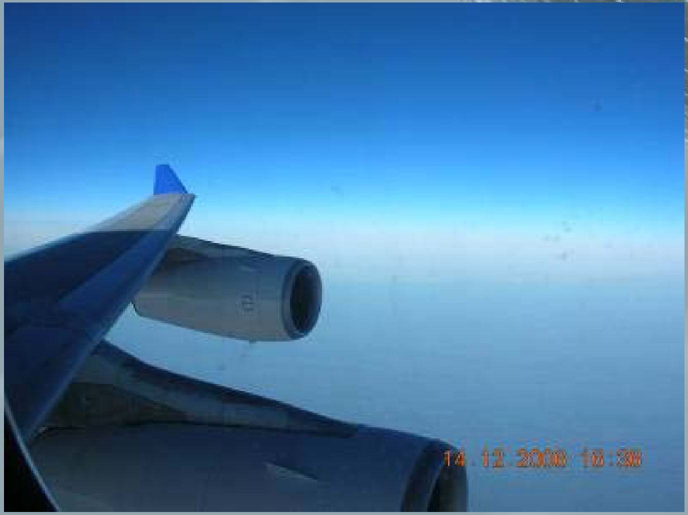
Flight envelope

- Stabilized flight at different constant altitudes up to FL 390
- Flight at constant alpha
- Descent flight at alpha = 0
- Descent at constant sink rate
- Constant Nz, stabilized

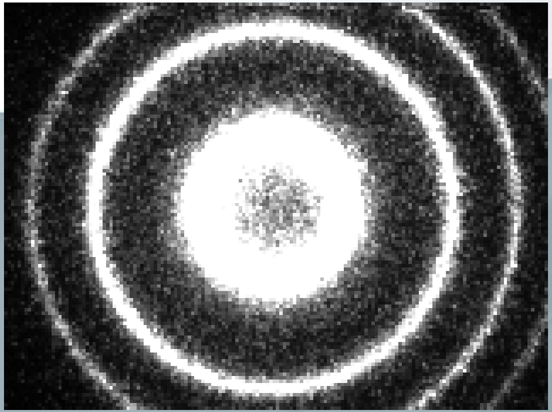
Validation in definite flight conditions by comparison with on-board a/c reference system



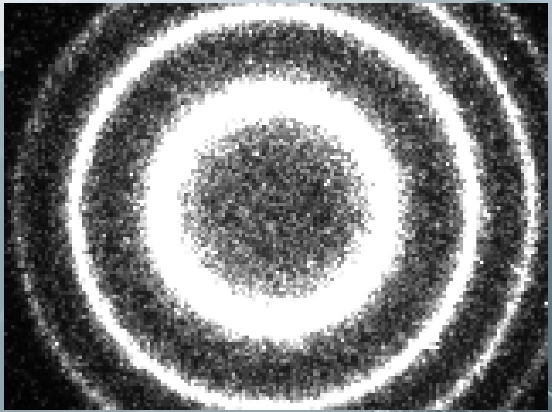
FL 390 view through cabin window



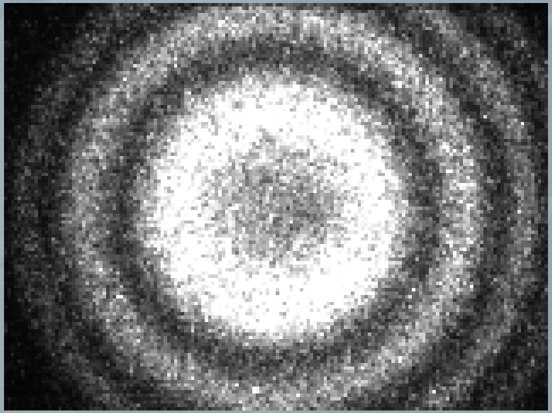
Fabry-Perot Fringe images



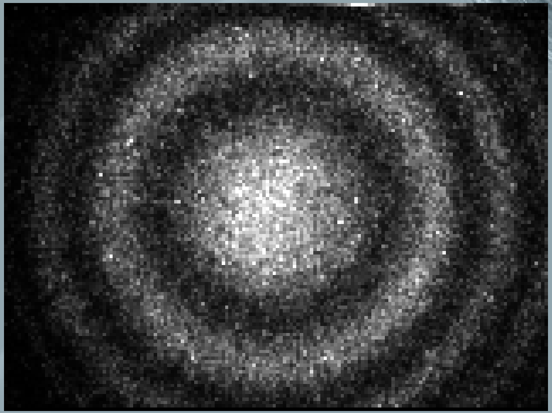
Reference signal (laser)



Backscatter in dense clouds
(nearly pure Mie)



Backscatter at 12,000 ft altitude
(Rayleigh & Mie)



Backscatter at 39,000 ft altitude
(nearly pure Rayleigh)

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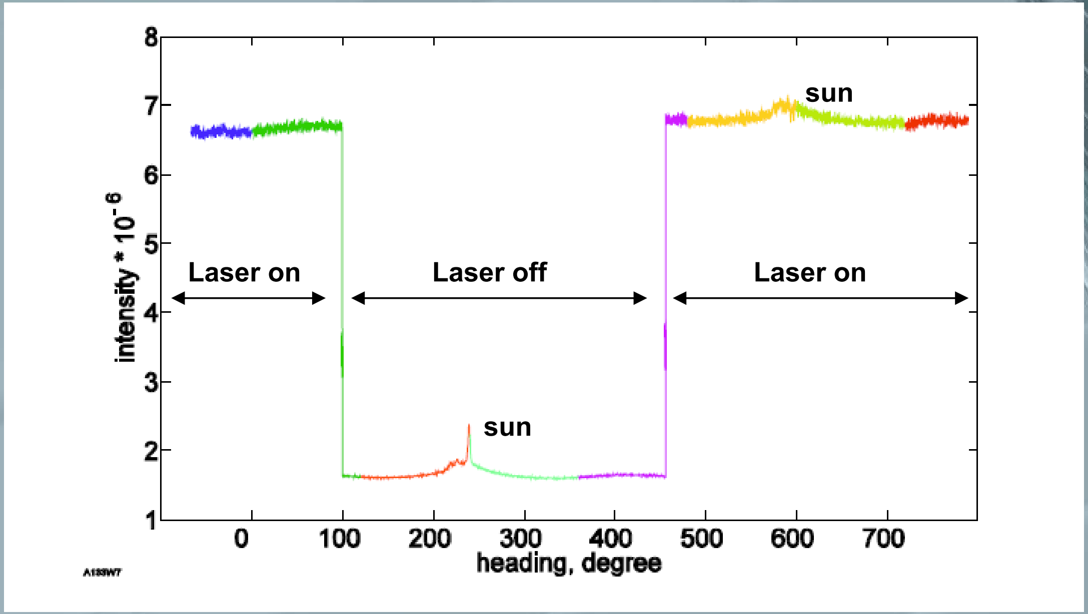
Signal and backscatter measurement during two left-turn 360° circles at FL 390



The aircraft flew two left turns 360° circles at 39,000 ft altitude, 30° banking angle, 3,25° pitch angle. 1° yaw.

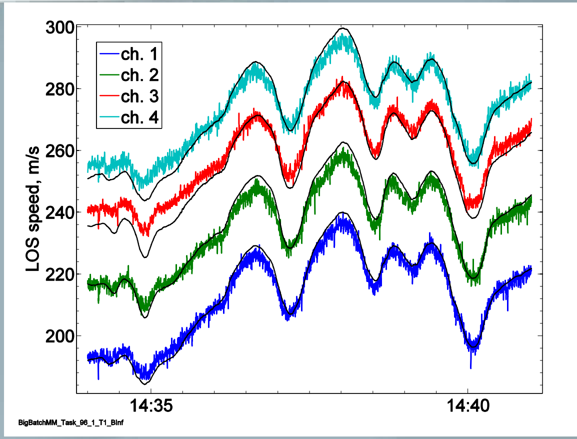
-5°0 to 100° and 460° to 780°: Laser on (signal)

100° to 460°: Laser off (backscatter and noise)

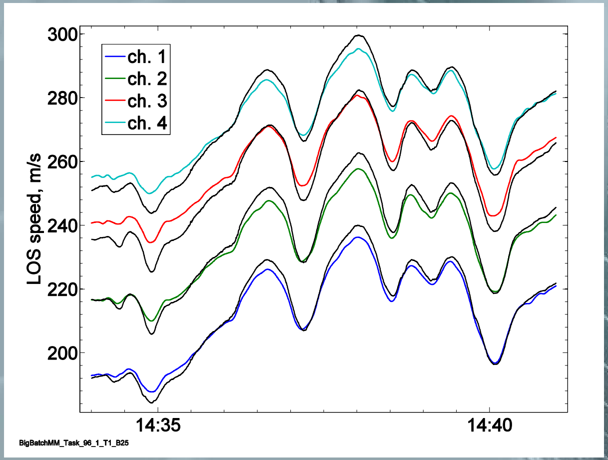
Sun was in Toulouse in December at 15:18 UT at azimuth 227° and elevation 8.5°

The plotted channel 4 was pointing at the given flight attitude (bank, pitch, yaw) at azimuth a/c – 13,7°, elevation 6.9°.

Dynamic sequences of varying airspeed unfiltered and filtered



Unfiltered



Filtered

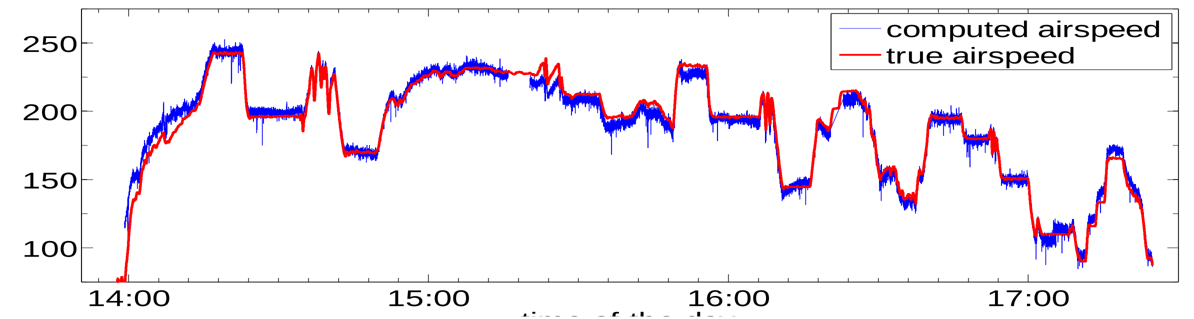
Example of dynamic flight sequence with changing true air speed:

Sensor line-of-sight speeds (colored signal curves) and aircraft TAS sensor data projected to line of sight (black curves).

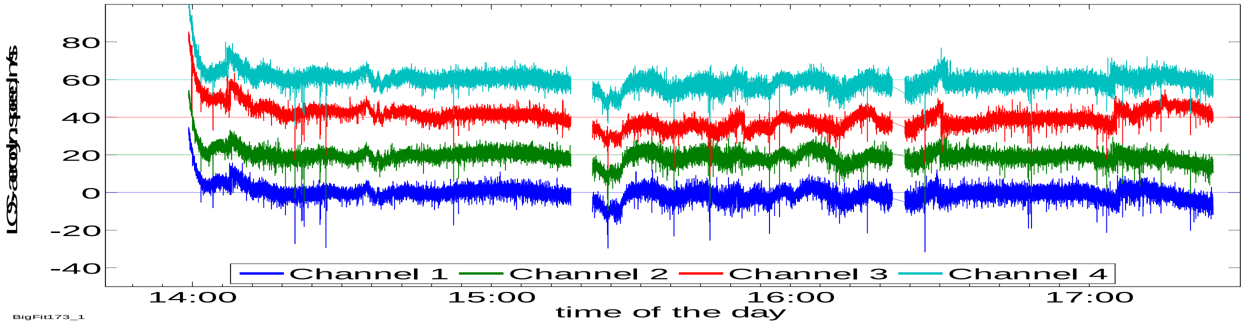
Plots ch. 2-4 artificially upshifted by 20 m/s each for better visibility.

Unfiltered signal (left) and filter signal (right; 0.25 Hz)

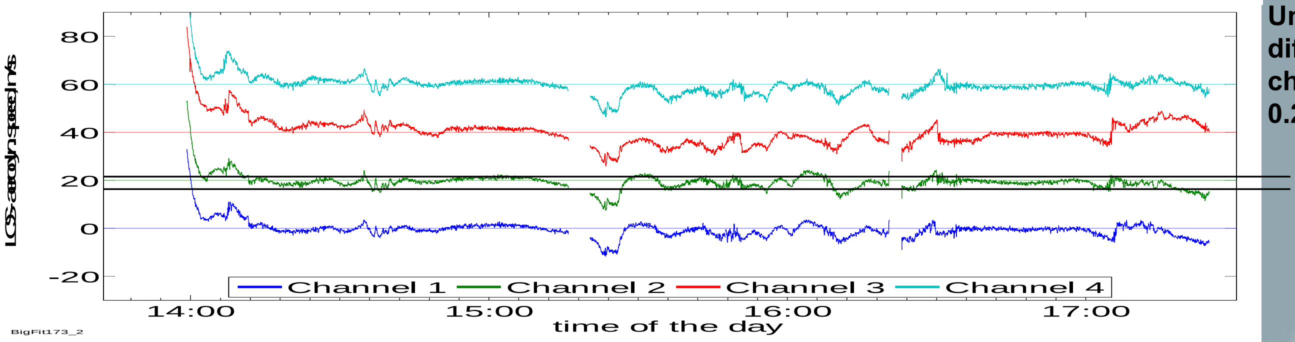
Absolute LOS airspeed versus a/c reference for full flight



Unfiltered speed channel 3 (blue) versus a/c ref. (red)



Unfiltered speed differences, all channels unfiltered



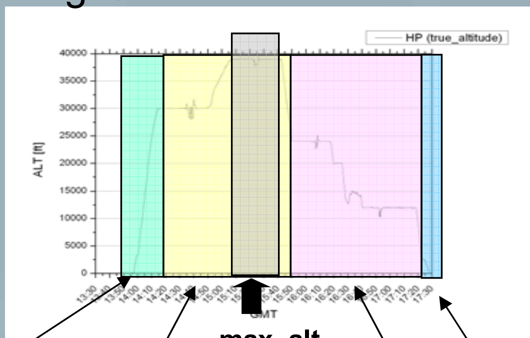
Unfiltered speed differences, all channels filtered 0.25 Hz

Difference about +/- 3 m/s for filtered data

LOS standard deviations – example channel 3

Assumptions: All deviation is interpreted as error, even induced by turbulence, due to lack of reference measurement (worst case evaluation)

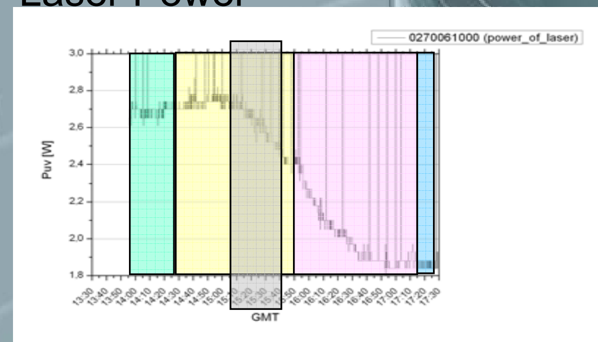
Flight ALT



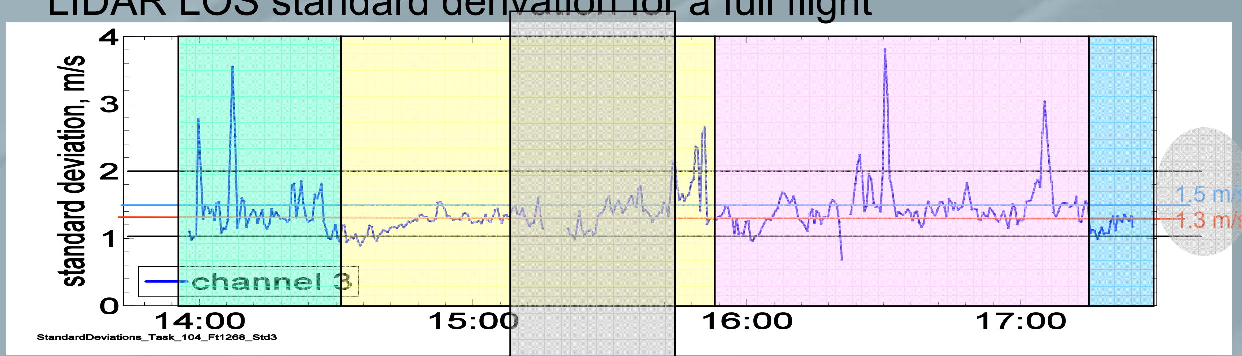
max. alt.

climbing high altitude lower altitude /appr.

Laser Power

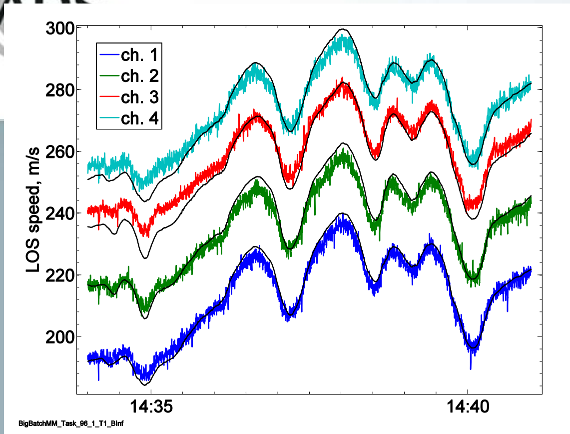


LIDAR LOS standard derivation for a full flight

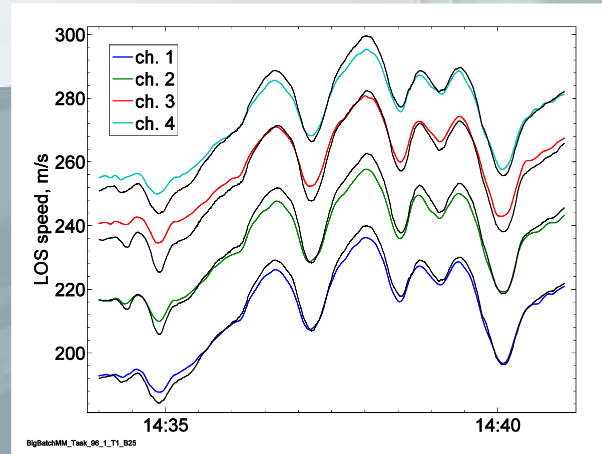


Standard deviation calculated for 1s windows, shifted by 0.5 seconds

LOS speeds as before and y/z-components

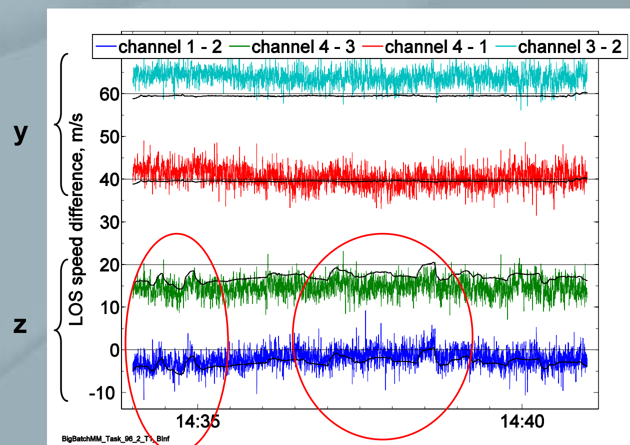


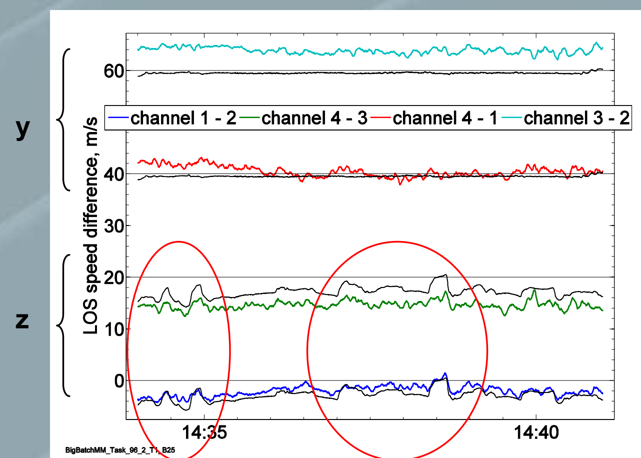
Unfiltered



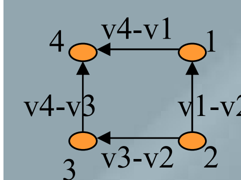
Filtered

LOS LIDAR speeds (solid: a/c sensor in LOS)

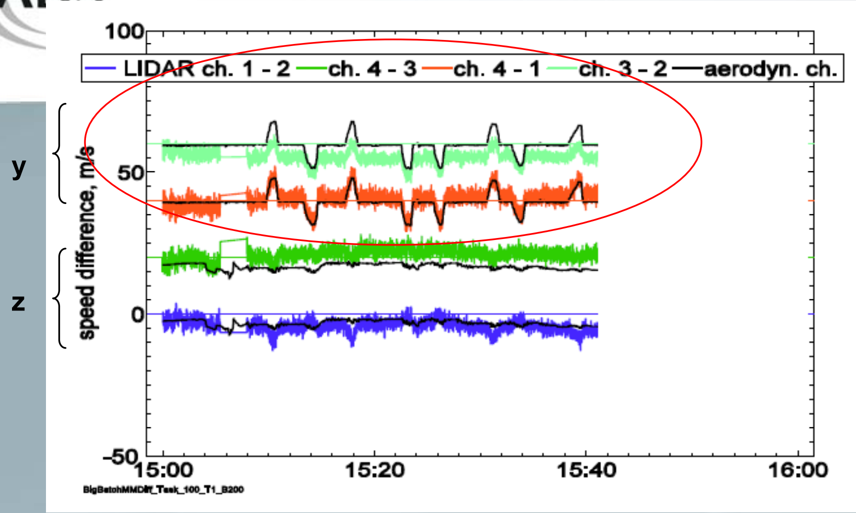




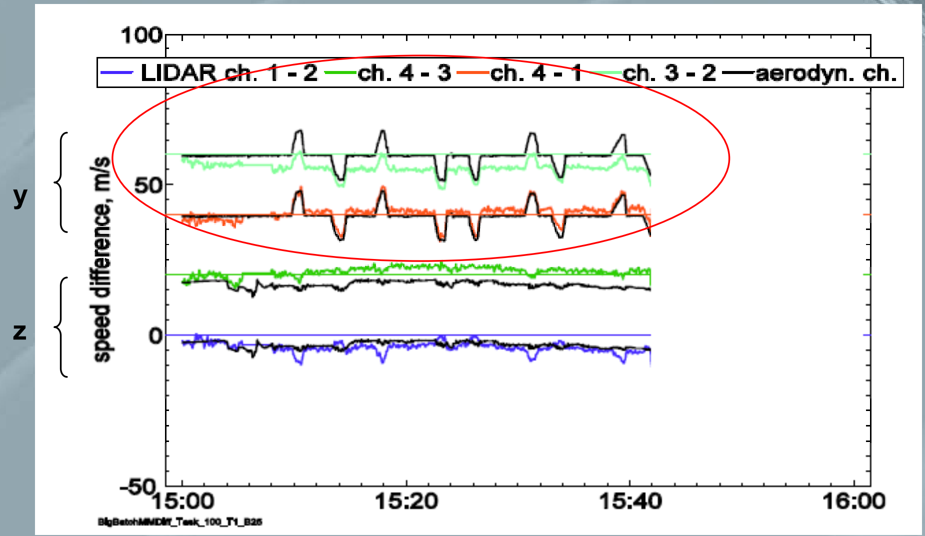
z-component of LOS LIDAR speed (solid: a/c sensor differences in LOS direction)



y-components during specific flight manuever

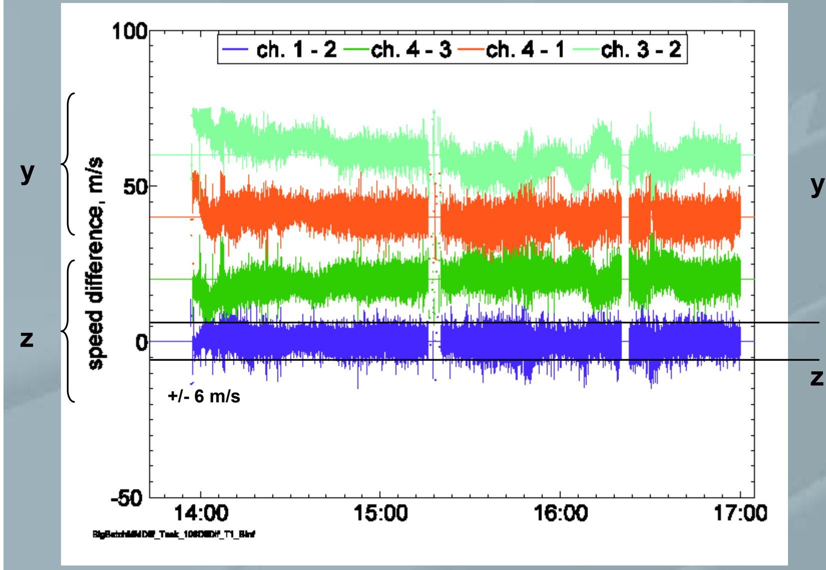


Unfiltered

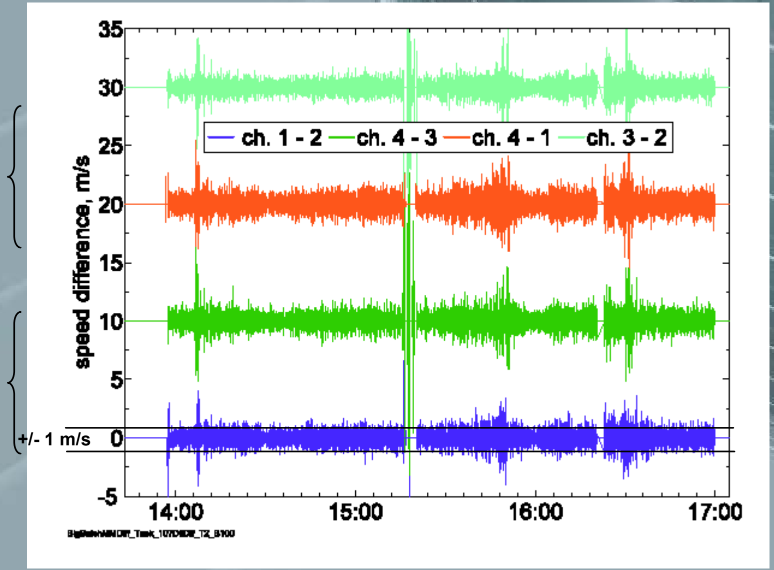


Filtered

Absolute z- and y-speeds filtered and unfiltered



unfiltered



filtered 0.25 Hz

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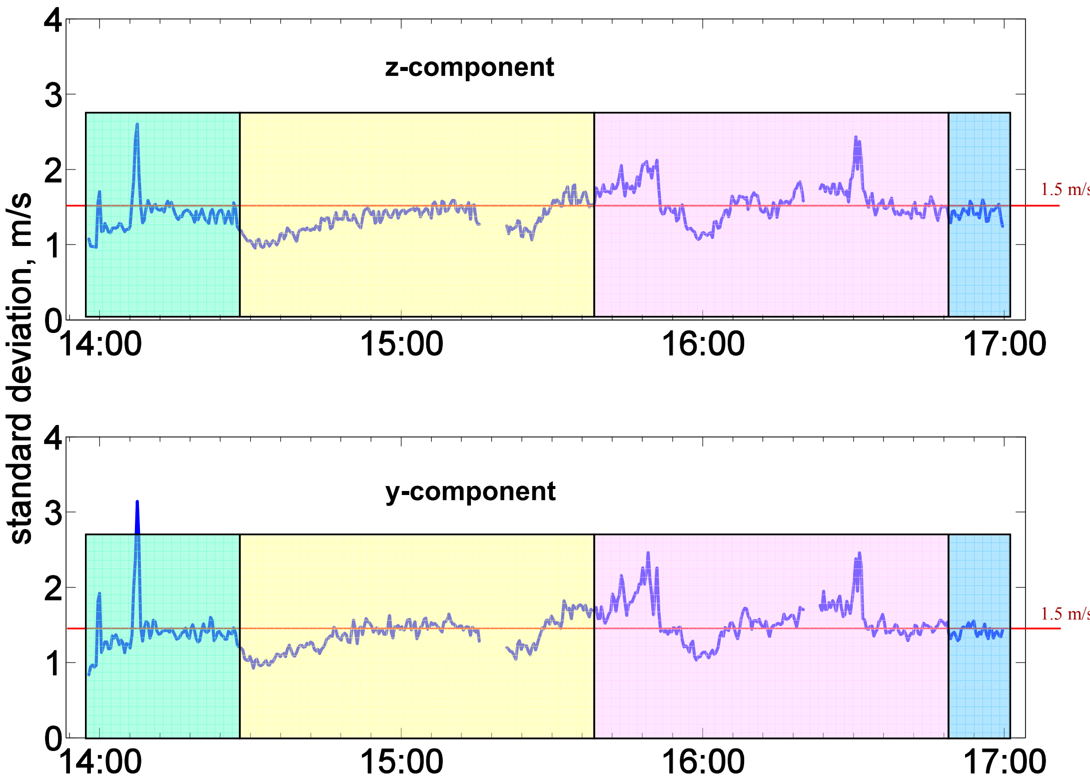
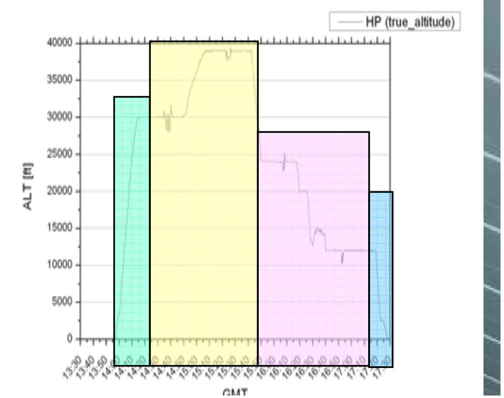
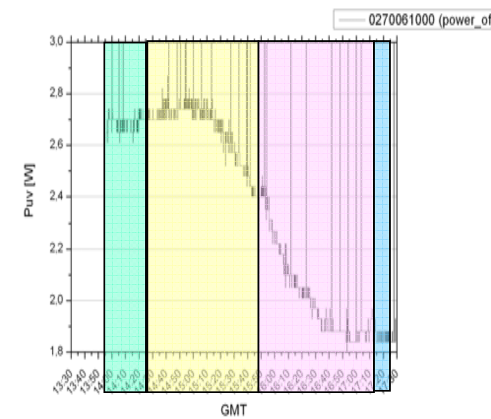
Standard deviation of z-component (top) and y-component (bottom)

To be multiplied by 2.9 for a/c y-z-axis projection



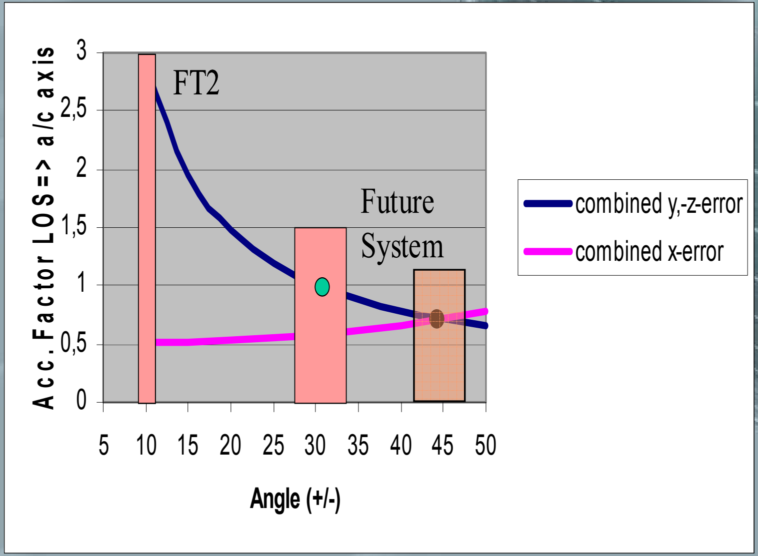
BigBatchMMDiff_Task_107_AllDiff_BInf





Expected parameters for new design:

- Air backscatter LOS speed accuracy: ~ +/-1 m/s
- y, z-accuracy: ~ +/- 0.7 –1 m/s
- Range: 50-250 m



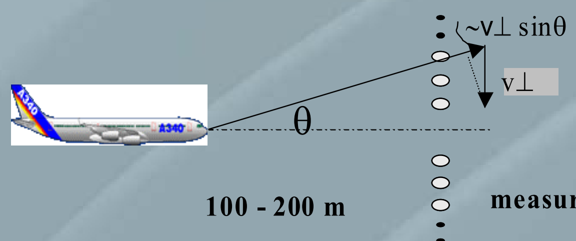
Challenges / next steps:

- Real-time data processing
- Feed-forward to flight control
- Miniaturization
- Skin conformal integration

Outlook: Extension of turbulence sensor for wake vortex control

Turbulence sensor with scanning wake vortex mode

Wake Vortex mode: Scanning short pulse Doppler LIDAR



Outlook:

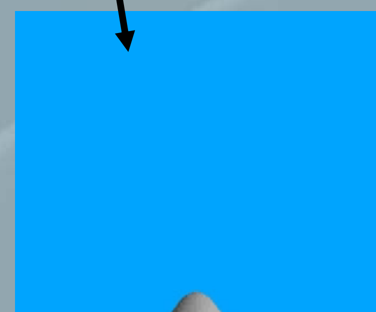
Combination of

- gust load alleviation applications with
- wind shear and
- wake vortex

with same sensor for onboard short-range measurement for control

Wind sheer

Wake vortices



Clear-Air-Turbulences

Summary 1/2:

- Unique onboard direct detection UV (molecular) LIDAR developed to operate even at high altitude (cruise) in aerosol depleted air
- Validation tests (ground test) achieved LOS accuracy +/-0,5- 1 m/s
- Accuracy is photon count limited, not instrument limited
- System successfully integrated in VFW 614 ATTAS (side looking, reported earlier) and A340-300 in (forward looking configuration)
- 6 flights with ATTAS, principal test of the system, all weather capability proven in clouds, rain and ice rain
- 8 flights performed with A340-300, (forward looking, improved performance)

Summary 2/2:

- Very intense fringe signals up to FL 390 (a/c limit)
  Reliable in pure Raleigh, pure Mie and mixed scatter conditions
- LOS speed comparison to aircraft data very good, follows dynamics.
  Absolute deviation accuracy +/- 3 m/s filtered.
- LOS standard deviation at FL 390 in clear air unfiltered ~ +/- 1.3-1.5 m/s
- In clouds ~ 1 m/s
- y,z-speed comparison to aircraft data good coincidence, even small changes of some m/s can be measured.
- y,z-standard standard deviation unfiltered : 2.9*1.5= ~ 4.5 m/s
  (due to +/- 10° beam angles)

System should to be connected to aircraft flight control in a next step