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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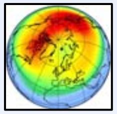
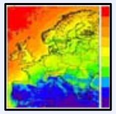
DLR Institut für Physik der Atmosphäre





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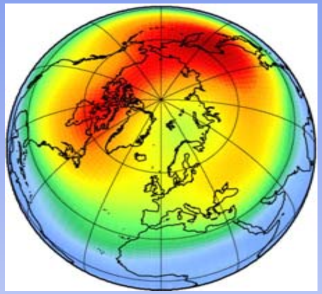
Outline of the Seminar

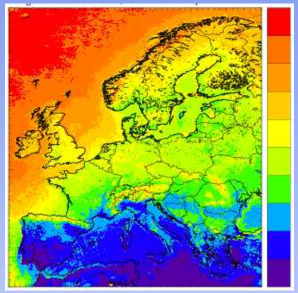
- Short introduction to lidar principle and results from recent lidar activities at DLR
- Airborne Doppler lidar observations during A-TReC 2003, and results of assimilation and impact studies with ECMWF model
- The first spaceborne wind lidar on the Atmospheric Dynamics Mission ADM-Aeolus: summary of latest status

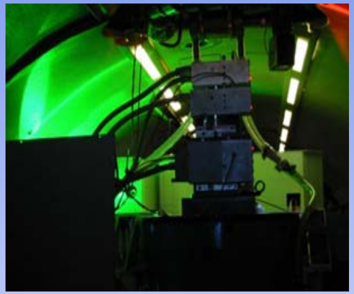
DLR Institute of Atmospheric Physics

Prof. Ulrich Schumann

Atmospheric Dynamics	Atmospheric Trace Gases	Remote Sensing	Cloud Physics and Traffic Meteorology	Lidar
Prof. Robert Sausen	Dr. Hans Schlager	Dr. Bernhard Mayer	Dr. George Craig	Dr. Gerhard Ehret







Climate and chemical models

Noise

Trace gas detection systems

Nitrogen Oxides

Aerosol

Radiation transport

Satellite-retrieval

Radar-systems

Cloud-physics

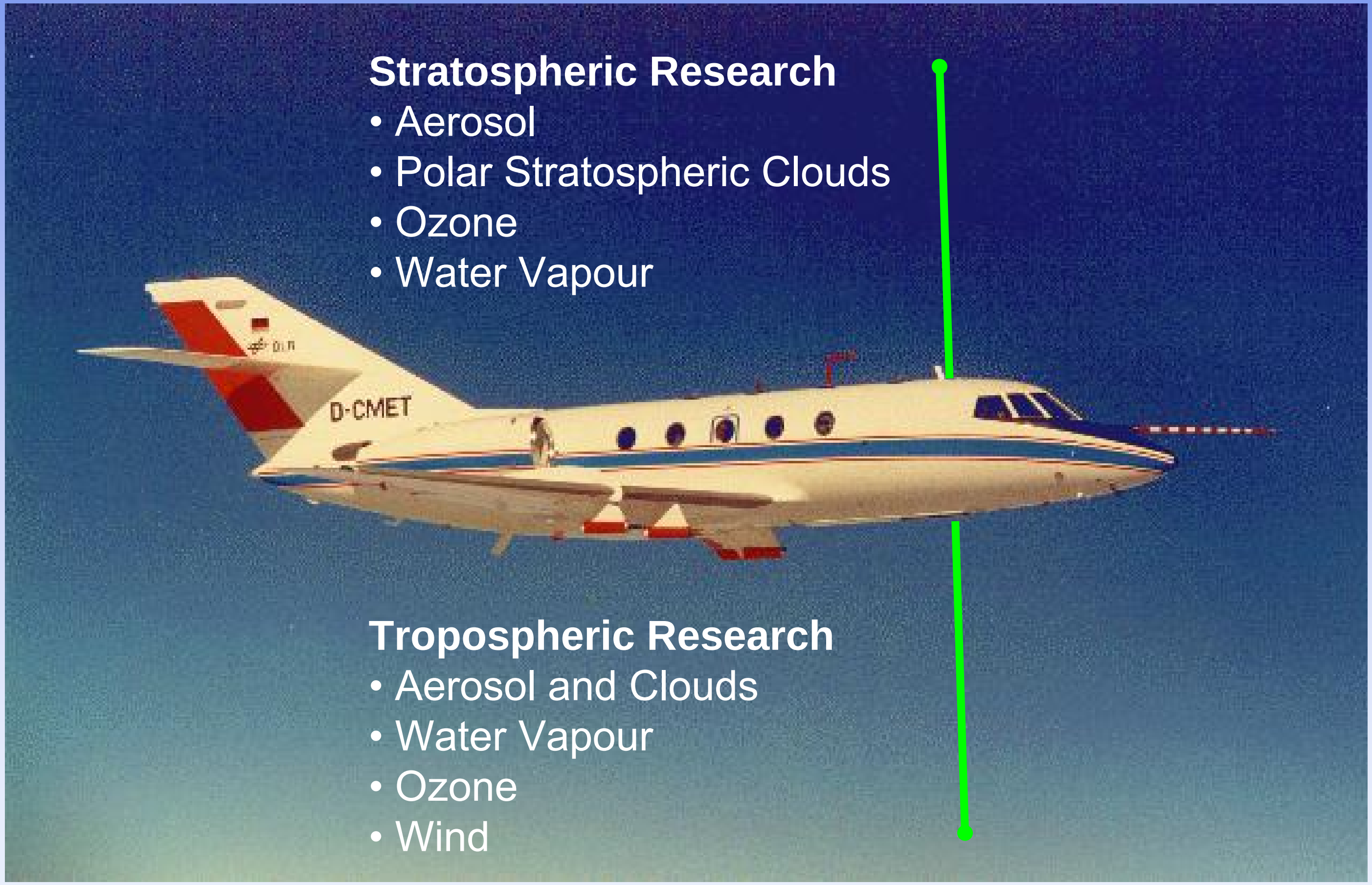
Wake vortex simulation

Trace gas- and wind lidar

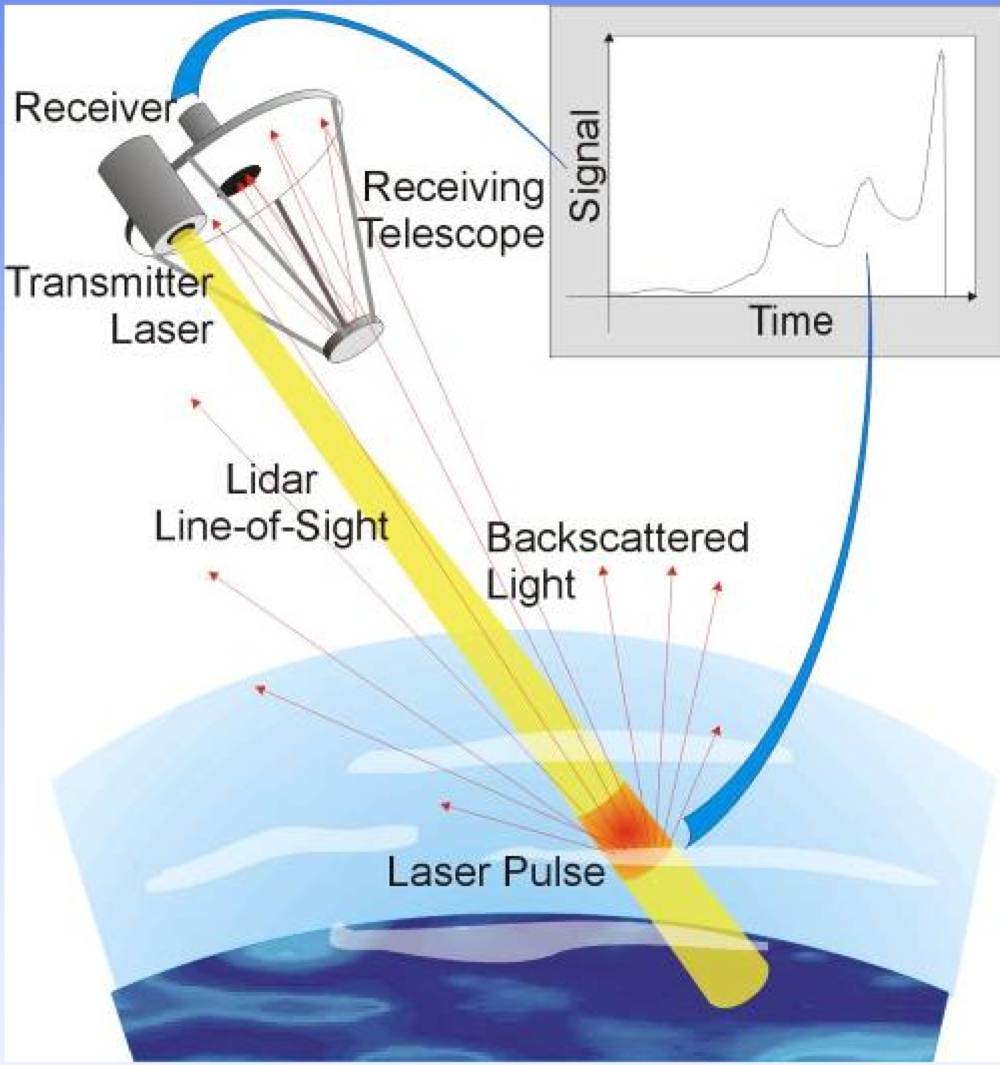
tunable laser

Wake vortex detection

Airborne Lidar for Tropospheric and Stratospheric Research on DLR Falcon Aircraft



Optical Remote Sensing with LIDAR
LIght Detection And Ranging



Characteristics of lidar observations

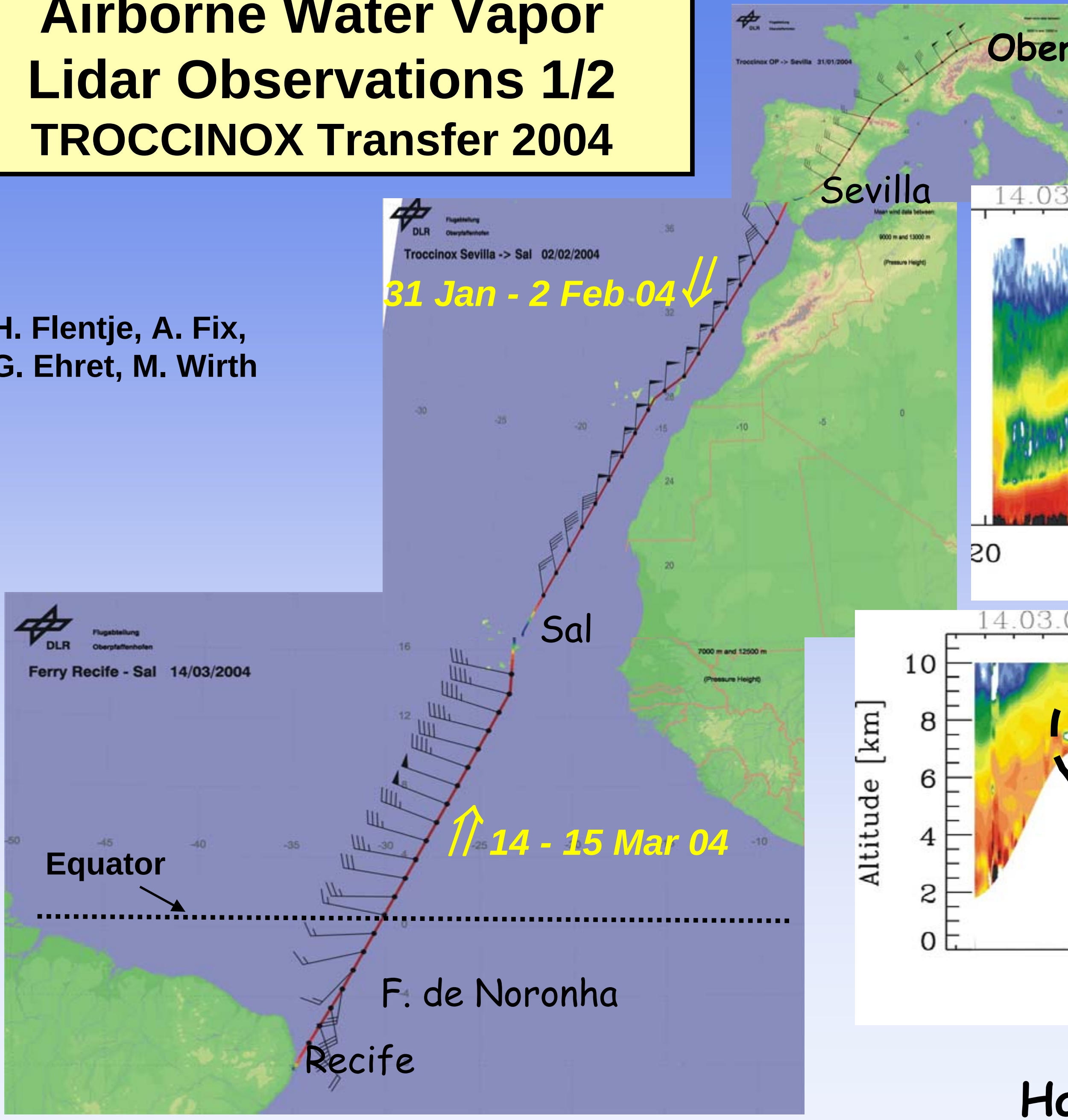
- measurement of vertical profiles with adjustable vertical resolution
- random error can be determined for every observation; low systematic error and error correlations
- data retrieval in clear air and partly cloudy conditions possible
- high representativity due to line or volume averages

⇨ **differential absorption of 2 wavelengths** ⇨ **trace gas**

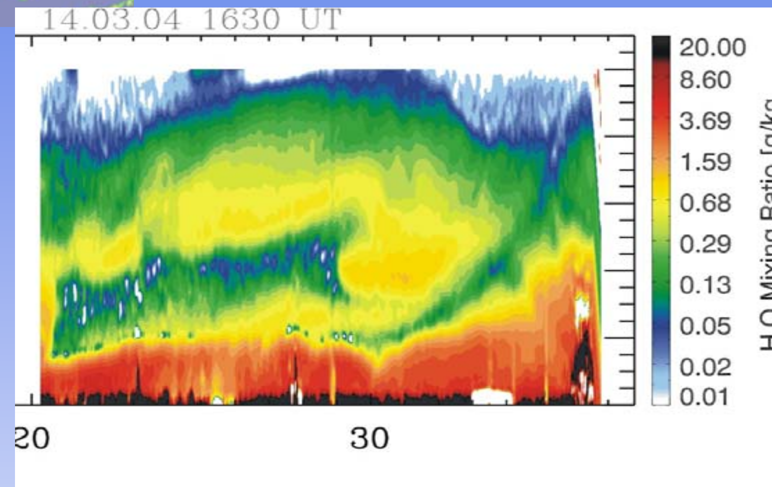
⇨ **frequency shift due to Doppler effect** ⇨ **wind speed**

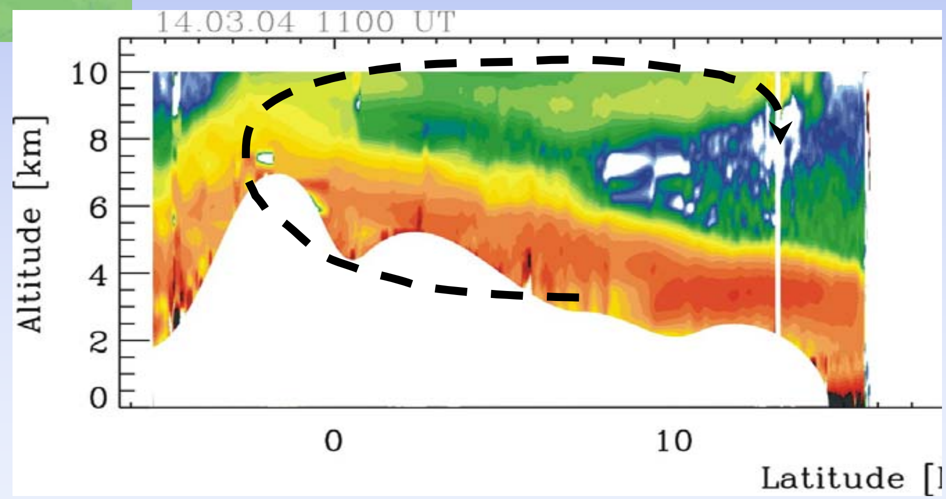
Airborne Water Vapor Lidar Observations 1/2
TROCCINOX Transfer 2004

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



Airborne Water Vapor DIAL measurements on March 14, 2004



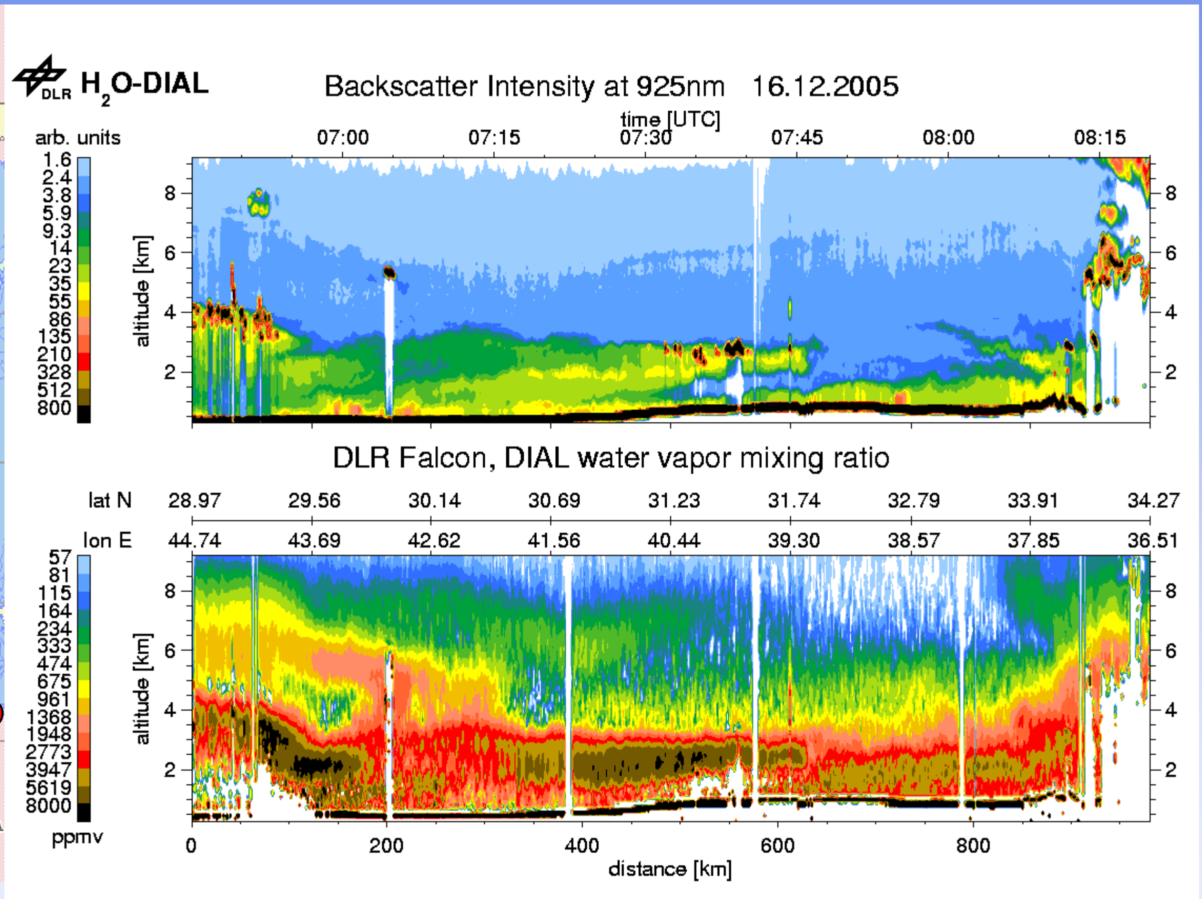


Hadley Circulation

Airborne Water Vapor Lidar Observations 2/2
SCOUT Transfer 2005

SCOUT Transfer Flights Nov/Dec 2005

Transfer back: Dubai - Larnaca on 16/12/2005

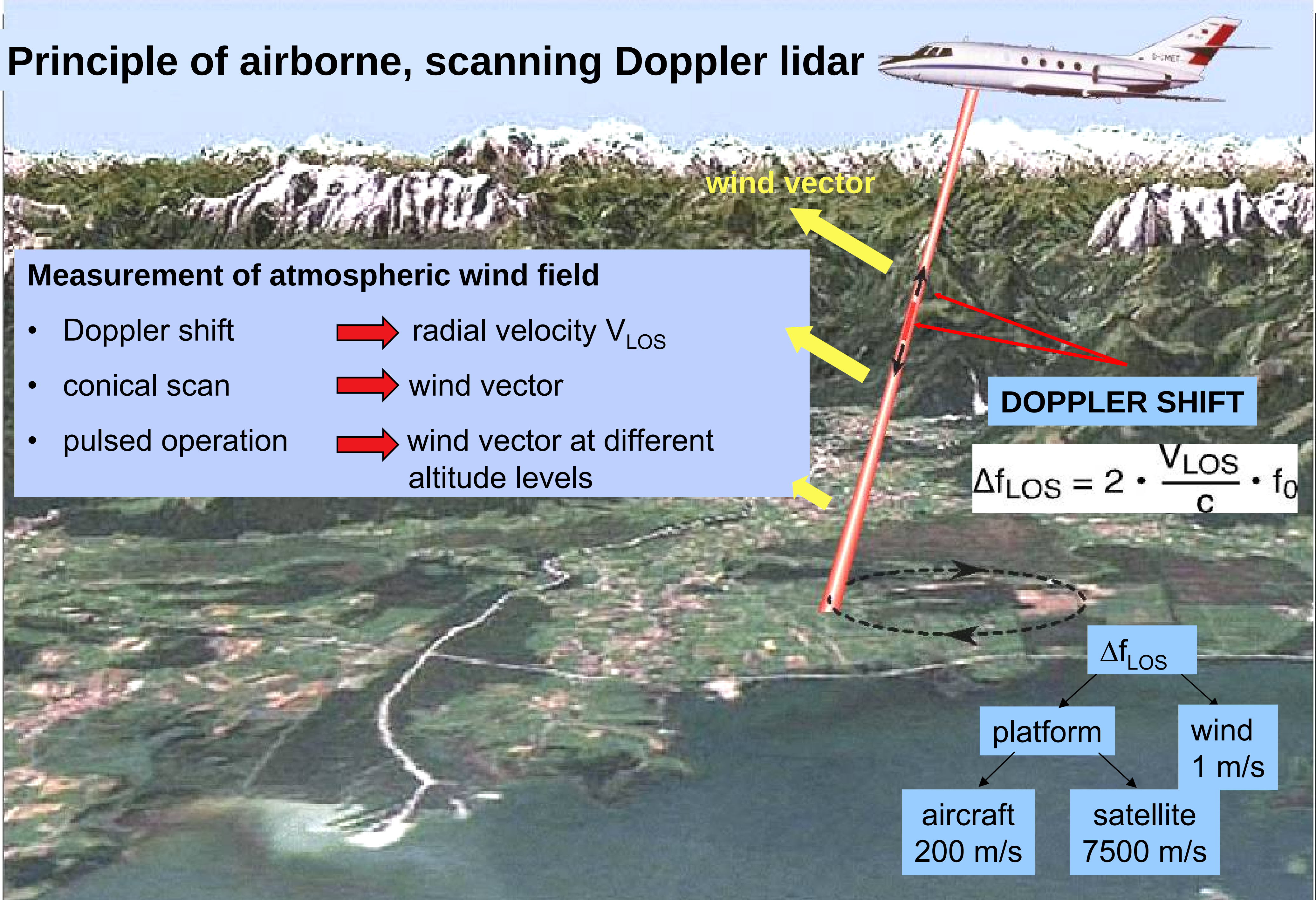


by Andreas Fix, Christoph Kiemle, Gerhard Ehret

Principle of airborne, scanning Doppler lidar

Measurement of atmospheric wind field

- Doppler shift → radial velocity V_{LOS}
- conical scan → wind vector
- pulsed operation → wind vector at different altitude levels



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

Werner et al. 2001, Opt. Eng.

Reitebuch et al. 2001, J. Atmos. Ocean. Tech.

Reitebuch et al. 2003, Quart. J. Roy. Met. Soc.

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

Köpp, Rahm, Smalikho 2004, J. Atmos. Ocean. Tech.

Airborne Doppler Lidar at DLR 2/2

ALADIN Airborne Demonstrator A2D

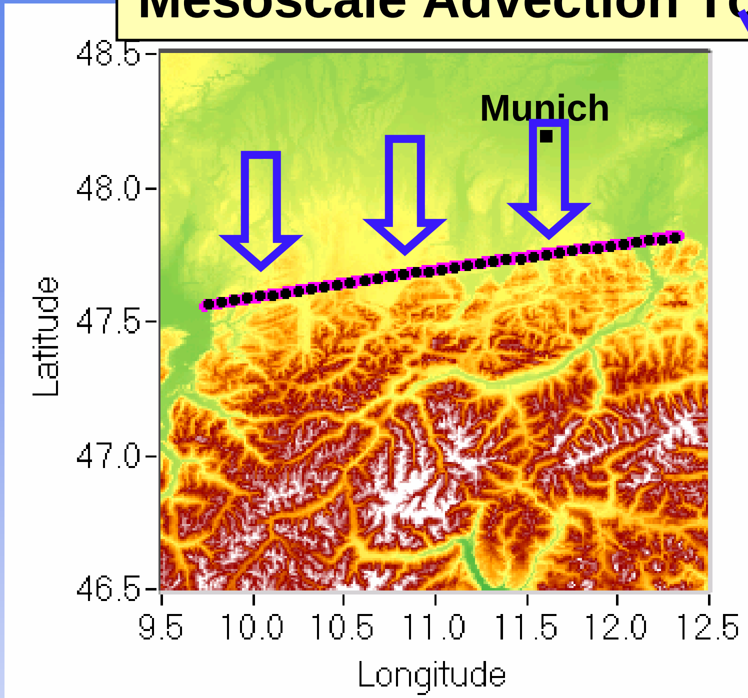
- Airborne prototype of satellite ADM-Aeolus instrument ALADIN to obtain measurements in nadir geometry like from space at a wavelength of 355 nm
- First airborne direct detection Doppler lidar
- Development since 2003 by team of EADS-Astrium France, Germany and DLR
- First functional test flights in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

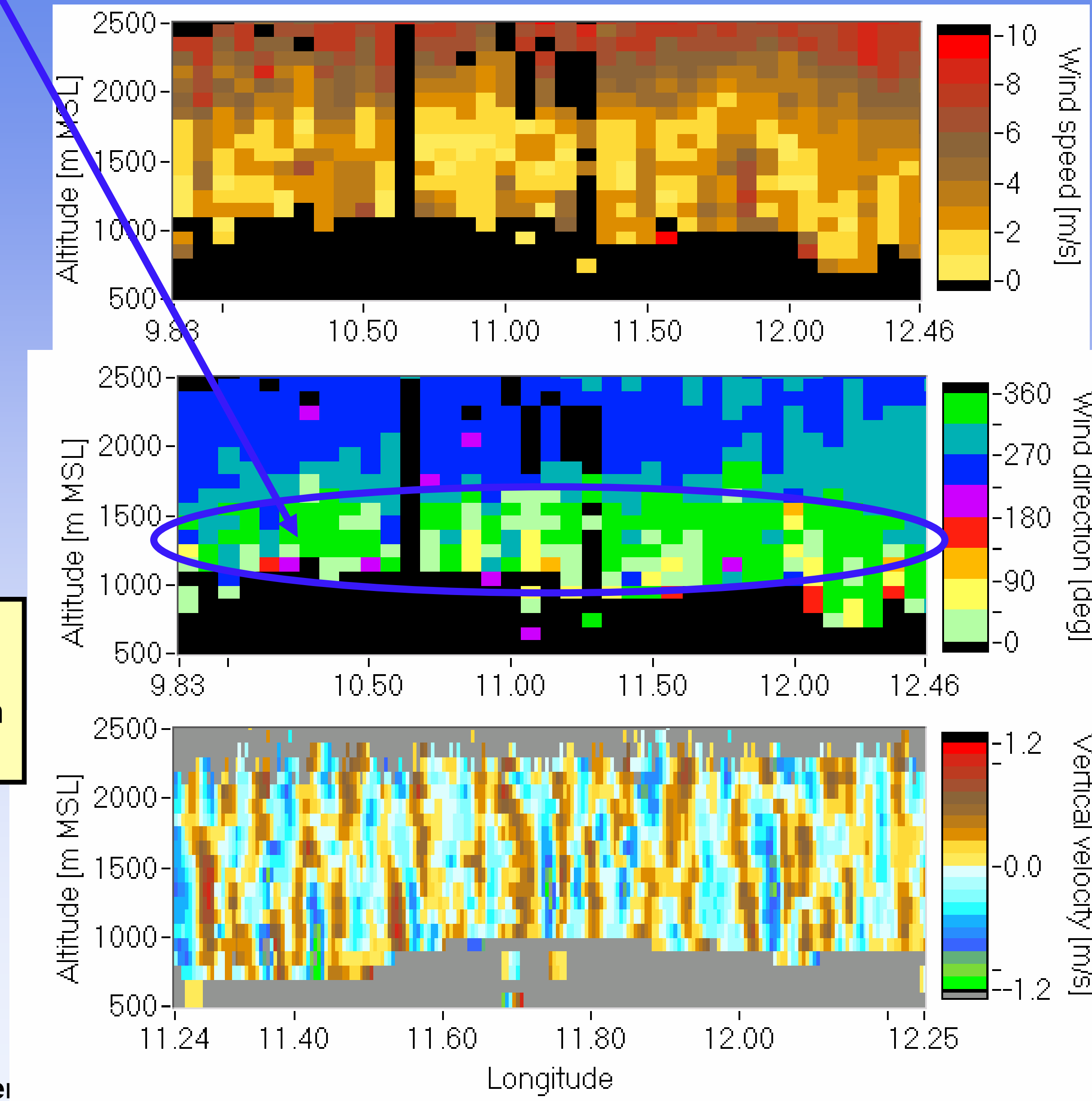
Reitebuch et al. 2003, Proc. Int. Symp. Tropos Profiling

Durand et al. 2003, Proc. SPIE

Airborne Doppler Lidar Observations
Mesoscale Advection Towards the Alps in 2003

VERTIKATOR





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

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

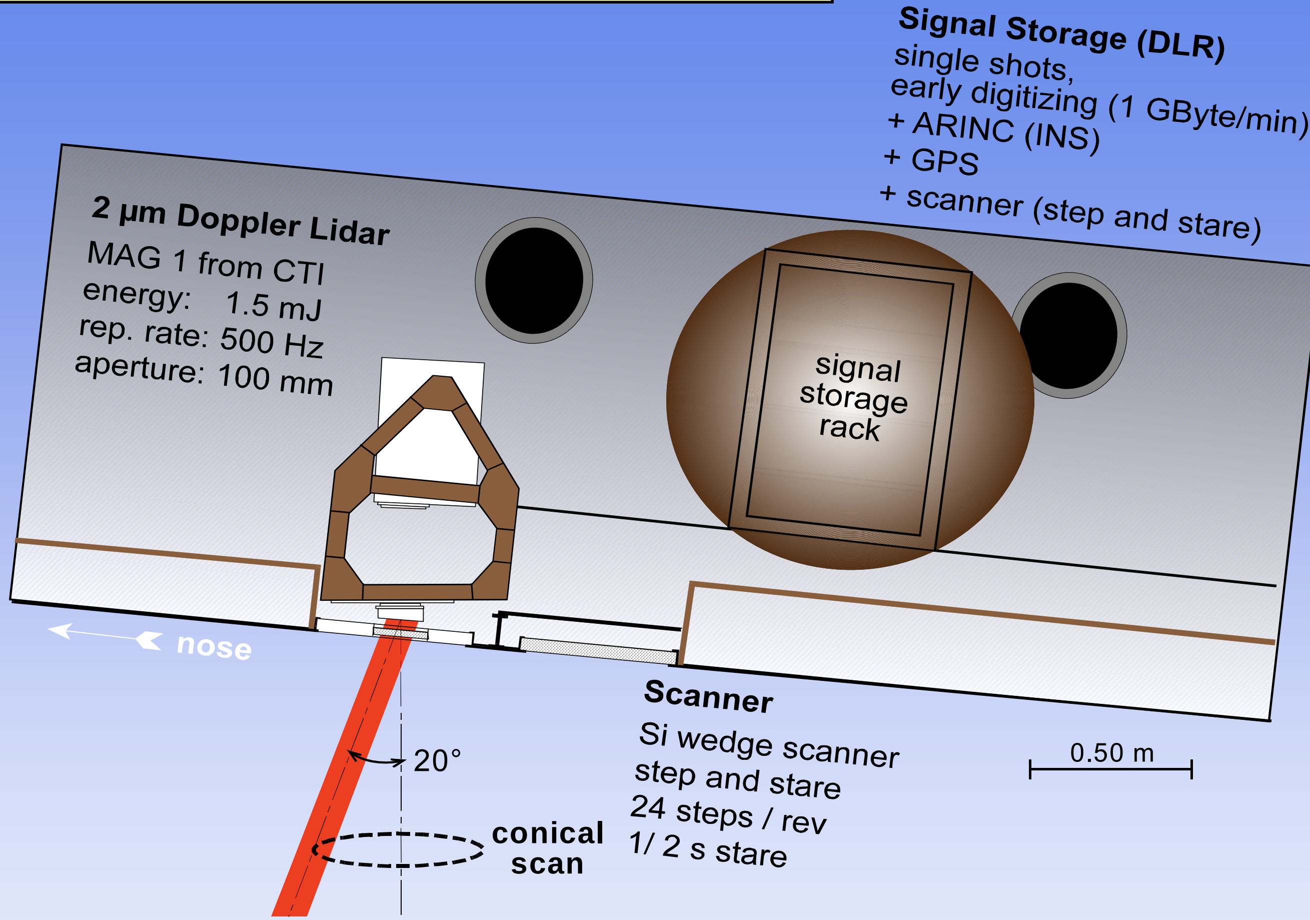
Weissmann, Busen, Dörnbrack, Rahm, Reitebuch (2005), J. Atmos. Ocean. Tech.

Weissmann and Cardinali (2006) Quart. J. Roy. Met. Soc., revised

further information:

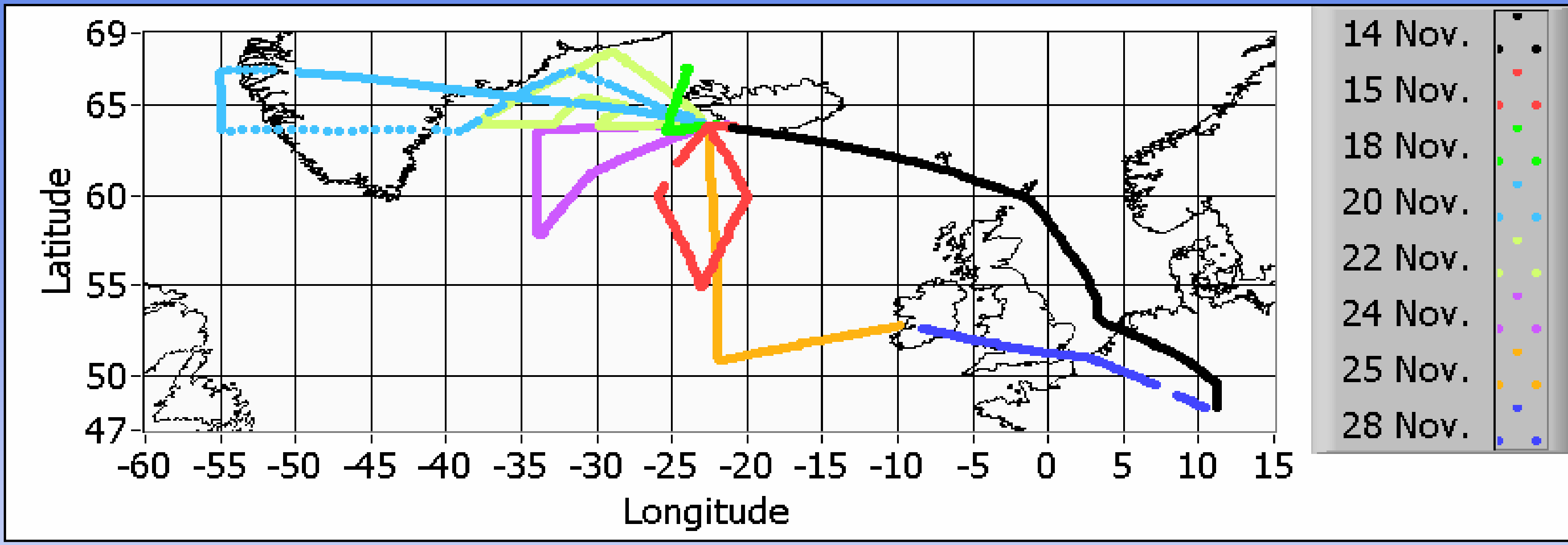
www.pa.op.dlr.de/na-trec/

DLR Airborne 2-µm Doppler Lidar



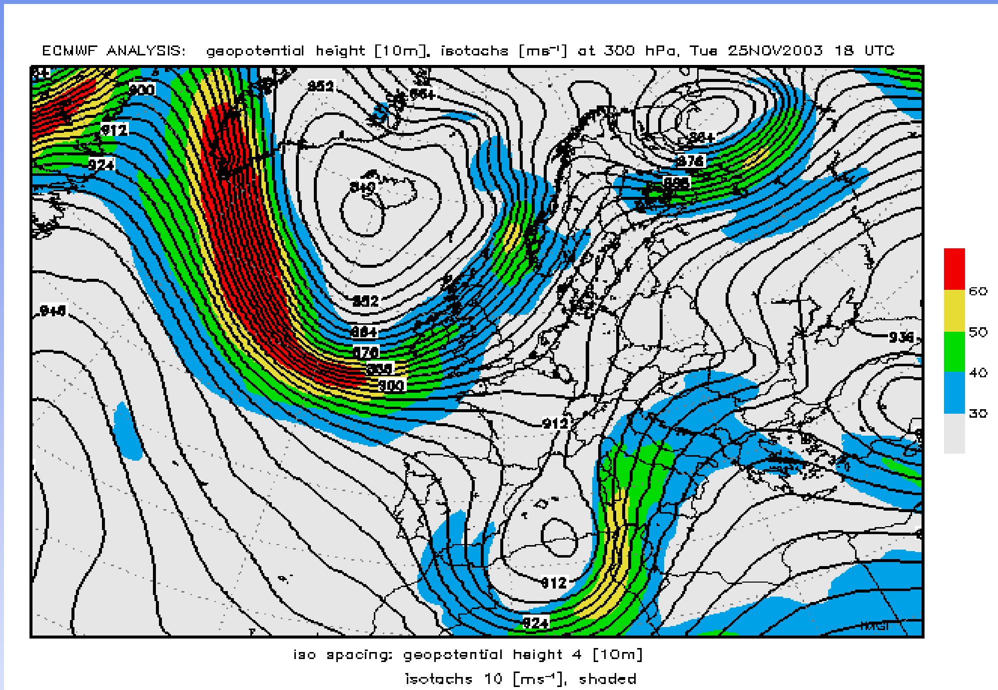
1 conical scan = 24 LOS positions (~ 30 s or 54 s)
vertical profile of wind vector (u,v,w)
horizontal resolution 5 - 10 km for one scan,
vertical resolution 100 m

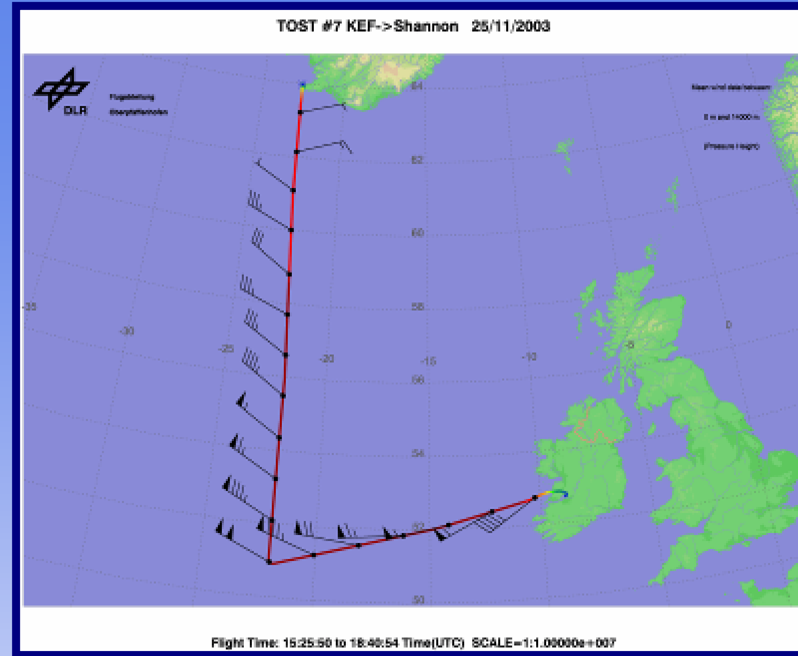
Flight Tracks



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

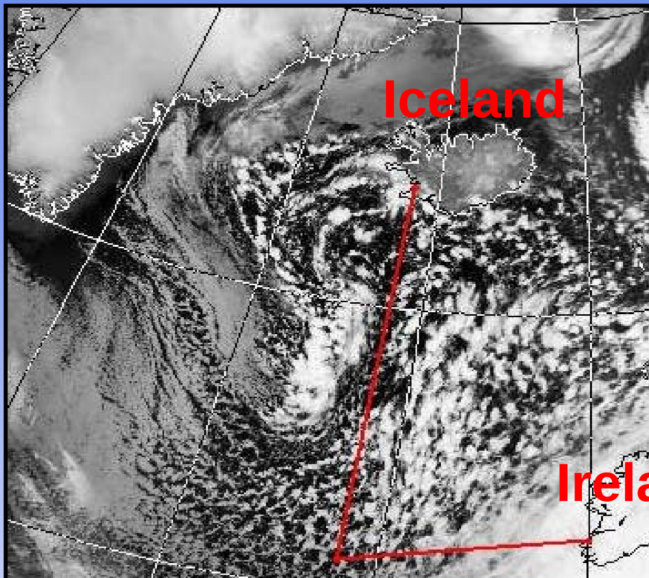
Targeted Flight on November 25, 2003



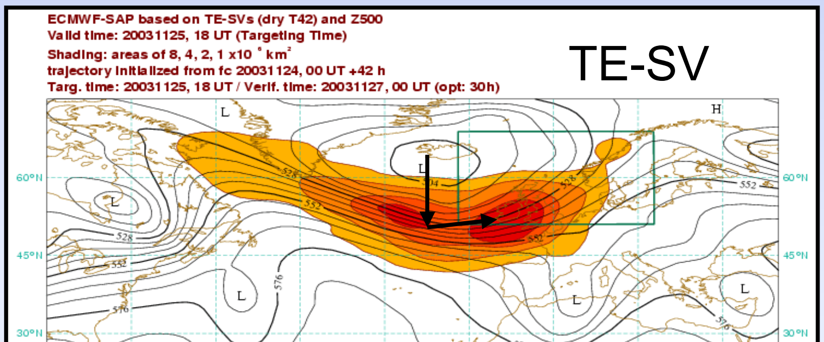


ECMWF analysis 25 Nov 2003, 18 UTC
geopotential height at 300 hPa
and isotachs

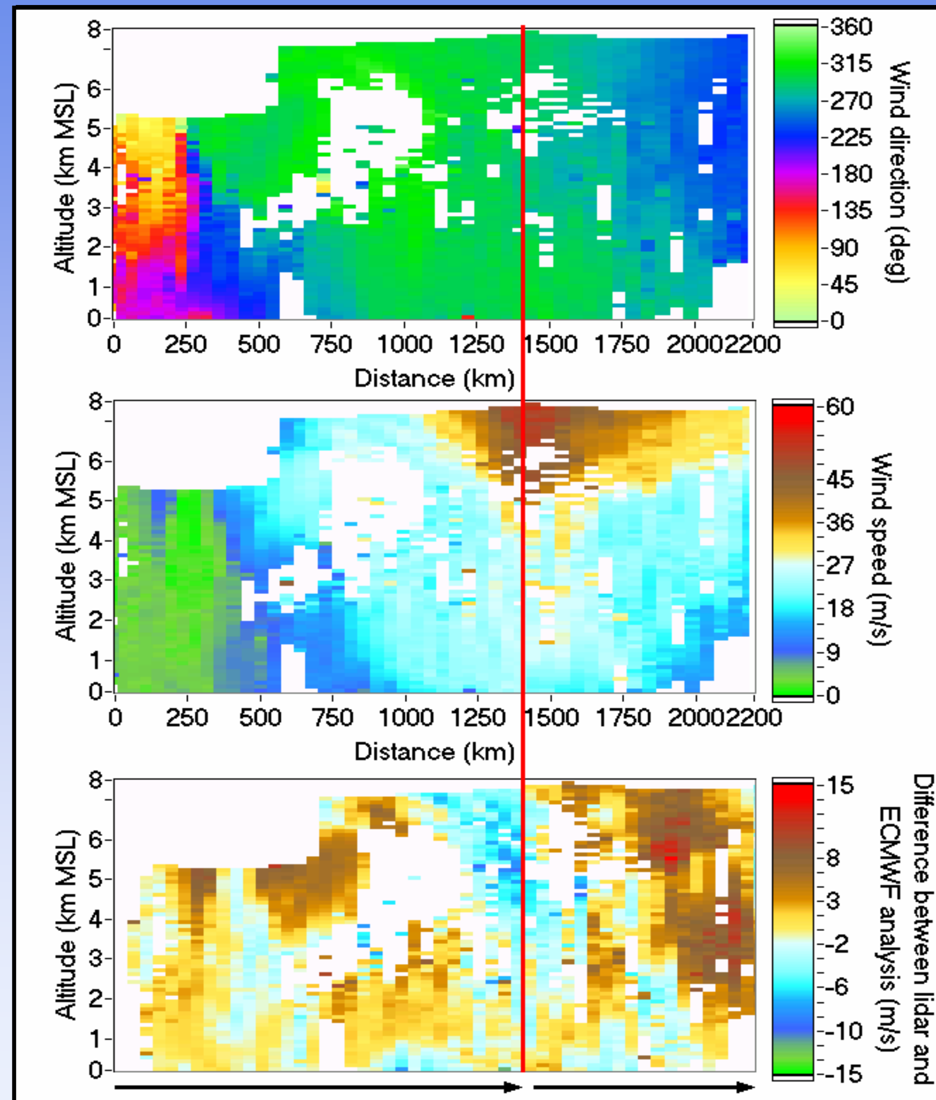
Flight on November 25, 2003, 1530-1830 UTC



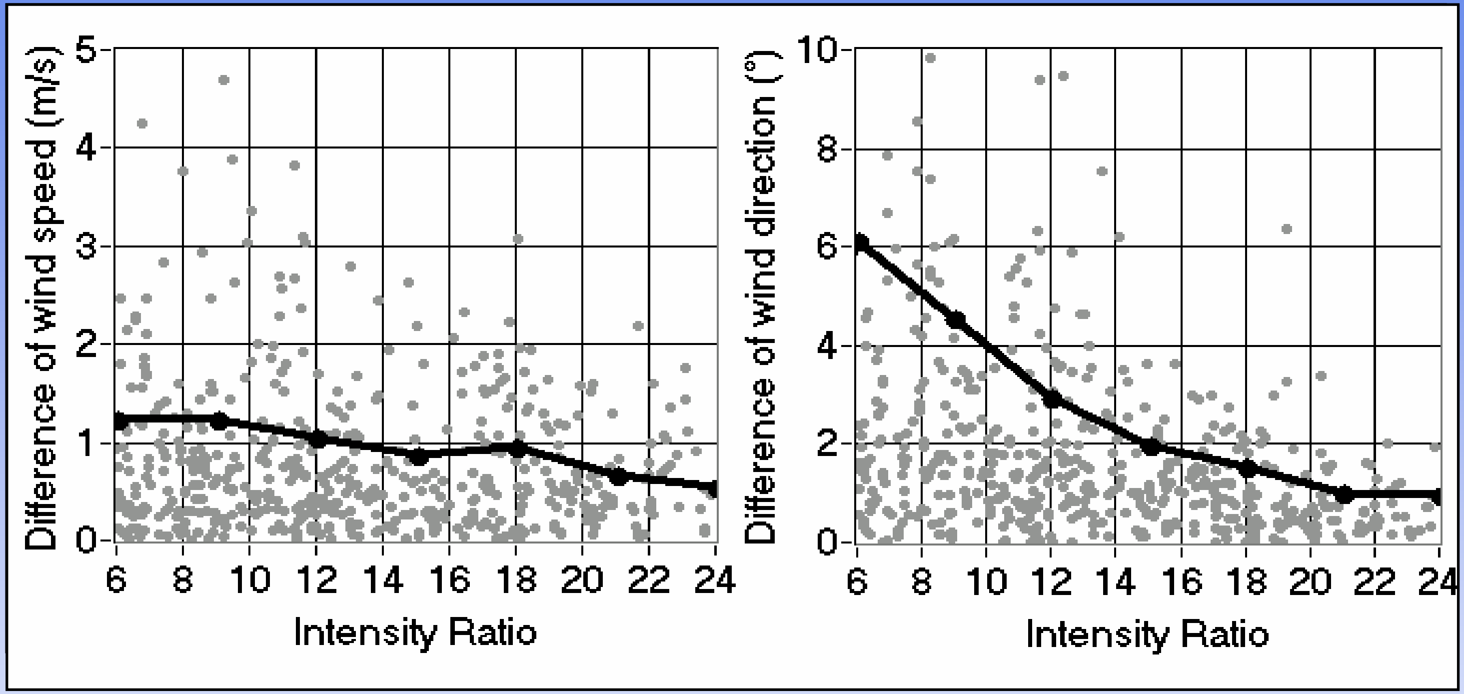
http://www.sat.dundee.ac.uk/



ECMWF sensitivity plot and 500 hPa



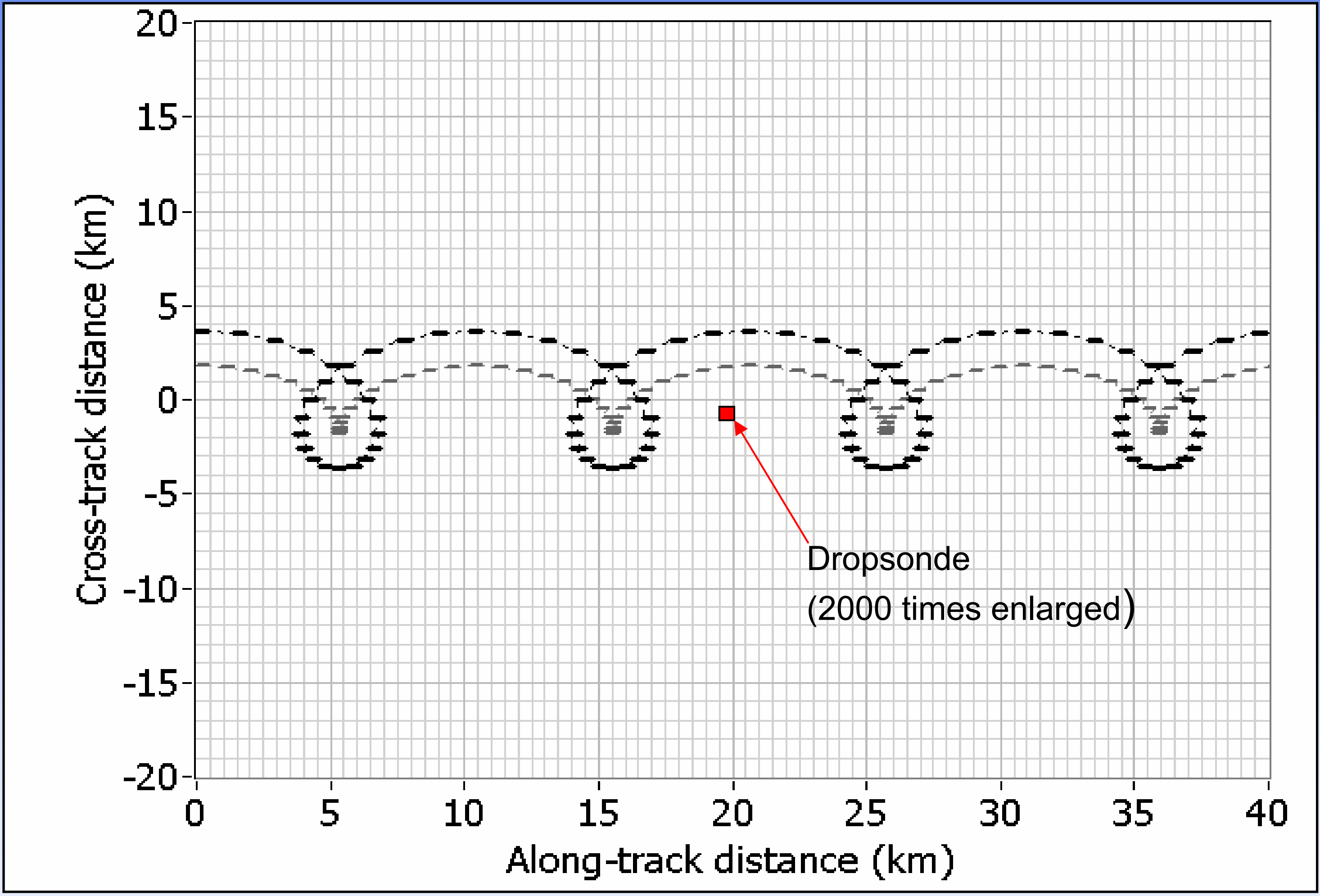
Statistical comparison of lidar and dropsondes



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

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

Total Observation Errors Assigned during Assimilation



Typical size of grid box in ECMWF global model and lidar scan

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

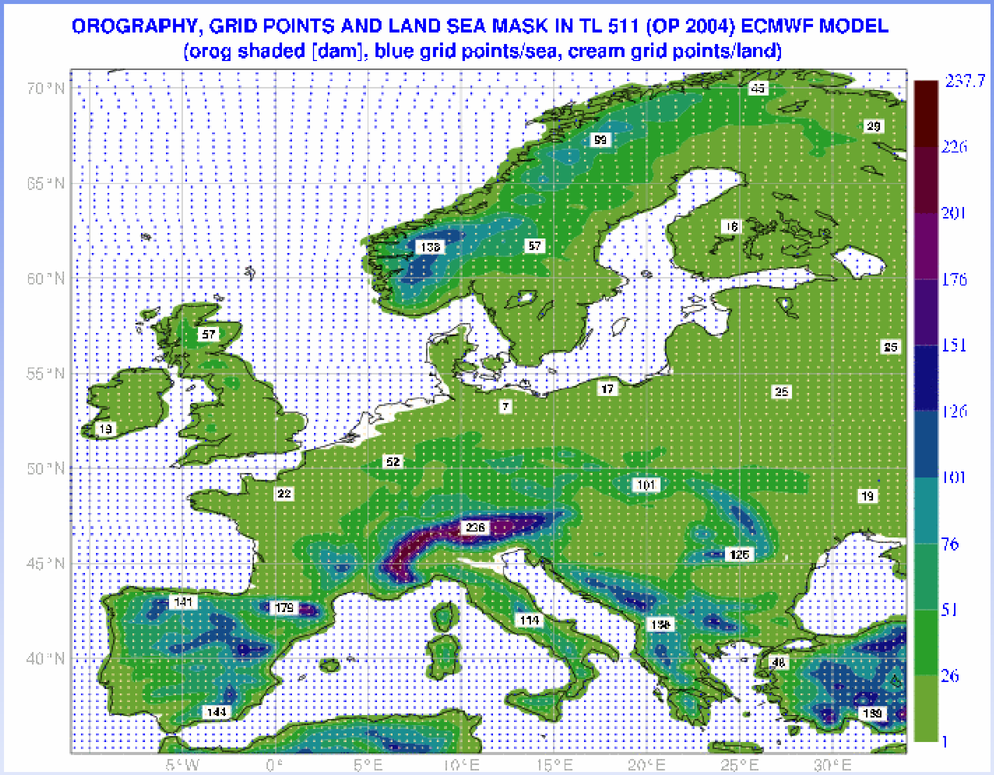
Total error ADM HLOS: 2-3 m/s

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

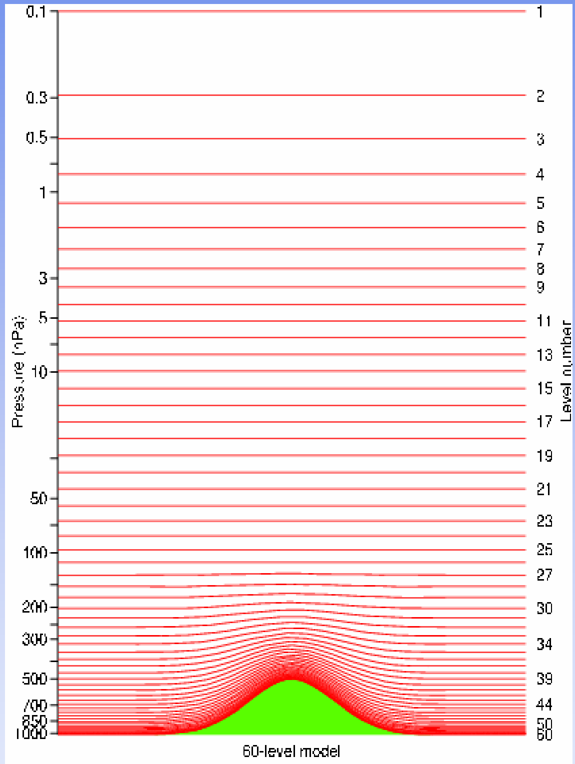
Total error Cloud Motion Vectors: 2-6 m/s

ECMWF Global Model used for Assimilation Experiments

wavenumber T511: 40 x 40 km



60 Levels between 0 und 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)
analyses = 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

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

Thinning of Lidar Observations

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.

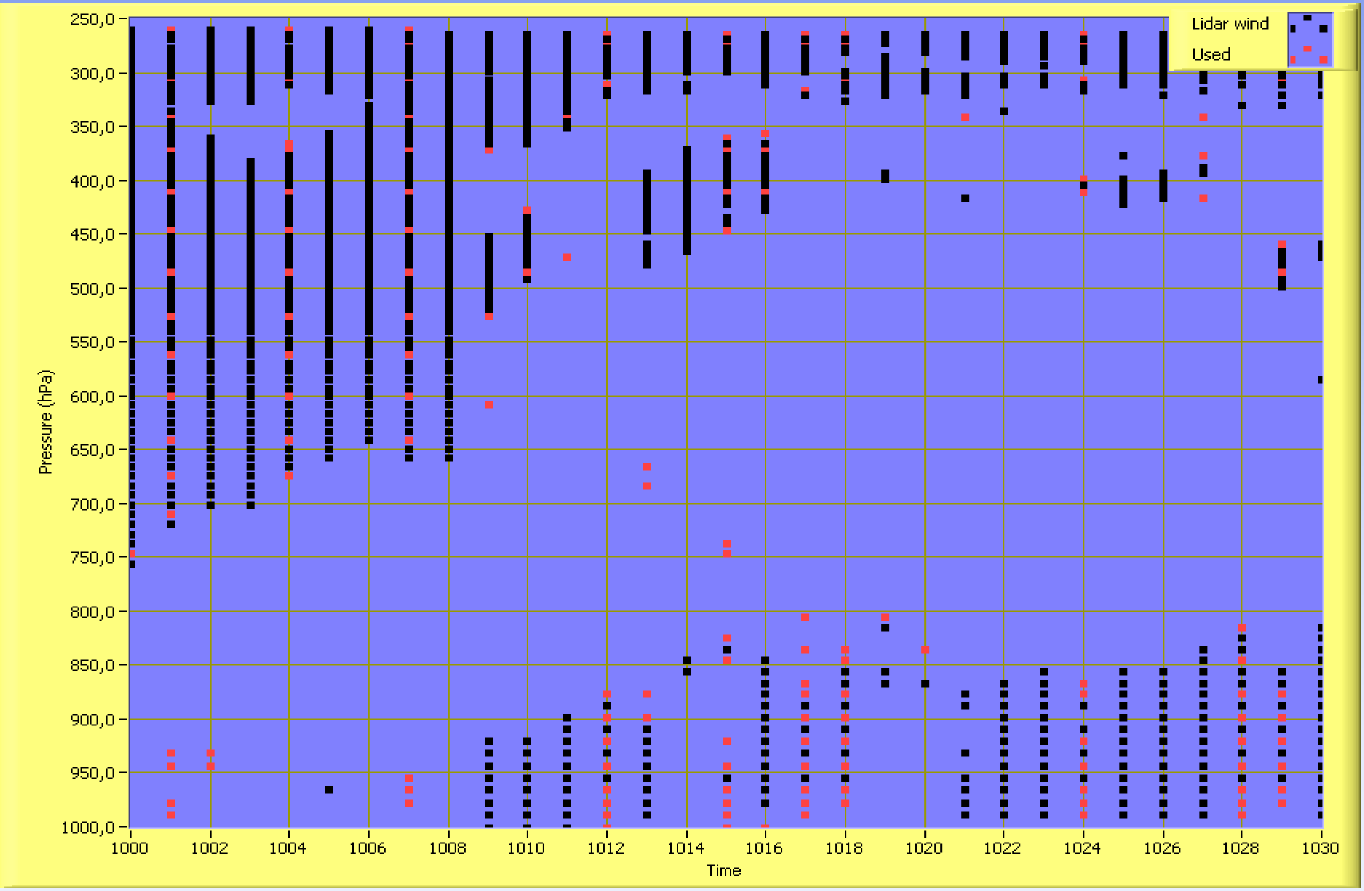
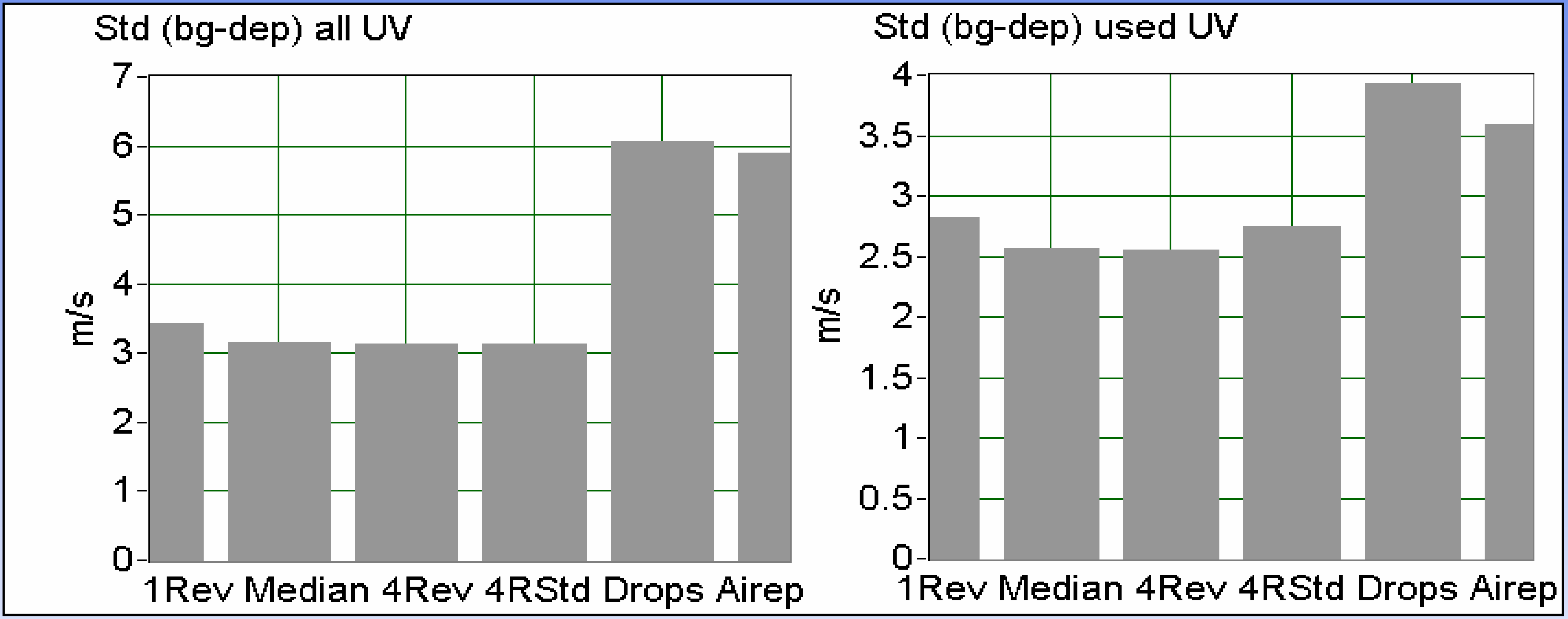


Figure: Thinning of 10 km lidar data to model resolution

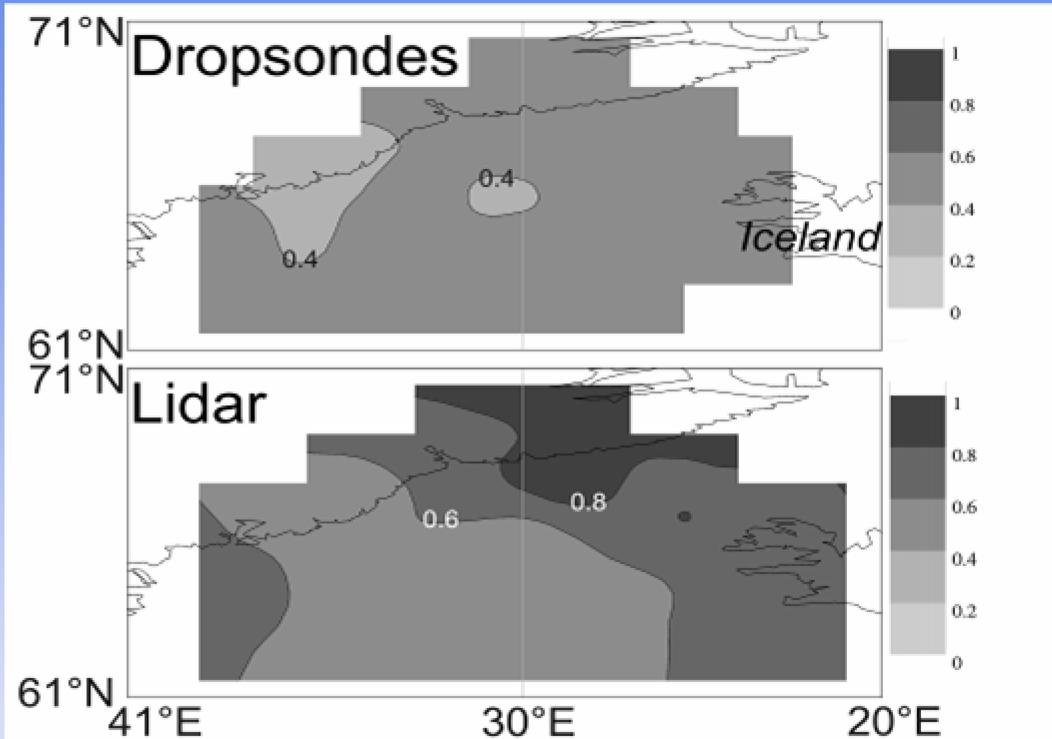
Background Departures



background departure bg-dep = Observation obs - First-Guess Fg

$(\text{Std(bg-dep)})^2 = (\text{error}_{Obs})^2 + (\text{error}_{Fg})^2$

Observation Influence on Targeted Flight



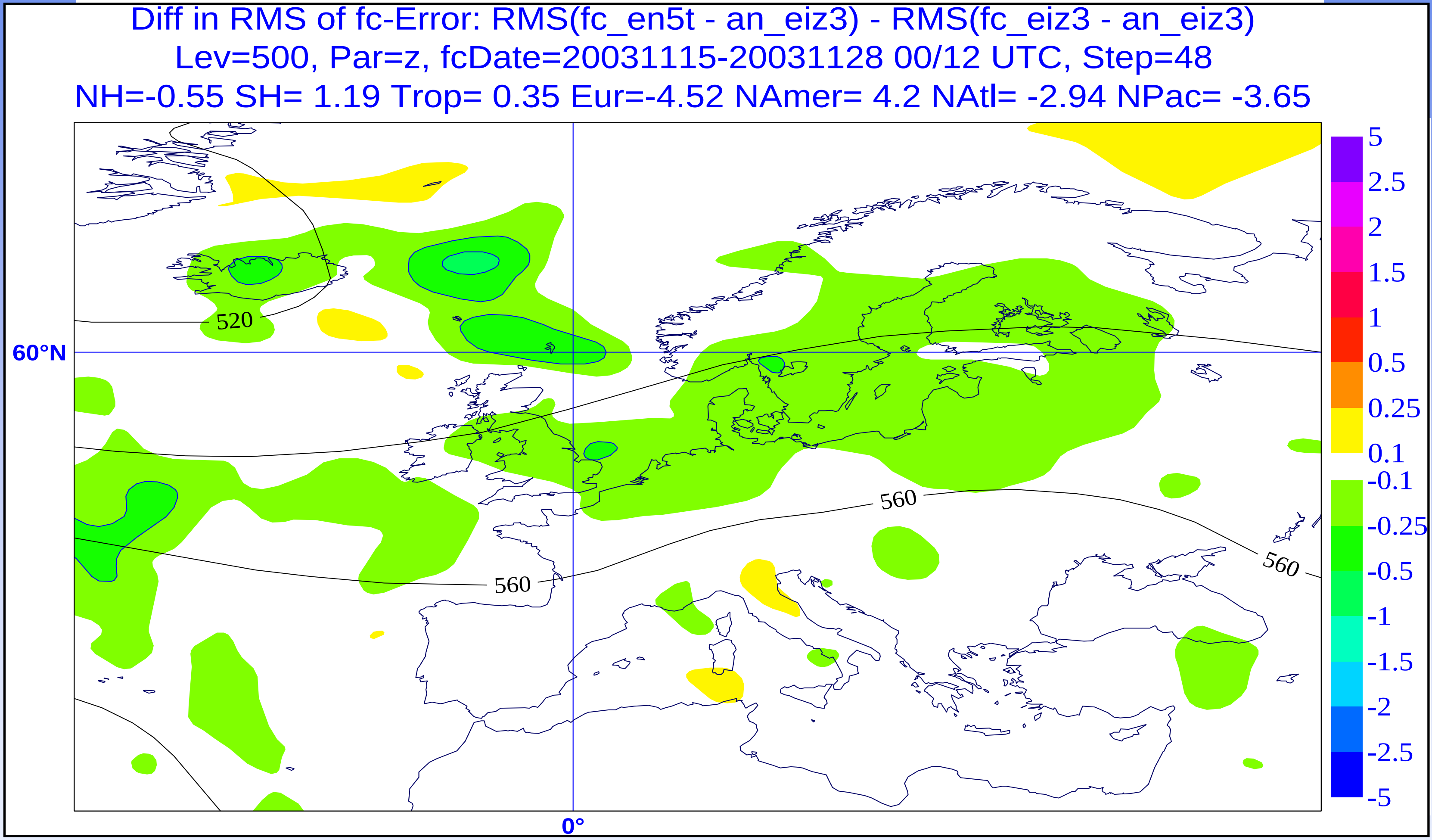
Observations from 22 November 2003

	Lidar u, v	Dropsonde u, v
Observation influence OI	0.63	0.45
Number of observations N	758	388
Information content IC IC = OI · N	477.5	174.6

Observation influence (Cardinali et al. 2004):

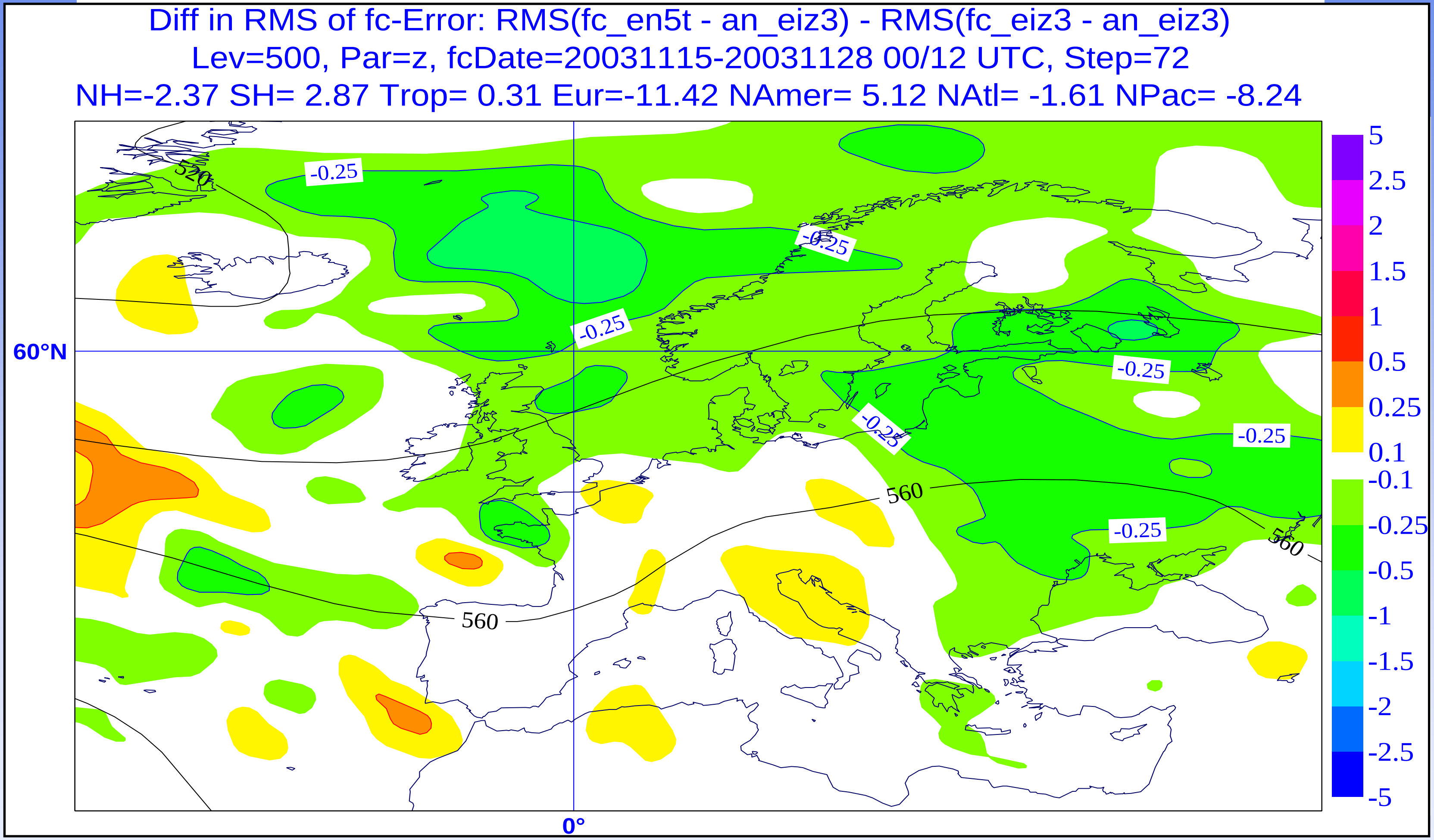
0 --> no influence of observation; analysis is determined by background
1 --> no influence of background; analysis is determined by observation
mean global observation influence = 0.15
mean observation influence radiosondes in NH/ET is 0.3
mean observation influence of aircraft and CMV is 0.15

Reduction of Forecast Error for 48 h for 500 hPa Height



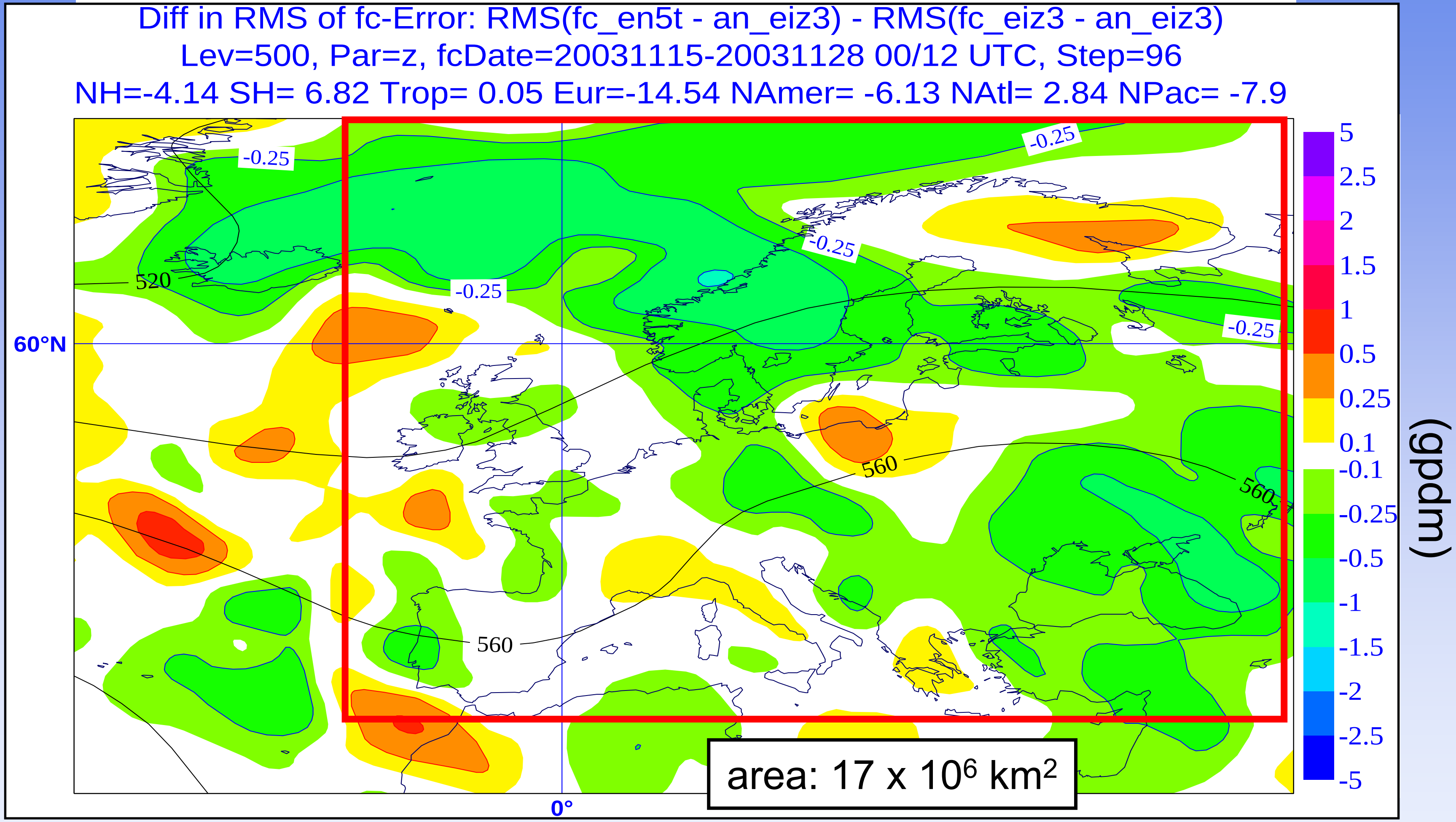
Mean forecast error difference for period 15-28 November 2003 for lidar experiment 4RStd (40 km, 1.5 m/s)

Reduction of Forecast Error for 72 h for 500 hPa Height



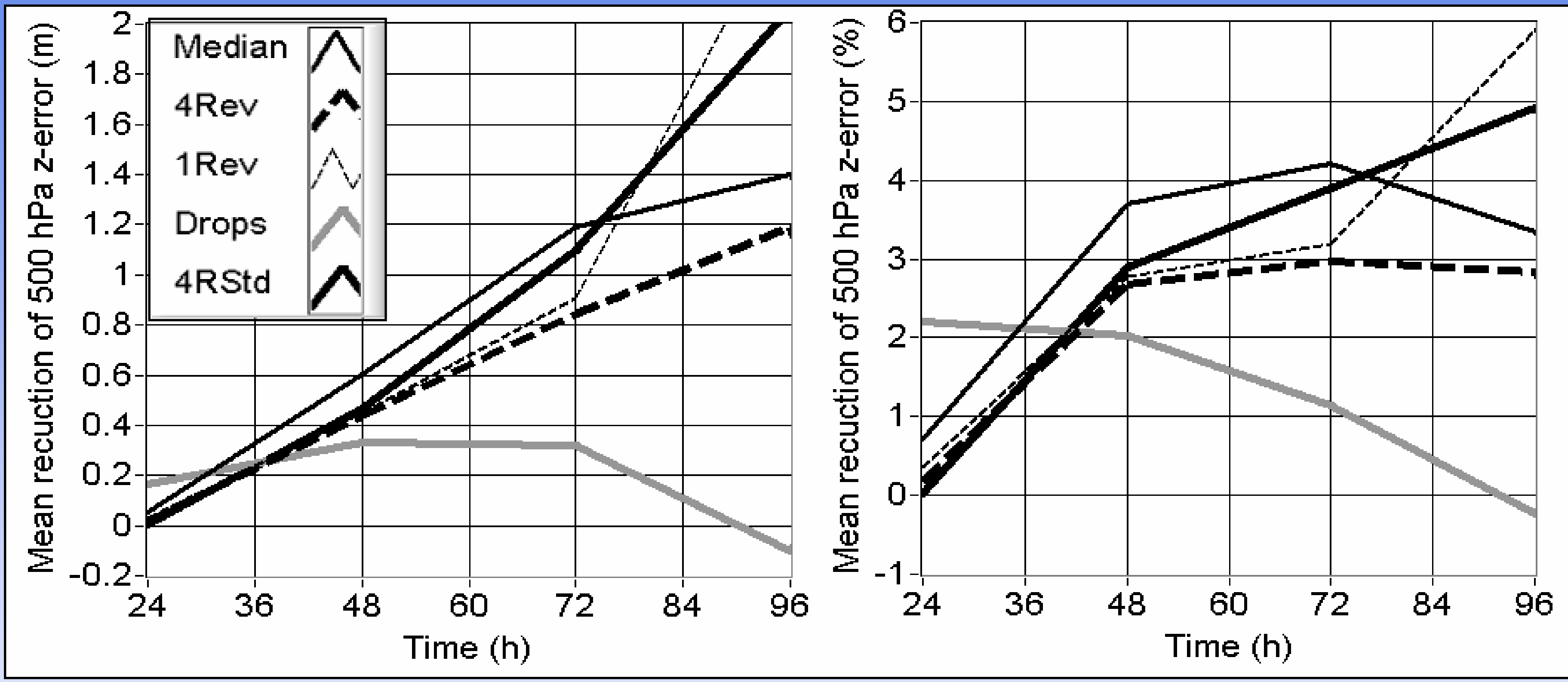
Mean forecast error difference for period 15-28 November 2003 for lidar experiment 4RStd (40 km, 1.5 m/s)

Reduction of Forecast Error for 96 h for 500 hPa Height



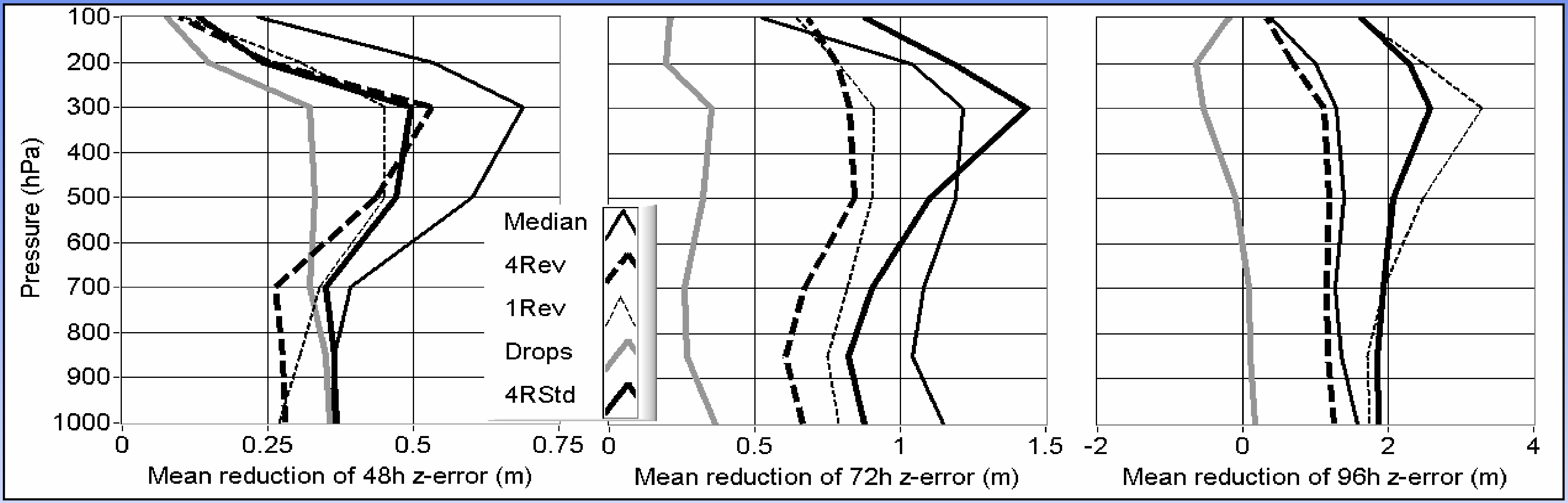
Mean forecast error difference for period 15-28 November 2003 for lidar experiment 4RStd (40 km, 1.5 m/s)

Reduction of Forecast Error for 500 hPa Height



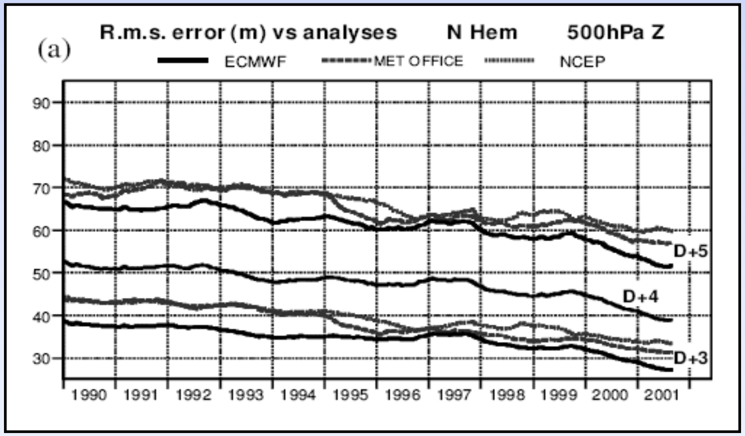
average over 29 forecasts during 14 days over Europe
reduction of experiment run compared to control run (left)
normalised reduction with average forecast error of control run (right)

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

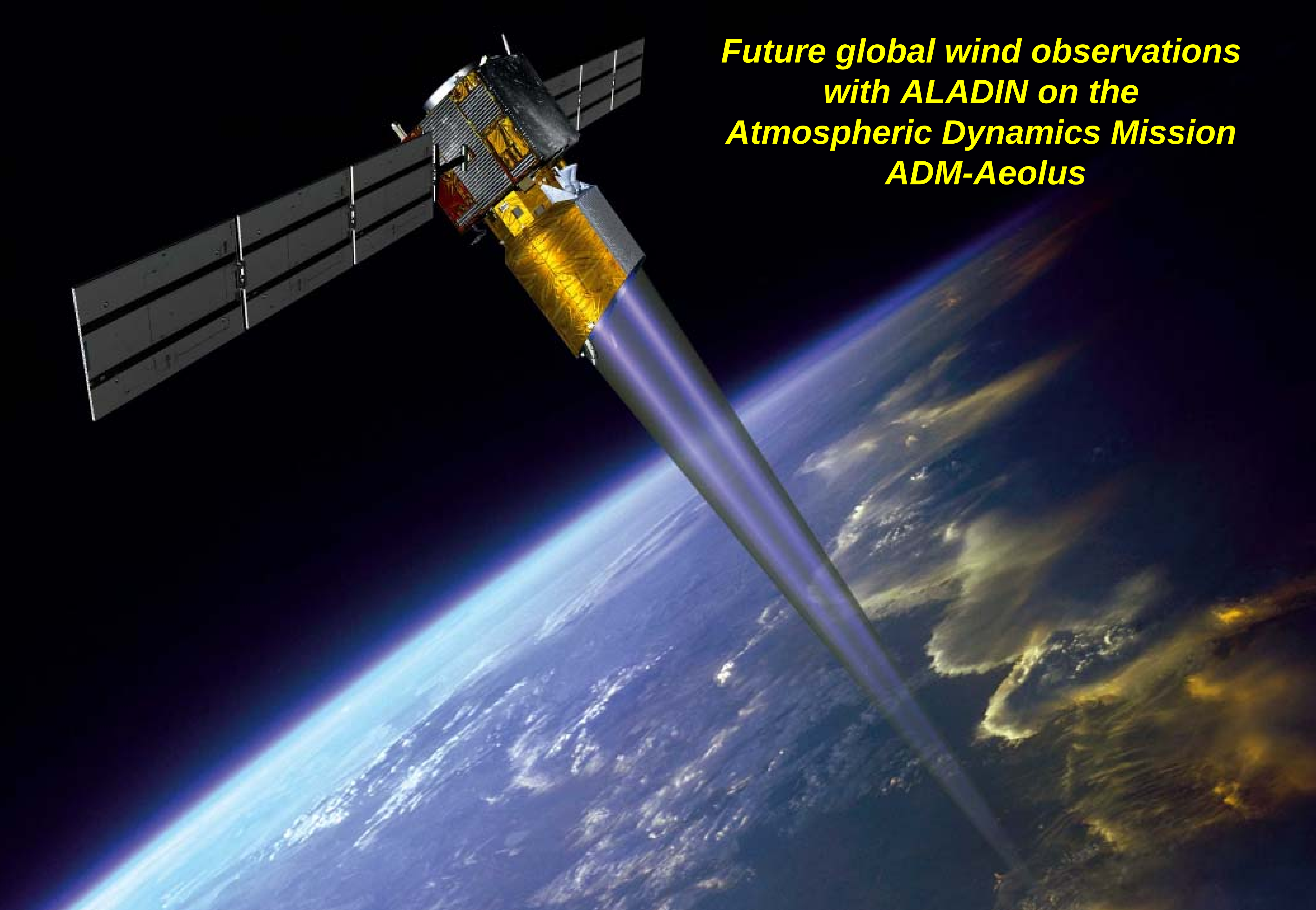
- First time that Doppler lidar observations were assimilated into global model (BUFR, error assignment, thinning) => study of background departures and influence on analysis and forecast skills; only one other study by Kamineni 2006, 2003 is known where water vapor lidar observations were assimilated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

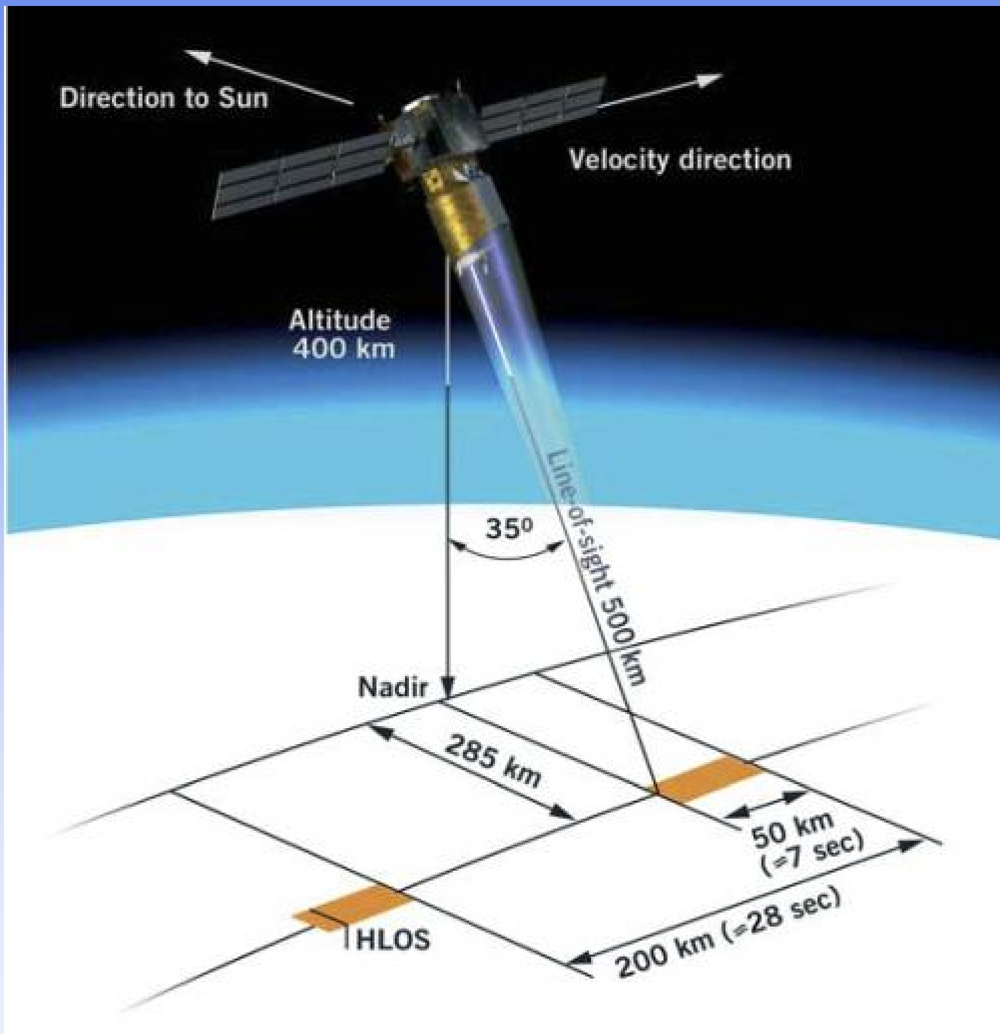
- Study demonstrates importance of real lidar wind measurements for forecast improvements and is benificial for wind lidar applications on airborne and satellite platforms


Future global wind observations
with ALADIN on the
Atmospheric Dynamics Mission
ADM-Aeolus

Aeolus Mission Requirements and Design Drivers

Vertical resolution: 0.5 km to 2 km 1 km to 16 km 2 km to 30 km total up to 25 layers	Requires Mie and Rayleigh channel to measure over full altitude range
Horizontal average wind over 50 km Profile spacing 200 km to fit NWP needs	7 s averaging 28 s per observation
Global coverage (200 profiles per orbit) for three years in orbit	Drives lifetime qualification
Horizontal HLOS wind accuracy: 1 m/s up to 2 km 2 m/s up to 16 km	Drives sizing of lidar
Bias: less than 0.4 m/s HLOS offset Linearity: less than 0.7 % of actual speed	Drives stability of lidar calibration
Dynamic range: -150 to +150 m/s	spectral range

ADM-Aeolus Implementation

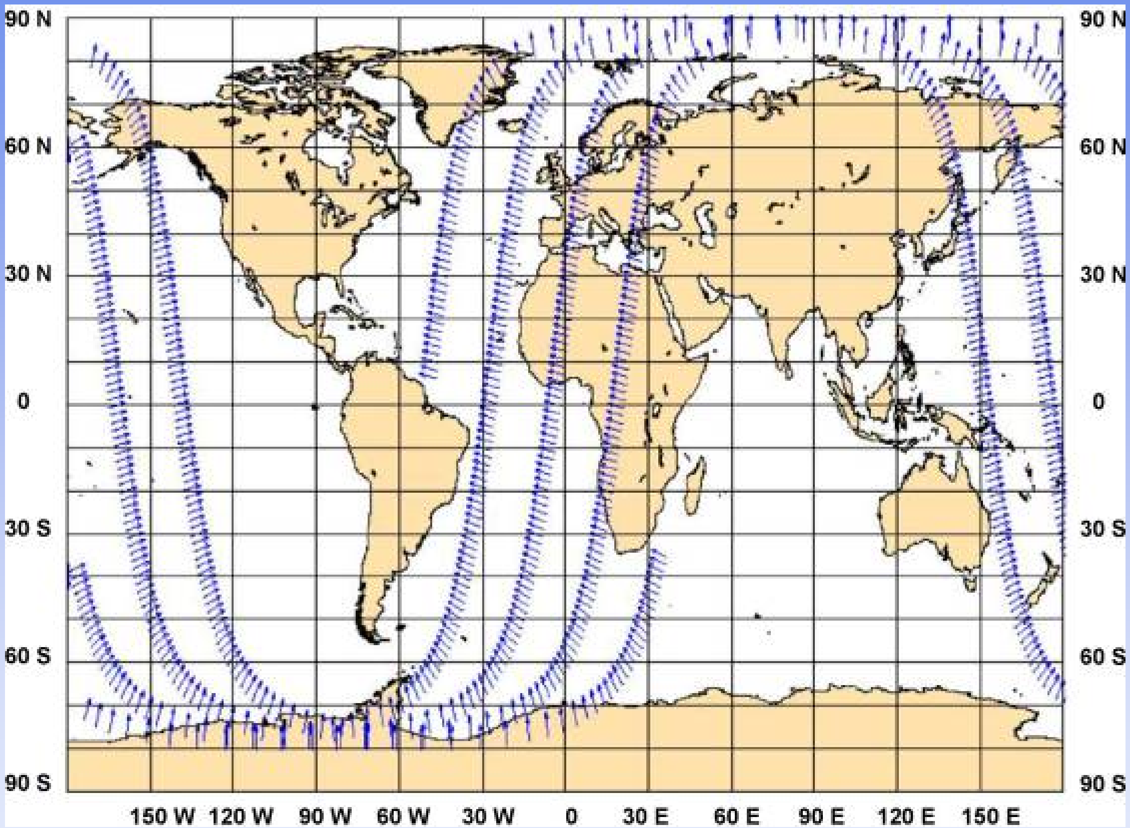


Atmospheric LAser Doppler INstrument

ALADIN

- First Doppler lidar in space
- Operating in ultraviolett @ 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 averaed winds every 200 km
- First High Spectral Resolution Lidar HSRL in space to obtain aerosol/cloud optical properties

ADM-Aeolus Coverage and Data Availability

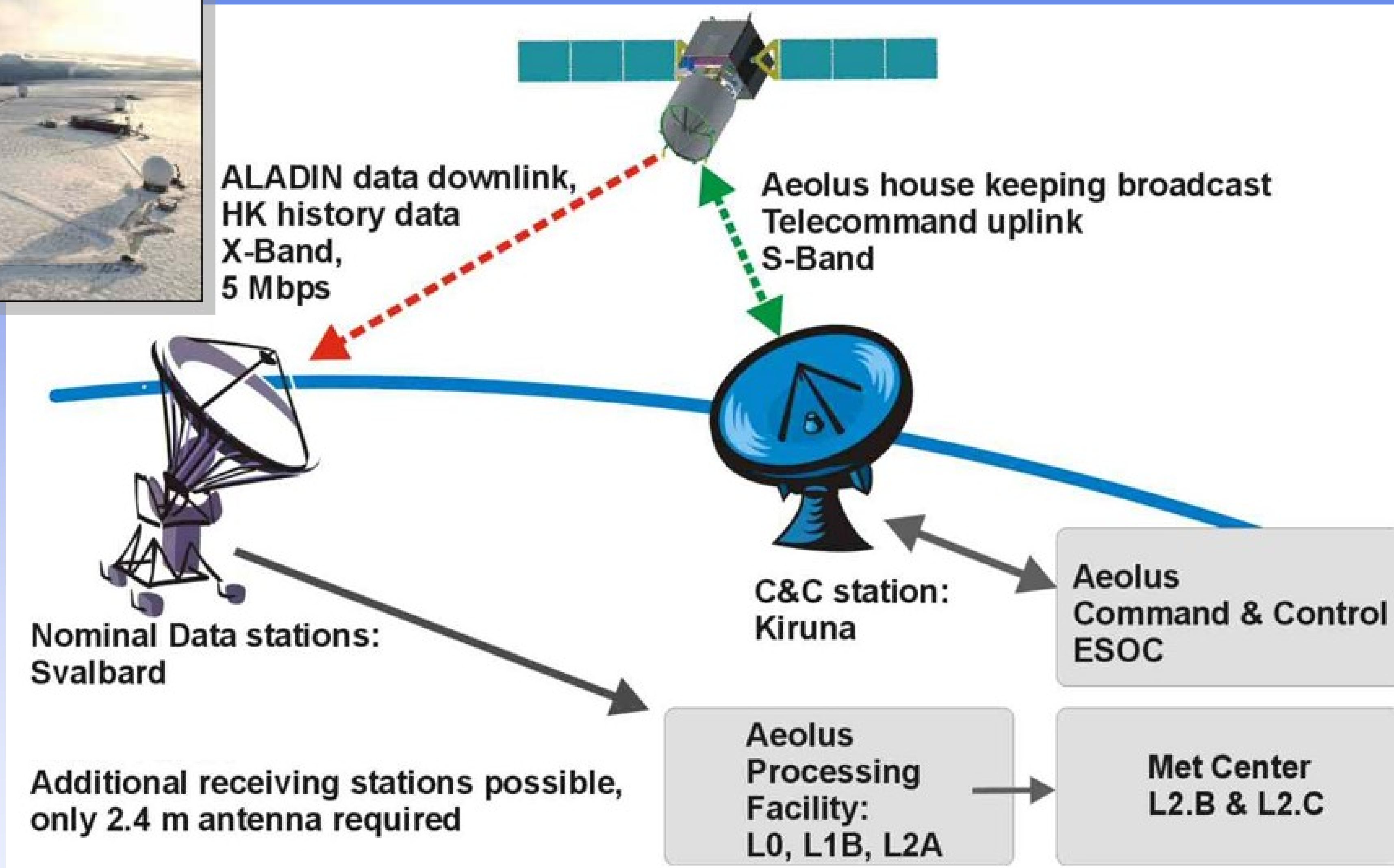


50 km Observations during 6 hour period

- 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

Overview paper about ADM-Aeolus: Stoffelen et al. 2005, Bull. Am. Met. Soc.

ADM-Aeolus Ground Segment



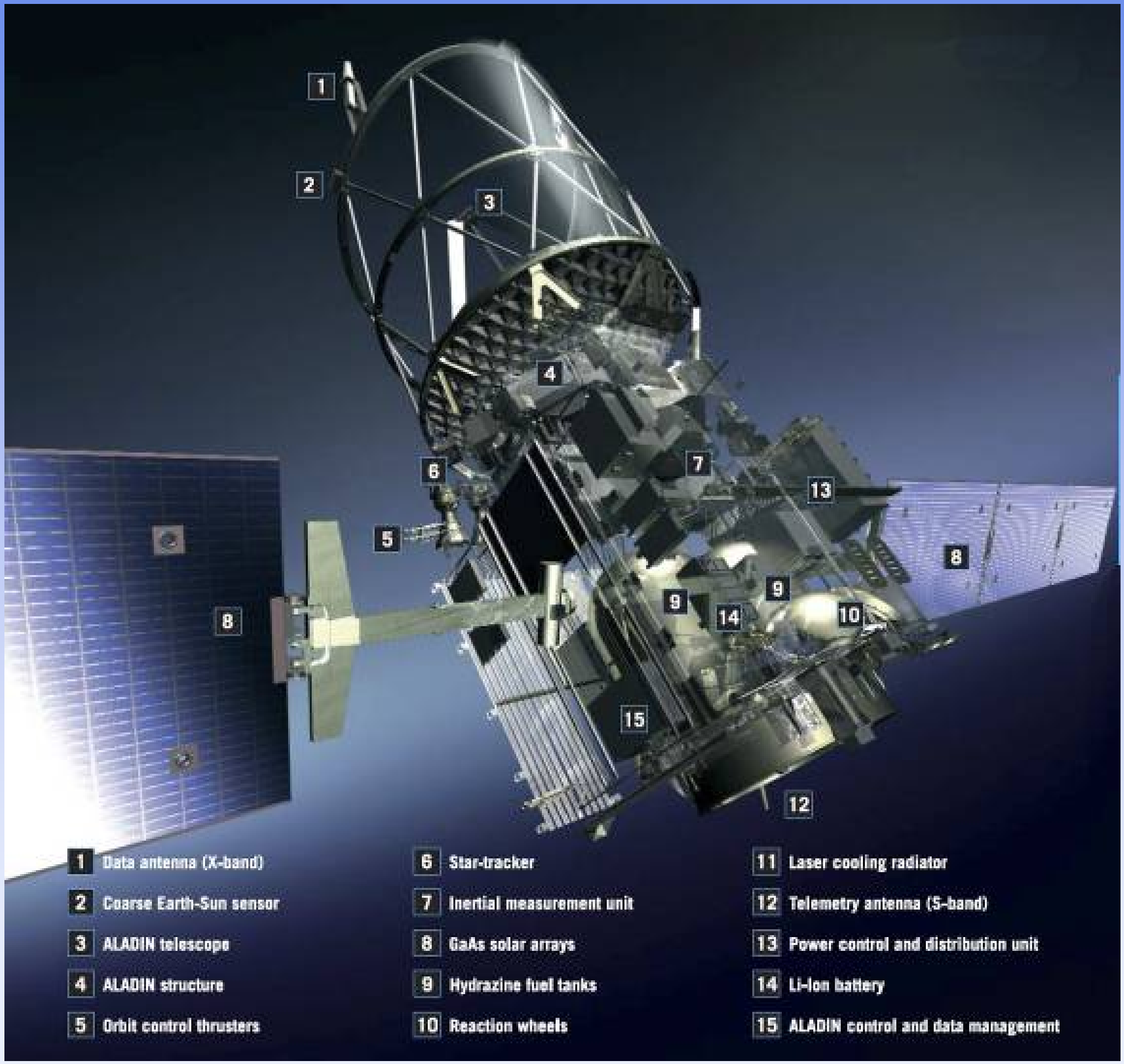
Tromsö, Norway

ECMWF

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

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

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)

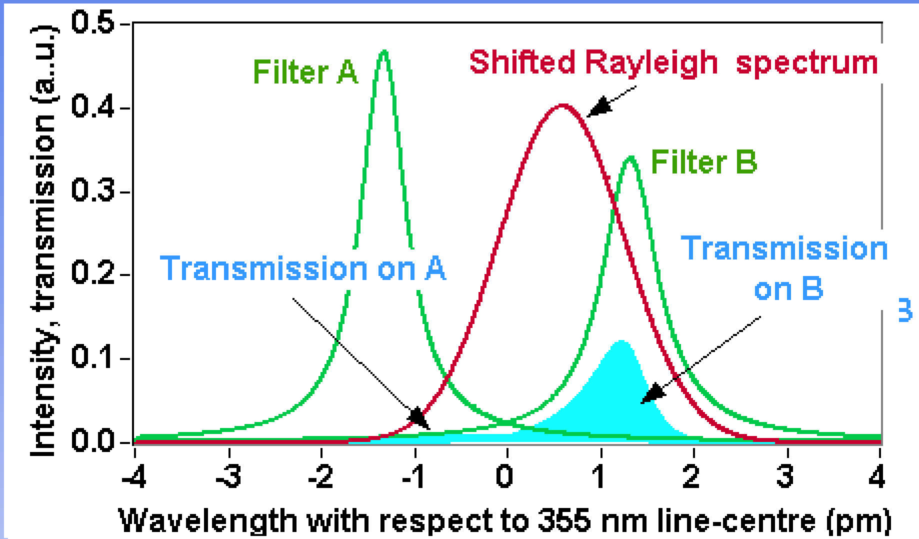
Doppler Lidar Instrument ALADIN
Nd:YAG laser in burst mode operation
(125 mJ - 150 mJ @ 355 nm, 100 Hz)
1.5 m Cassegrain telescope
Dual-Channel-Receiver with ACCD
(Accumulating CCD Detector)

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

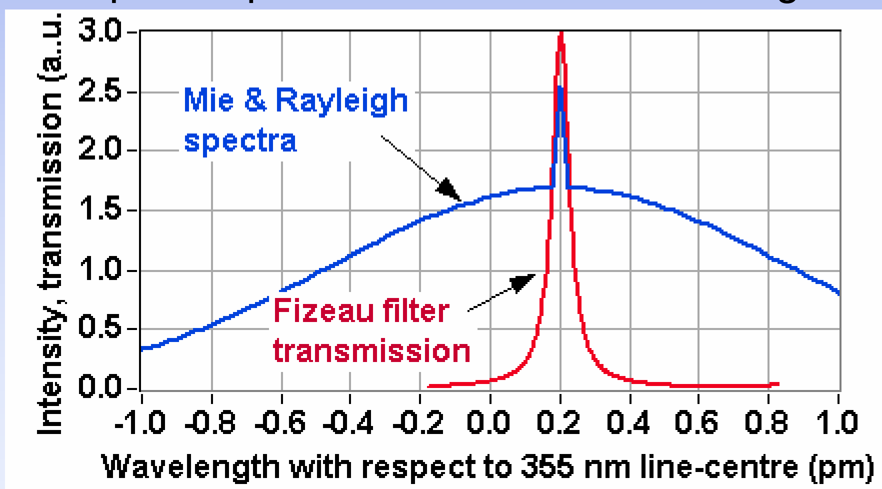
Launcher
Rockot (SS-19 ICBM), Dnepr (SS-18 ICBM) or Vega (ESA)

Fig. U. Paffrath

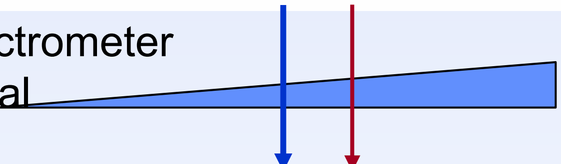
Principle of Wind Measurement with ALADIN



Principle of spectrometer für molecular signal



principle of spectrometer für aerosol signal

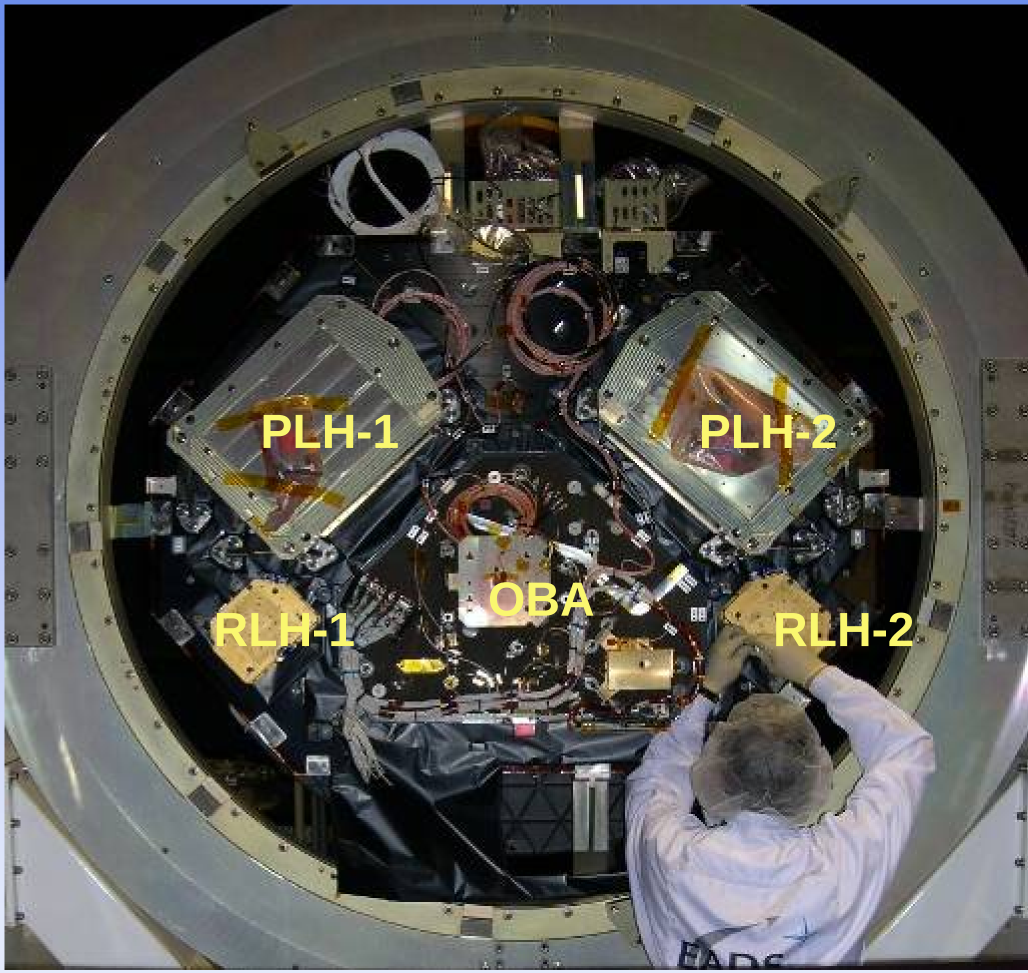


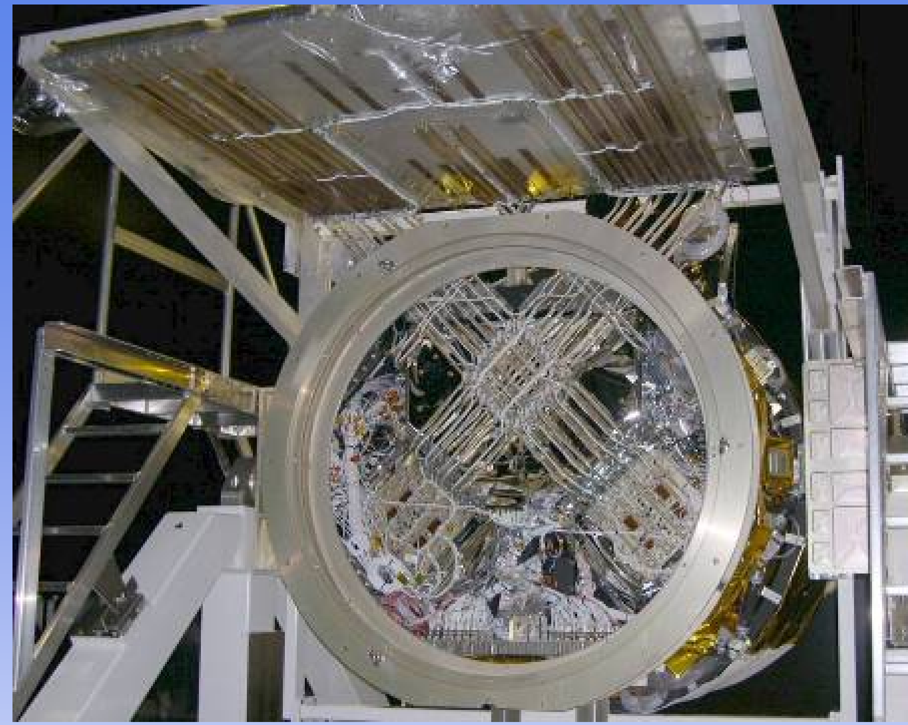
Atmospheric LAser Doppler INstrument ALADIN

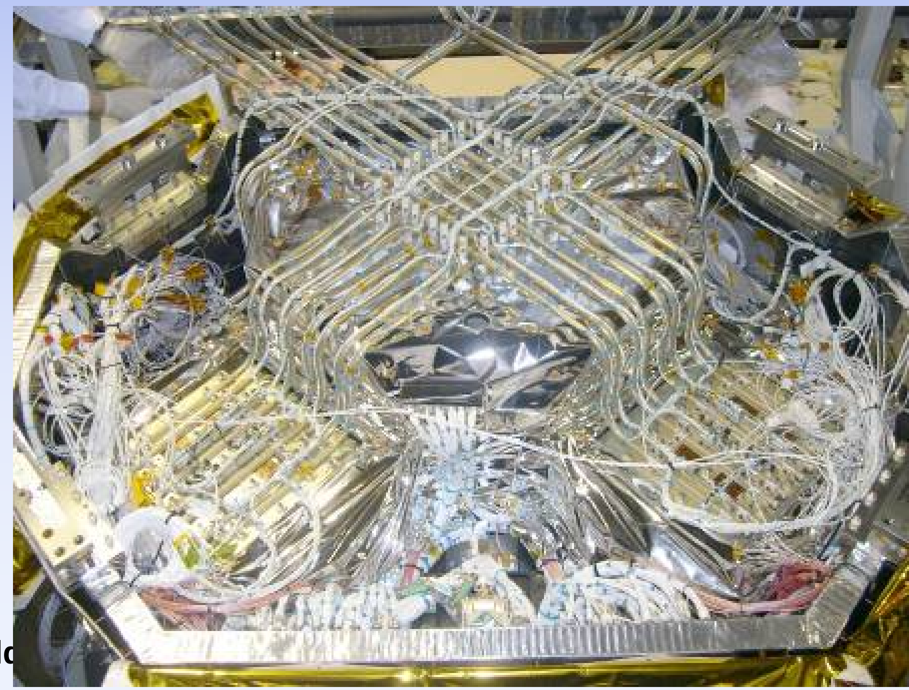
- Direct-Detection Doppler Lidar at 355 nm with 2 spectrometers to analyse backscatter signal from molecules (Rayleigh) and aerosol/clouds (Mie)
- Double edge technique for spectrally broad molecular return, e.g. NASA GLOW instrument (Gentry et al. 2000), but sequential implementation
- Fizeau spectrometer 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

Aeolus Structure Model Acoustic and Shaker Test 2005

ALADIN OSTM (left) and Laser Radiator (right)

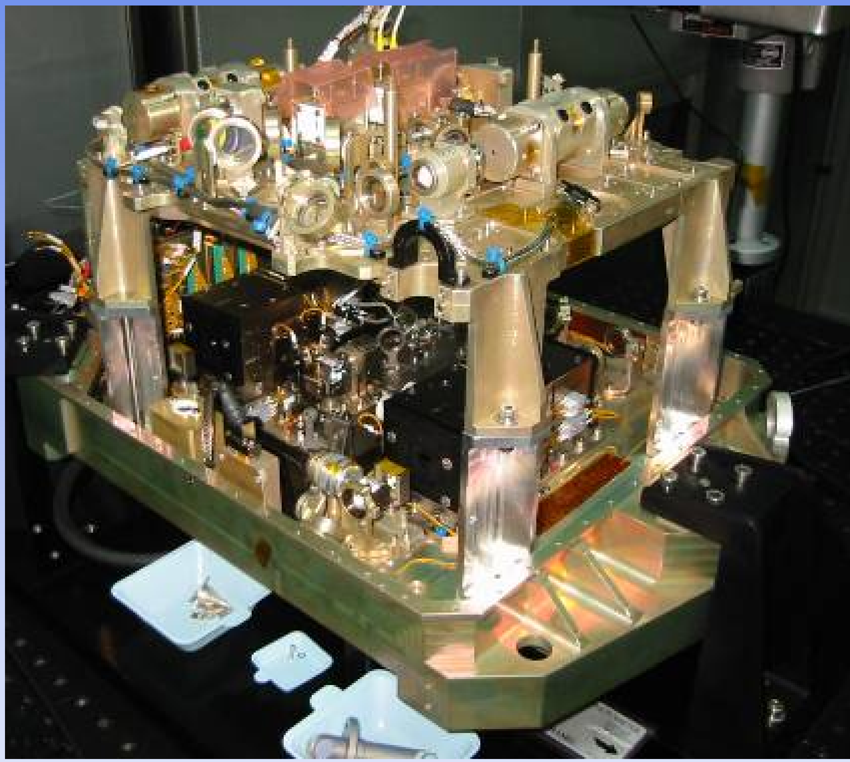




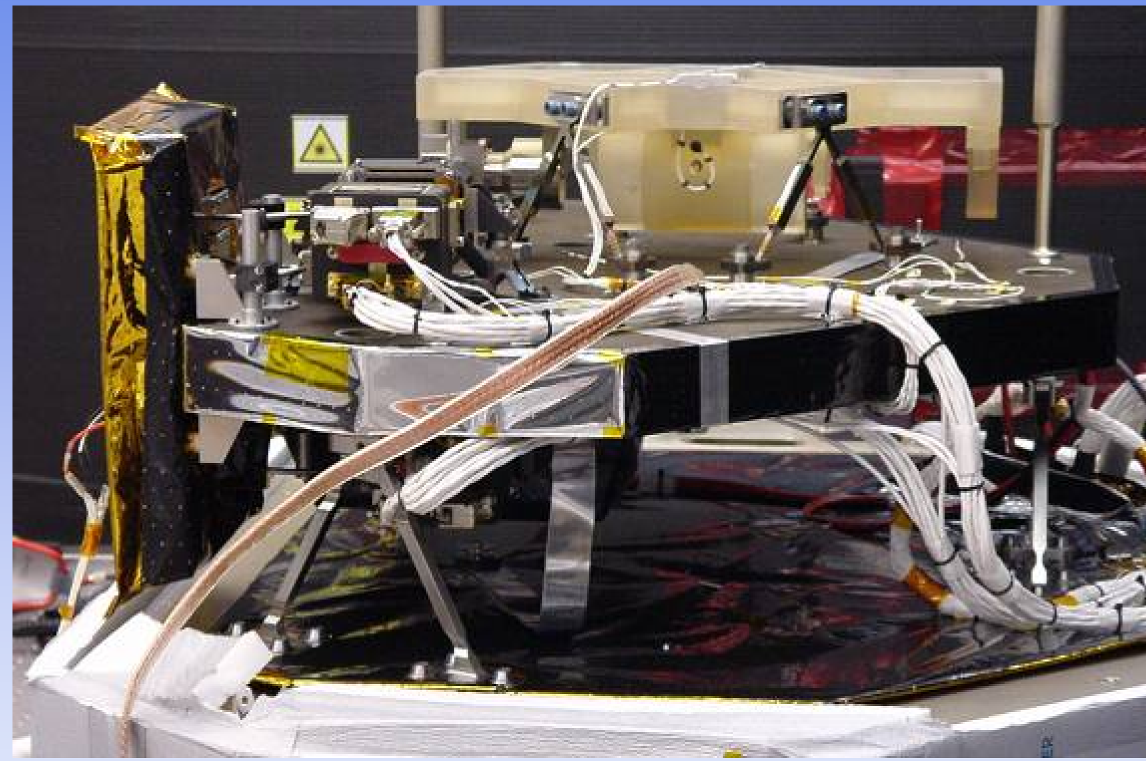


Optical Structure Thermal Model (OSTM), Power Laser Head (PLH), Reference Laser Head (RLH) Optical Bench Assembly (OBA)

ALADIN Laser and Optical Receiver



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

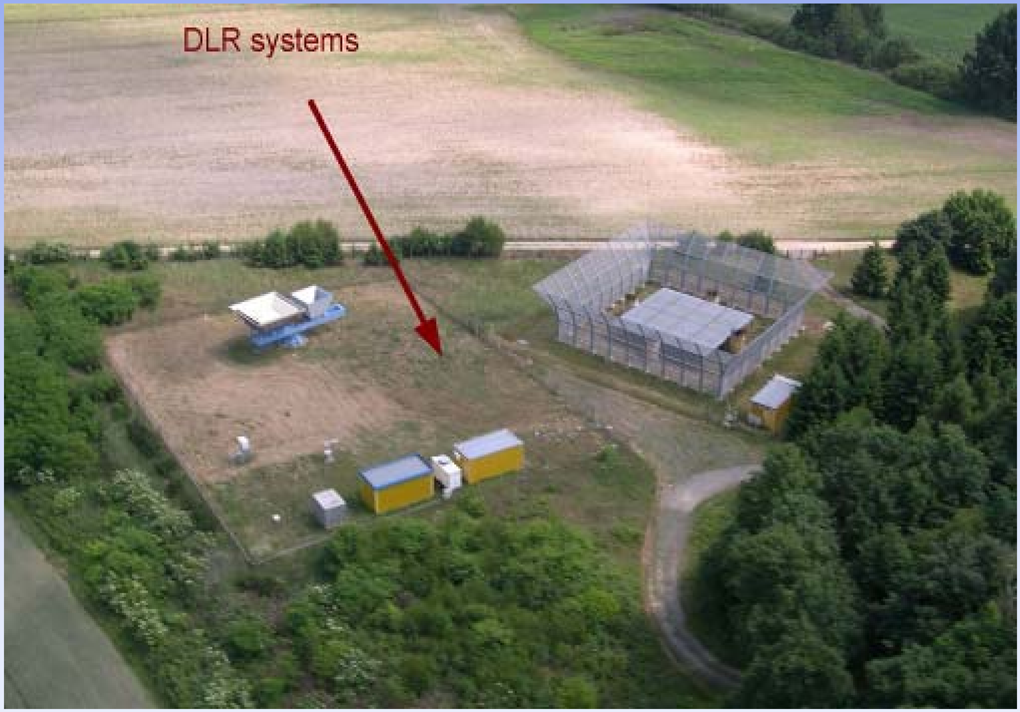
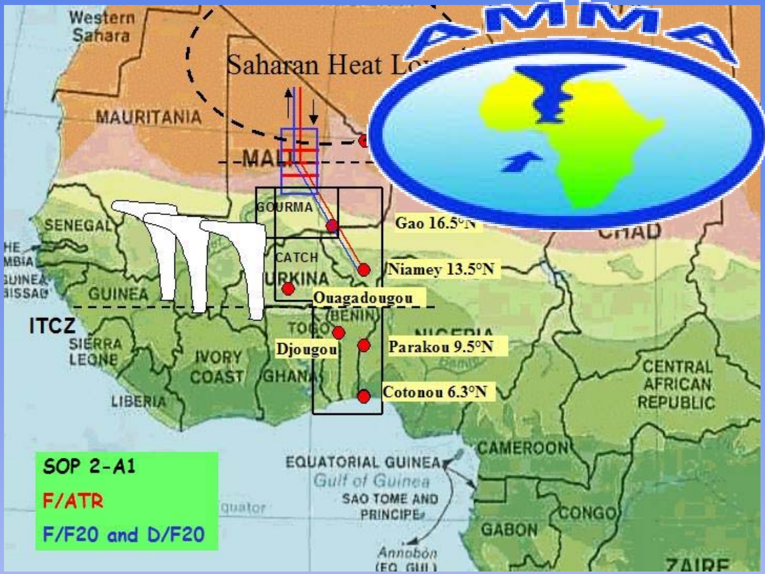


Fig. Volker Lehmann (DWD)

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

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: H_2O-DIAL and 2-µm Doppler lidar on Falcon in June-Aug 2007

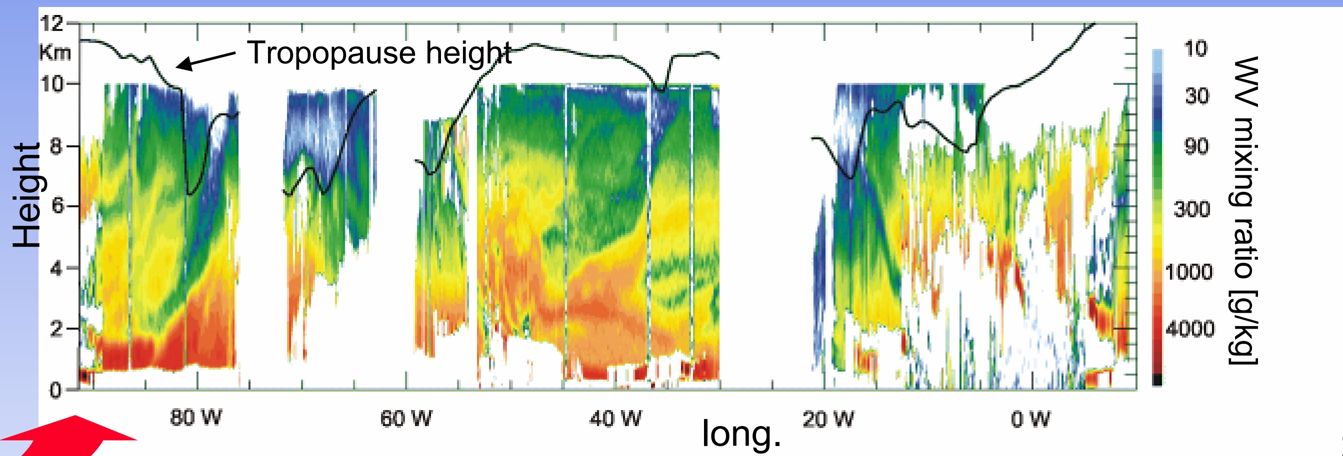
- Interest in involvement in THORPEX Pacific-Asian Regional Campaign PARC in 2008, but funding open

- New Gulfstream G550 aircraft HALO at DLR operational in 2009

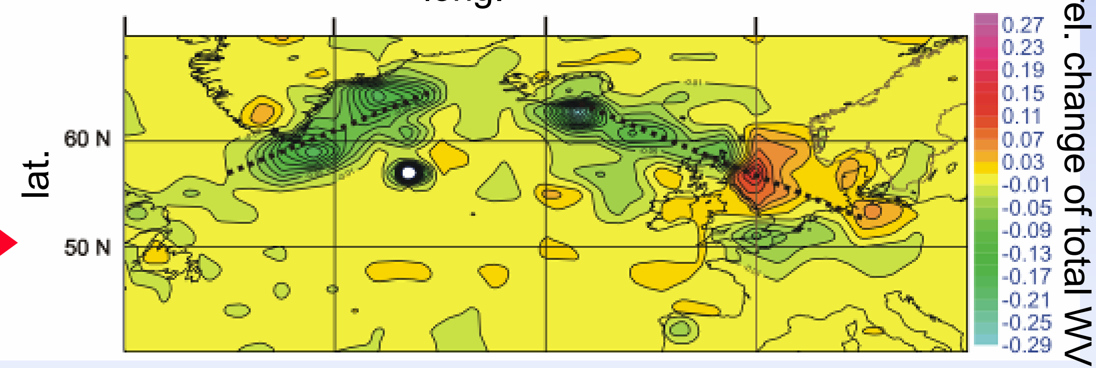
First Assimilation of Water Vapor Observations

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 H_2O-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 H_2O-DIAL data into T511 global ECMWF model (Elias Holm, ECMWF, Reading)

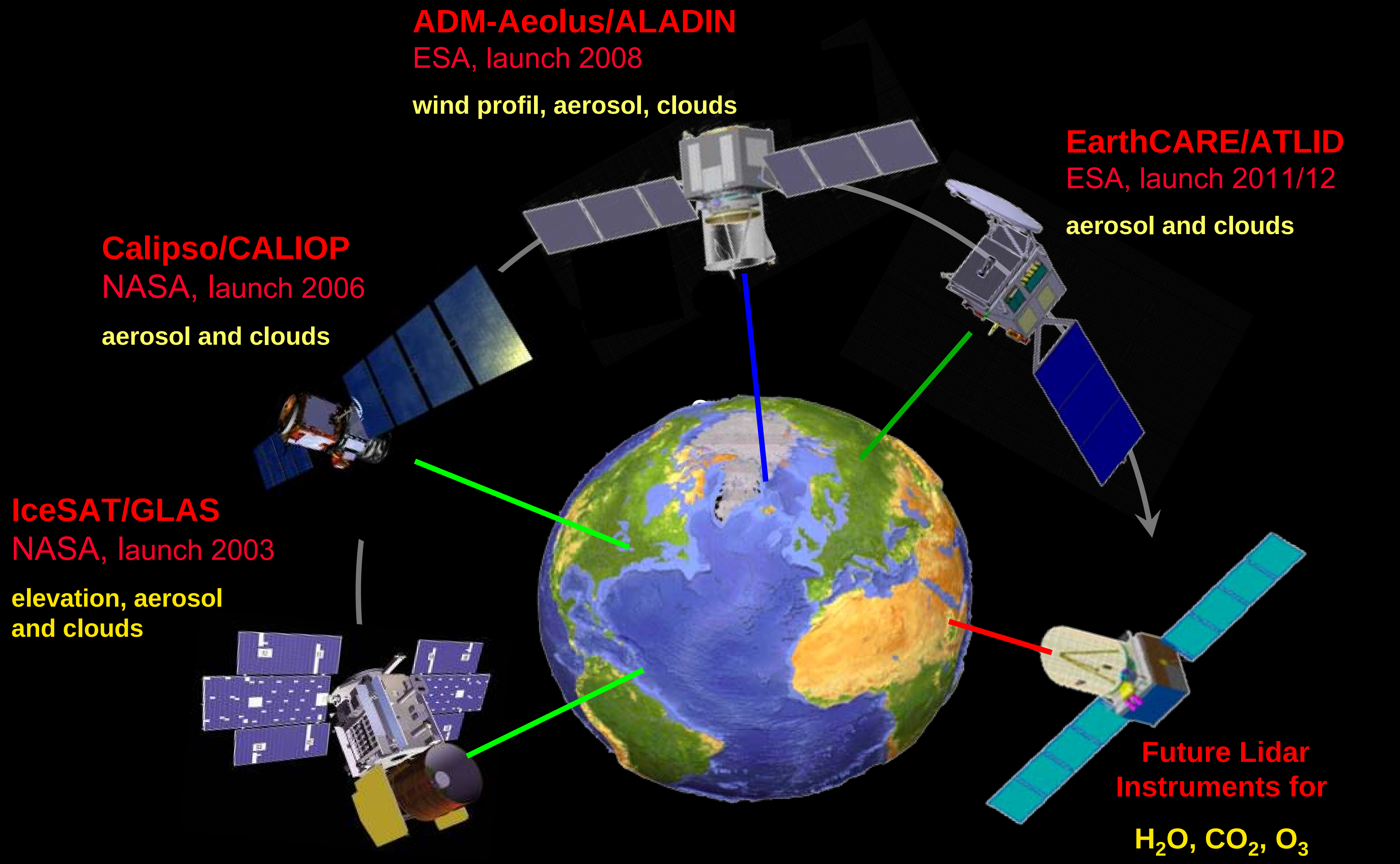


relative change of 12 h forecast error of total water vapour over the North Atlantic

Join the ADM-Aeolus Workshop in September 2006 at ESTEC

further information under www.congrex.nl/06c05

LIDAR Instruments for Earth Observation Missions



Tower of the Winds in Athens