Atmospheric Wind Sensing with Doppler Lidar

Results of Impact Studies of Airborne Wind Lidar Observations and Progress Towards the Space Mission ADM-Aeolus

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Carla Cardinali (ECMWF Reading, UK)

with co-author for ADM-Aeolus
Martin Endemann (ESA-ESTEC Noordwijk, The Netherlands)
Outline of the Seminar

- Short introduction to lidar principle and results from recent lidar activities at DLR

- Airborne Doppler lidar observations during A-TReC 2003, and results of assimilation and impact studies with ECMWF model

- The first spaceborne wind lidar on the Atmospheric Dynamics Mission ADM-Aeolus: summary of latest status
DLR Institute of Atmospheric Physics

Prof. Ulrich Schumann

Atmospheric Dynamics
Prof. Robert Sausen

Atmospheric Trace Gases
Dr. Hans Schlager

Remote Sensing
Dr. Bernhard Mayer

Cloud Physics and Traffic Meteorology
Dr. George Craig

Lidar
Dr. Gerhard Ehret

Climate and chemical models
Noise
Trace gas detection systems
Nitrogen Oxides
Aerosol
Radiation transport
Satellite-retrieval
Radar-systems
Cloud-physics
Wake vortex simulation
Trace gas- and wind lidar
tunable laser
Wake vortex detection
Airborne Lidar for Tropospheric and Stratospheric Research on DLR Falcon Aircraft

**Stratospheric Research**
- Aerosol
- Polar Stratospheric Clouds
- Ozone
- Water Vapour

**Tropospheric Research**
- Aerosol and Clouds
- Water Vapour
- Ozone
- Wind
Characteristics of lidar observations

- measurement of vertical profiles with adjustable vertical resolution
- random error can be determined for every observation; low systematic error and error correlations
- data retrieval in clear air and partly cloudy conditions possible
- high representativity due to line or volume averages

- differential absorption of 2 wavelengths
- trace gas
- frequency shift due to Doppler effect
- wind speed
Airborne Water Vapor Lidar Observations 1/2
TROCCINOX Transfer 2004

H. Flentje, A. Fix, G. Ehret, M. Wirth

Airborne Water Vapor DIAL measurements on March 14, 2004

Hadley Circulation
Airborne Water Vapor Lidar Observations 2/2
SCOUT Transfer 2005

SCOUT Transfer Flights Nov/Dec 2005
Transfer back: Dubai - Larnaca on 16/12/2005

by Andreas Fix, Christoph Kiemle, Gerhard Ehret

Institut für Physik der Atmosphäre

JCSDA Seminar, NOAA World Weather Building, Camp Springs (MD), 15 May 2006
Principle of airborne, scanning Doppler lidar

Measurement of atmospheric wind field
- Doppler shift: radial velocity $V_{\text{LOS}}$
- Conical scan: wind vector
- Pulsed operation: wind vector at different altitude levels

$\Delta f_{\text{LOS}} = 2 \cdot \frac{V_{\text{LOS}}}{c} \cdot f_0$

Doppler shift

Platform
- Wind: 1 m/s
- Aircraft: 200 m/s
- Satellite: 7500 m/s
200th Anniversary of Christian Doppler in 2003

born 29 November 1803 in Salzburg, Austria
died 17 March 1853 in Venice, Italy

Christian Doppler 1842:
Über das farbige Licht der Doppelsterne und einiger anderer Gestirne des Himmels.
„About the coloured light of double stars and some other stars of the heaven.“

Daguerreotypie from about 1844
**Airborne Doppler Lidar at DLR 1/2**

**10 µm System WIND**
DLR/CNRS/CNES/Meteo-France
development: since end 80's
vert./hor. res.: 250 m, 3-15 km
accuracy: 0.5 - 2 m/s
first flight: 1999

**2-µm System**
DLR/CTI-MAG1
since 2000
100 m, 3-10 km
0.2 - 2 m/s
2001


ALADIN Airborne Demonstrator A2D

- Airborne prototype of satellite ADM-Aeolus instrument ALADIN to obtain measurements in nadir geometry like from space at a wavelength of 355 nm
- First airborne direct detection Doppler lidar
- Development since 2003 by team of EADS-Astrium France, Germany and DLR
- First functional test flights in October 2005

Durand et al. 2003, Proc. SPIE
Airborne Doppler Lidar Observations
Mesoscale Advection Towards the Alps in 2003

2-µm Doppler lidar on Falcon, 19 July 2002,
1514-1534 VAD, 1536-1554 UTC LOS
5 km (VAD), 360 m (LOS) horizontal resolution
100 m vertical resolution, total length 198 km

Weissmann, Braun, Gantner,
Mayr, Rahm, Reitebuch 2005,
Mon. Weath. Rev.

Winkler, Lugauer, Reitebuch 2006; promet
Latest DLR Doppler Lidar Observations from Ground
Terrain-Induced Rotor Experiment T-REX 2006

DLR-PI: Martin Weissmann, Andreas Dörnbrack
Deployment of 2-µm Doppler Lidar (CTI/CLR)
from 14 March - 24 April 2006
in Owens Valley, Sierra Nevada

IOP 25 March 2006

pictures and quicklooks
http://www.pa.op.dlr.de/trex/
DLR Falcon with 2-µm Doppler Lidar and Dropsondes during the Atlantic THORPEX Regional Campaign A-TReC in 2003

Base: Keflavik, Iceland
Period: 14 - 28 November 2003 for Falcon
13 October - 12 December 2003 for A-TReC
Flights: 6 local flights + 2 transfer flights
28.5 h of lidar measurements
Funds: EUCOS, DLR


further information:
www.pa.op.dlr.de/na-trec/
1 conical scan = 24 LOS positions (~ 30 s or 54 s)
vertical profile of wind vector (u,v,w)
horizontal resolution 5 - 10 km for one scan,
vertical resolution 100 m
4 flights in "sensitive areas" with targeted observations
1 flight for study of Greenland tip jet
1 flight for comparison with ASAR on ENVISAT
2 transfer flights

8 flights, 28.5 h, 49 dropsondes, 43 used dropsondes
1600 profiles with 40 000 wind observations @ 10 km resolution
400 profiles with 15 000 wind observations @ 40 km resolution
Targeted Flight on November 25, 2003

ECMWF analysis 25 Nov 2003, 18 UTC
geopotential height at 300 hPa
and isotachs
Flight on November 25, 2003, 1530-1830 UTC

Iceland

Ireland

http://www.sat.dundee.ac.uk/

ECMWF sensitivity plot and 500 hPa
Statistical comparison of lidar and dropsondes

Comparison of 33 wind profiles with > 500 measurements for MFAS (Maximum Function of Accumulated Spectra, Smalikho 2003); and inversion algorithm (see Weissmann 2005)

Combination of both is used to obtain higher coverage

(Total error)$^2 = (\text{lidar})^2 + (\text{dropsonde})^2 + (\text{representativity/sampling error})^2$

Mean instrument error lidar $(u,v)$: RMS < 0.75-1 m/s, no bias

Best case error lidar $(u,v)$: RMS < 0.5 m/s
Instrumental error lidar: 0.75-1 m/s

Rep. error (Frehlich and Sharman (2004)) < 0.5 m/s

Total error airborne lidar: 1-1.5 m/s

Total error ADM HLOS: 2-3 m/s

Total error Dropsonde/Radiosonde: 2-3 m/s

Total error Cloud Motion Vectors: 2-6 m/s
wavenumber T511: 40 x 40 km

60 Levels between 0 and 65 km

4DVAR: 4-Dimensional variational assimilation with 12 hour window with T95/T159
minimisation of global cost-function = difference measurement and first-guess (background)
alyses = 80% background + 20% observations
background = model + earlier observations
Performed Lidar and Dropsonde Experiments

Conversion to BUFR as unused aircraft observation type with reduced observation error

6 experiments performed for period 14-30 November 2003

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Resolution</th>
<th>Obs. Error</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>all operational obs., no other A-TReC obs.</td>
<td></td>
<td></td>
<td>control run</td>
</tr>
<tr>
<td>1Rev</td>
<td>lidar (u,v) 1 scanner rev.</td>
<td>10 km</td>
<td>1.0 m/s</td>
<td>best lidar resolution</td>
</tr>
<tr>
<td>4Rev</td>
<td>lidar (u,v) averaged profile</td>
<td>40 km</td>
<td>1.0 m/s</td>
<td>averaging to horizontal resolution of model</td>
</tr>
<tr>
<td>Median</td>
<td>lidar (u,v) median profile</td>
<td>40 km</td>
<td>1.0 m/s</td>
<td>test of different averaging method</td>
</tr>
<tr>
<td>4RStd</td>
<td>lidar (u,v,) averaged profile</td>
<td>40 km</td>
<td>1.5 m/s</td>
<td>assignment of higher error due to cloudy scenes</td>
</tr>
<tr>
<td>Drops</td>
<td>97 dropsondes (u,v,T) from DLR Falcon and other a/c</td>
<td>2-3 m/s</td>
<td></td>
<td>comparison of dropsonde vs. lidar observations</td>
</tr>
</tbody>
</table>
Thinning of lidar observations with resolution 10 km / 40 km (hor.), resp. 100 m (vertical) to grid point resolution 40 km (hor.), resp. 60 vertical levels

~ 80% of lidar obs. unused
~ 6000 used lidar obs. (u,v) during 2 weeks (40 km res.)

$5 \cdot 10^6$ used operational obs. per day

0.01% additional lidar obs.

Figure: Thinning of 10 km lidar data to model resolution
Background Departures

background departure \(bg\text{-}dep\) = Observation obs - First-Guess Fg

\[
(\text{Std}(bg\text{-}dep))^2 = (\text{error}_{\text{Obs}})^2 + (\text{error}_{\text{Fg}})^2
\]
Observation Influence on Targeted Flight

Observation influence (Cardinali et al. 2004):
0 --> no influence of observation; analysis is determined by background
1 --> no influence of background; analysis is determined by observation
mean global observation influence = 0.15
mean observation influence radiosondes in NH/ET is 0.3
mean observation influence of aircraft and CMV is 0.15

Observations from 22 November 2003

<table>
<thead>
<tr>
<th></th>
<th>Lidar u, v</th>
<th>Dropsonde u, v</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observation influence OI</td>
<td>0.63</td>
<td>0.45</td>
</tr>
<tr>
<td>Number of observations N</td>
<td>758</td>
<td>388</td>
</tr>
<tr>
<td>Information content IC IC = OI · N</td>
<td>477.5</td>
<td>174.6</td>
</tr>
</tbody>
</table>
Reduction of Forecast Error for 48 h for 500 hPa Height

Mean forecast error difference for period 15-28 November 2003 for lidar experiment 4RStd (40 km, 1.5 m/s)
Reduction of Forecast Error for 72 h for 500 hPa Height

Mean forecast error difference for period 15-28 November 2003 for lidar experiment 4RStd (40 km, 1.5 m/s)
Reduction of Forecast Error for 96 h for 500 hPa Height

Mean forecast error difference for period 15-28 November 2003 for lidar experiment 4RStd (40 km, 1.5 m/s)
average over 29 forecasts during 14 days over Europe
eduction of experiment run compared to control run (left)
normalised reduction with average forecast error of control run (right)
Reduction of Forecast Error for 24 h, 48 h, 96 h

Reduction of forecast error of geopotential 500 hPa height:

Lidar 48 h: ~ 0.5 m (3%)
Lidar 72 h: ~ 1 m (3.5%)

Simmons, Hollingsworth 2002:
72 h : 10 m in 10 years
Conclusion on Airborne Doppler Lidar Assimilation

- First time that Doppler lidar observations were assimilated into global model (BUFR, error assignment, thinning) => study of background departures and influence on analysis and forecast skills; only one other study by Kamineni 2006, 2003 is known where water vapor lidar observations were assimilated for hurricane forecast studies into global model

- Airborne lidar observations have lowest observation error of all operational wind observations of 1 - 1.5 m/s due to higher representativity and low instrument error of 0.75 - 1 m/s

- Observation influence on analysis is about 40 % higher for lidar than dropsondes; total information content is about 3 times higher

- Lidar observations over North Atlantic reduce forecast error by 2 - 6% (mean 3 %, dropsondes 1 %) and show clear positive impact on forecast skills for the forecast range 2-4 days

- Study demonstrates importance of real lidar wind measurements for forecast improvements and is beneficial for wind lidar applications on airborne and satellite platforms
Future global wind observations with ALADIN on the Atmospheric Dynamics Mission ADM-Aeolus
<table>
<thead>
<tr>
<th>Vertical resolution:</th>
<th>Requires Mie and Rayleigh channel to measure over full altitude range</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 km to 2 km</td>
<td></td>
</tr>
<tr>
<td>1 km to 16 km</td>
<td></td>
</tr>
<tr>
<td>2 km to 30 km</td>
<td></td>
</tr>
<tr>
<td>total up to 25 layers</td>
<td></td>
</tr>
<tr>
<td>Horizontal average wind over 50 km</td>
<td>7 s averaging</td>
</tr>
<tr>
<td>Profile spacing 200 km to fit NWP needs</td>
<td>28 s per observation</td>
</tr>
<tr>
<td>Global coverage (200 profiles per orbit) for three years in orbit</td>
<td>Drives lifetime qualification</td>
</tr>
<tr>
<td>Horizontal HLOS wind accuracy:</td>
<td>Drives sizing of lidar</td>
</tr>
<tr>
<td>1 m/s up to 2 km</td>
<td></td>
</tr>
<tr>
<td>2 m/s up to 16 km</td>
<td></td>
</tr>
<tr>
<td>Bias: less than 0.4 m/s HLOS offset</td>
<td>Drives stability of lidar calibration</td>
</tr>
<tr>
<td>Linearity: less than 0.7 % of actual speed</td>
<td>spectral range</td>
</tr>
<tr>
<td>Dynamic range: -150 to +150 m/s</td>
<td></td>
</tr>
</tbody>
</table>
Atmospheric LAser Doppler INstrument ALADIN

- First Doppler lidar in space
- Operating in ultraviolet @ 355 nm to measure wind from molecular Rayleigh backscatter and aerosol/cloud Mie backscatter
- Line-of-Sight LOS wind profiles in troposphere to lower stratosphere with vertical resolution from 250 m - 2 km
- LOS is pointing 35 ° from nadir orthogonal to the ground track velocity vector to minimize the Doppler shift from the 7.6 km/s satellite velocity
- 50 km averaged winds every 200 km
- First High Spectral Resolution Lidar HSRL in space to obtain aerosol/cloud optical properties
ADM-Aeolus Coverage and Data Availability

- 3200 wind profiles per day: about factor 3 more than radiosondes
- 3 hour data availability after observation; 30 minutes data availability for parts of orbit
- launch planned for September 2008
- mission lifetime 3 years: observations from 2009-2011


50 km Observations during 6 hour period
ADM-Aeolus Ground Segment

ALADIN data downlink, HK history data
X-Band, 5 Mbps

Aeolus house keeping broadcast
Telecommand uplink
S-Band

Nominal Data stations:
Svalbard

Additional receiving stations possible,
only 2.4 m antenna required

C&C station:
Kiruna

Aeolus
Command & Control
ESOC

Aeolus
Processing
Facility:
L0, L1B, L2A

Met Center
L2.B & L2.C

Tromsö, Norway

ECMWF
## ADM-Aeolus Studies: ongoing (1-3), and finished (4-9)

<table>
<thead>
<tr>
<th>Title</th>
<th>Team</th>
</tr>
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<tbody>
<tr>
<td>Consolidation of ADM-Aeolus Ground Processing</td>
<td>DLR</td>
</tr>
<tr>
<td></td>
<td>Meteo-France, KNMI, IPSL, PSol</td>
</tr>
<tr>
<td>Development and Production of Aeolus Wind Data Products</td>
<td>ECMWF</td>
</tr>
<tr>
<td></td>
<td>Meteo-France, KNMI, IPSL, DLR</td>
</tr>
<tr>
<td>ADM-Aeolus Campaigns</td>
<td>DLR</td>
</tr>
<tr>
<td></td>
<td>Meteo-France, KNMI, IPSL, DWD, MIM</td>
</tr>
<tr>
<td>Consolidation of Algorithms for Supplementary Geophysical Products</td>
<td>IFT</td>
</tr>
<tr>
<td>Tropical Dynamics</td>
<td>University Stockholm</td>
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<tr>
<td>Prediction Improvement Extreme Weather PIEW</td>
<td>KNMI</td>
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<tr>
<td>Impact of Line Shape on Wind Measurements ILIAD</td>
<td>IPSL</td>
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<tr>
<td></td>
<td>Meteo-France, Hovemere, Onera</td>
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<tr>
<td>Atmospheric Wind Statistics</td>
<td>University Stockholm</td>
</tr>
<tr>
<td>Measurement Error Correlation Impact</td>
<td>KNMI</td>
</tr>
<tr>
<td></td>
<td>Meteo-France, IPSL, DNMI, MISU</td>
</tr>
</tbody>
</table>
Aeolus Satellite

Budgets by CDR 2005
mass: 1100 kg dry +116-266 kg fuel
power: 1.4 kW avg. (solar array 2.5 kW)
mass instrument: 470 kg
power instrument: 840 W avg. (laser 510 W)

Doppler Lidar Instrument ALADIN
Nd:YAG laser in burst mode operation
(125 mJ - 150 mJ @ 355 nm, 100 Hz)
1.5 m Cassegrain telescope
Dual-Channel-Receiver with ACCD
(Accumulating CCD Detector)

Pointing and Orbit Control
GPS, Star-Tracker, Inertial Measurement Unit, Yaw steering to compensate for earth rotation

Launcher
Rockot (SS-19 ICBM), Dnepr (SS-18 ICBM) or Vega (ESA)
Principle of Wind Measurement with ALADIN

Atmospheric LAser Doppler INstrument ALADIN

- Direct-Detection Doppler Lidar at 355 nm with 2 spectrometers to analyse backscatter signal from molecules (Rayleigh) and aerosol/clouds (Mie)
- Double edge technique for spectrally broad molecular return, e.g. NASA GLOW instrument (Gentry et al. 2000), but sequential implementation
- Fizeau spectrometer for spectrally small aerosol/cloud return
- ALADIN is a High-Spectral Resolution Lidar HSRL with 3 channels: 2 for molecular signal, 1 for aerosol/cloud signal => retrieval of profiles of aerosol/cloud optical properties possible
  - backscatter coefficient
  - extinction coefficient
  - lidar ratio
ALADIN OSTM (left) and Laser Radiator (right)

Optical Structure Thermal Model (OSTM), Power Laser Head (PLH), Reference Laser Head (RLH) Optical Bench Assembly (OBA)
Power Laser Head Engineering-Qualification Model EQM during tests in Sep. 2005: first UV laser output achieved

Optics from Pre-Development Model PDM; now part of ALADIN Airborne Demonstrator
ADM-Aeolus Pre-Launch Campaigns in 2006 and 2007

Ground Campaign at Meteorological Observatory of German Weather Service DWD in Lindenberg (close to Berlin) for fall 2006 with ALADIN Airborne Demonstrator, 2-µm Doppler Lidar, 482 MHz windprofiler radar and other instruments.

2 airborne campaigns with ALADIN Airborne Demonstrator and 2-µm Doppler lidar onboard DLR Falcon aircraft in 2007.

Fig. Volker Lehmann (DWD)
Summary of ADM-Aeolus status by May 2006

- Structural, environmental, optical test program passed successfully (June 2005)
- Critical Design Review CDR of instrument and satellite passed successfully (Sept. 2005)
- Manufacturing of Flight Model FM parts ongoing and partly finished, e.g. structure finished, instrument electronics and detection units finished, telescope mirrors polished (1 yr) and coated, spectrometer manufacturing almost completed, first FM laser under construction, laser diode stacks completed and endurance test started, optical alignment and test of the receiver will start in June 2006
- First versions of L1B Processor delivered, ground segment activities ongoing
- Launch planned for September 2008
- Pre-Launch Campaign Activities with ALADIN Airborne Demonstrator in 2006 and 2007
- ADM-Aeolus will path the way for operational wind lidar satellites => constellation of 2-3 satellites should be achieved for denser global coverage (KNMI study PIEW)
Outlook for Lidar Activities at DLR

- Study of single cases of targeted observations and quantification of impact in regional verification areas
- Study impact of water vapor lidar observations on global models with existing datasets of IHOP 2002, TROCCINOX 2004, 2005, and SCOUT 2005
- Next campaign activities:
  - African Monsoon AMMA: 10-µm Doppler Lidar WIND on Falcon in July 2006
  - ADM Pre-Launch Campaigns: 2-µm and A2D from ground in 2006 and airborne in 2007
  - Convective and Orographically-Induced Precipitation Study COPS: H₂O-DIAL and 2-µm Doppler lidar on Falcon in June-Aug 2007
  - Interest in involvement in THORPEX Pacific-Asian Regional Campaign PARC in 2008, but funding open
  - New Gulfstream G550 aircraft HALO at DLR operational in 2009
Significant improvement of 12 h forecast of water vapour column of up to 20% along the flight path over the North Atlantic

Measurement of WV cross sections with IPA's airborne H₂O-DIAL on the DLR Falcon during the IHOP transfer flight from Germany - Oklahoma from 13-15 May 2002 (A. Fix, G. Ehret, H. Flentje, G. Poberaj)

Significant decrease of 12 h forecast error by 4D-VAR assimilation of H₂O-DIAL data into T511 global ECMWF model (Elias Holm, ECMWF, Reading)
Join the ADM-Aeolus Workshop in September 2006 at ESTEC

Second Announcement and Call for Abstracts
26 to 28 September 2006 ESA/ESTEC Noordwijk, The Netherlands

further information under www.congres.nl/06c05
LIDAR Instruments for Earth Observation Missions

ADM-Aeolus/ALADIN
ESA, launch 2008
wind profil, aerosol, clouds

EarthCARE/ATLID
ESA, launch 2011/12
aerosol and clouds

Calipso/CALIOP
NASA, launch 2006
aerosol and clouds

IceSAT/GLAS
NASA, launch 2003
elevation, aerosol and clouds

Future Lidar Instruments for
H₂O, CO₂, O₃