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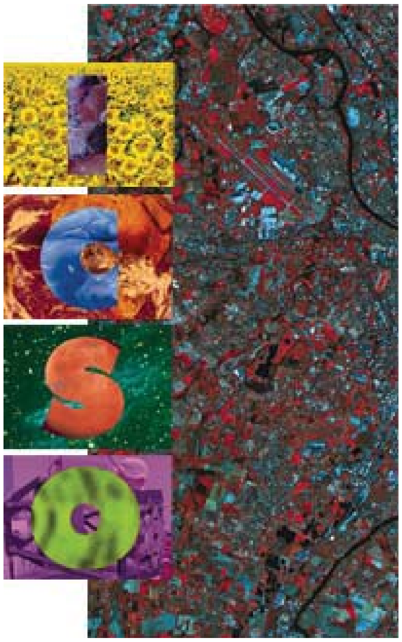

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VALIDATION OF DOPPLER LIDAR WIND MEASUREMENTS WITH THE LOCAL MODEL OF THE GERMAN WEATHER SERVICE

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ABSTRACT *- Doppler lidars measure the range resolved Line-of-Sight (LOS) wind component by extracting the Doppler shift of radiation backscattered from atmospheric aerosols and molecules.The virtual instrument was tested with an existing airborne Doppler lidar to get confidence on the simulation.The local model (LM) of the German Weather Service produced data for all the levels in the atmosphere with the same information as for the global model within a finer grid (7km).*

1 - INTRODUCTION

The purpose of the project WIND (**W**ind **IN**frared **D**oppler lidar) is the development of an airborne CO_2 Doppler lidar in French-German cooperation by CNRS/CNES and DLR [Wern 00]. The project is characterized by two objectives: The first one is to make a significant contribution to mesoscale meteorology by investigation of phenomena, like the orographic influence on atmospheric flows, the land-sea interaction, the dynamics of convective and stratiform clouds, and the transport of humidity. That defines the requirements on spatial resolution of 250 m in height, with a grid size of 10 x 10 km, and on velocity accuracy of 1 m/s for the horizontal wind component. The second objective is to act as a precursor for spaceborne projects, as currently foreseen in Europe, in the frame of the ESA Atmospheric Dynamics Mission Aeolus (Atmospheric Explorer for Observations with Lidar in Ultraviolett from Space) for global wind measurements. It allows to gather experience, both with components and algorithms, and with procedures, like the assimilation of flow models or the synergism of different sensors. For these cases, the accuracy for a single LOS component has to be 1m/s in range gates with high SNR (high backscatter, no speckle losses) and up to 3 m/s in low SNR regions.
Airborne Doppler lidars were used in the past [Bilb 78], [Bilb 84], [McCa 88], and are applied also as precursor experiments for spaceborne application of the technique [Roth 98]. During the development of the WIND instrument a cw-CO_2 laser Doppler anemometer [Rahm 95] was tested to get the first information on position accuracy . With the system described here the conical scanning is the new technique compared to the existing systems [Targ 96], [Vaug 87] .

A virtual instrument was developed to simulate LOS wind measurements by flying virtually over the atmosphere. The atmosphere contains all components which influences the lidar, i.e. wind, turbulence, aerosols, clouds etc. For a selected time period a data set of the atmospheric conditions was provided by the German Weather Service.
A virtual sensor and its environment can be tested directly and can therefore optimised without hardware development. The new ALIENS (Atmospheric Lidar End-to-End Simulator) contains a lot of modules [Stre 99]. A lidar system is defined with its laser wavelength, pulse shape and power, transceiver characteristics etc. A platform like the aircraft, a satellite or a ground based station can be chosen with its parameters. The atmosphere is acting as source (wind, clouds, molecule and aerosol

parameters) and as passive part for its role in extincting and scattering the optical beam. Different shots into the same atmosphere lead to different return signals based on the random distribution ofthe scatterers. The atmosphere is divided into slices of height intervals (1.5 m as lowest value).

The optical signal is specular. Speckle result from destructive and constructive interference of waves, scattered by randomly distributed particles. Due to the stochastic simulation, temporal and spatial speckles appear in the signal. For the coherent instrument, the signal field generation is followed by optical mixing with the local oscillator field on the detector. This was performed by the module AGNA (additive Gaussian noise approximation) which has been formerly developed by the TU Vienna [Winz 97]. The next specs are digitisation and signal processing. A number of different estimators like Pulse Pair (PP) or Maximum Likelihood (ML) can be selected. The result of the simulation is the comparison of calculated wind profile with the input wind field.

The virtual instrument is attached to the local wind field and produce data like in the global case. The flying virtual instrument scans as a real Doppler lidar with all the parameters like chirp and aerosol content. One can compare simulated signals with the measured signals. Results will be presented.

2 - WIND INSTRUMENT

2.1 - Principle of operation

Figure 1 shows the measuring principle.

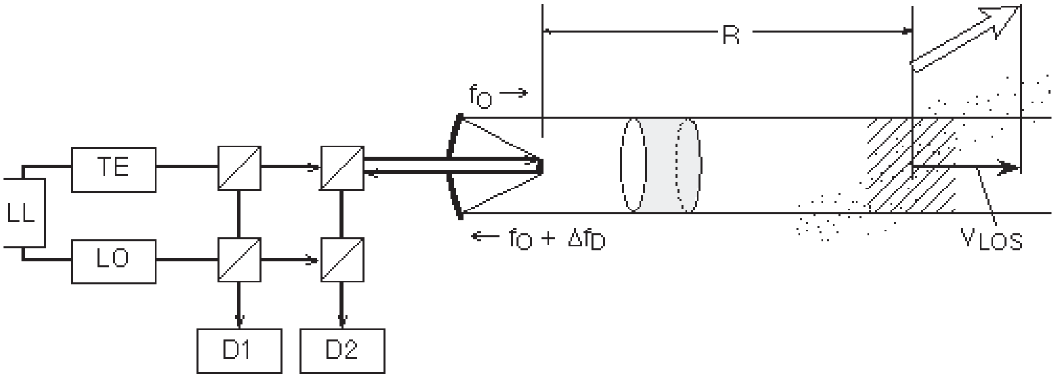


Fig. 1: Schematic of the coherent Doppler lidar.

A coherent Doppler lidar consists in principle of a pulsed, frequency-controlled laser transmitter (TE laser), a transmit and receive telescope, heterodyne detectors (D_1 and D_2) where the local oscillator radiation (LO) is mixed with outgoing pulse (D_1) and with the Doppler-shifted backscattered signal (D_2), and a signal processing system. A locking loop connects both lasers (LL). The laser pulse with a pulse length of a few microseconds and an optical carrier frequency f_0 is sent out via the transceiver telescope into the region of investigation. Some of the radiation is backscattered by small aerosol particles which move with the prevailing windspeed through the laser focus volume[9] . The single scattering lidar equation is used

$$P_r(R) = P_t \frac{A}{R^2} \beta(R) \tau^2 \tag{1}$$

with	$P_r(R)$	the received power at the detector
	P_t	the transmitted laser power
	A	the receiver area
	R	range
	ß(R)	backscatter coefficient at range R
	t^2	atmospheric transmission.

The windshifted Doppler frequency directly determines the line-of-sight (LOS) component (V_{LOS}) of the wind vector. At CO_2 laser wavelengths (l) of around 10.6 mm a velocity component of 1 m/s corresponds to a frequency shift, Δf_D of 189 kHz.This is obtained from the equation

$$\Delta f_D = 2\frac{V_{LOS}}{c} \cdot \ f_c \tag{2}$$

where c is the speed of light and f_0 is obtained from f = c/l.
By measuring at an azimuth angle q and an elevation angle j one gets a radial contribution V_{LOS} which depends on the wind vector components u, v, and w given by

$$V_{LOS} = u \sin\theta \cos \varphi + v \cos\theta \cos \varphi + w \sin\varphi \tag{3}$$

Caused by the aircraft speed, the Doppler shift Df_d contains mainly the contribution of the aircraft. For a ground based system one can determine the wind vector by sine-wave-fitting of eq.**3**. For the airborne system the aircraft component has to be removed before.

$$V_{LOS} = V_{LOS}\,(\text{wind component}) + V_{LOS}\,(\text{aircraft component}) \tag{4}$$

Figure 2 shows the situation for both systems, the ground-based one and the airborne one for a wind speed of about 10 m/s.

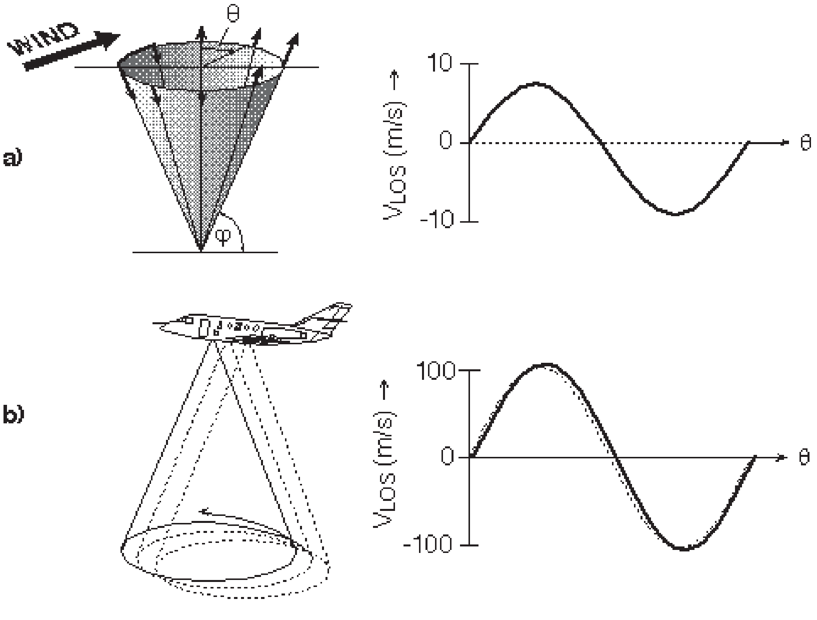


Fig. 2: Principle of ground-based and airborne conical scans.

In figure 2 it assumed that the wind has the same direction as the aircraft. For the ground-based system (fig 2a) the sine wave fitting gives 3 wind components u, v and w directly (eq.**3**). For the airborne system (fig.2b) the wind component is a minor contribution, the dashed curve is the sum of aircraft velocity contribution and wind (eq. 4), the solid curve is the aircraft contribution only. An exact aircraft data system is required to remove this influence.

3 - VIRTUAL INSTRUMENTS FOR WIND PROFILE MEASUREMENTS

LabVIEW (© National Instruments) provides a powerful instrumentation system for simulations, including an excellent graphical presentation environment and a graphical programming language G. A virtual sensor and its environment can be tested directly and can therefore optimised without hardware development.

The new ALIENS (Atmospheric Lidar End-to-End Simulator) contains a lot of new modules. Figure 3 shows a block diagram of the main modules.

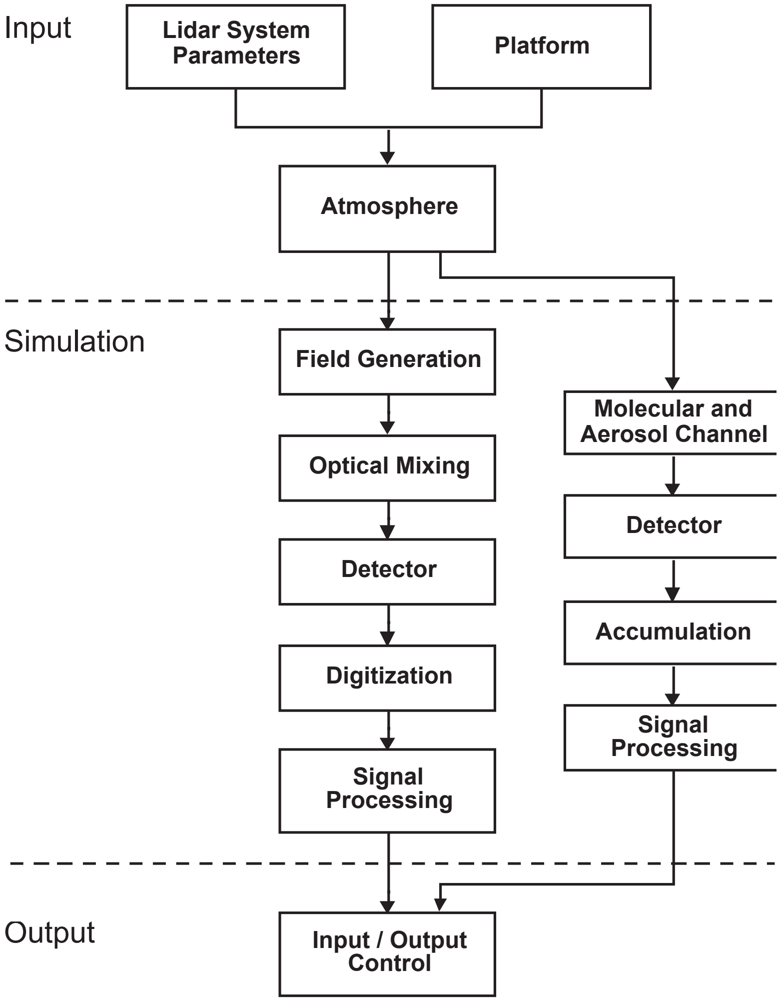
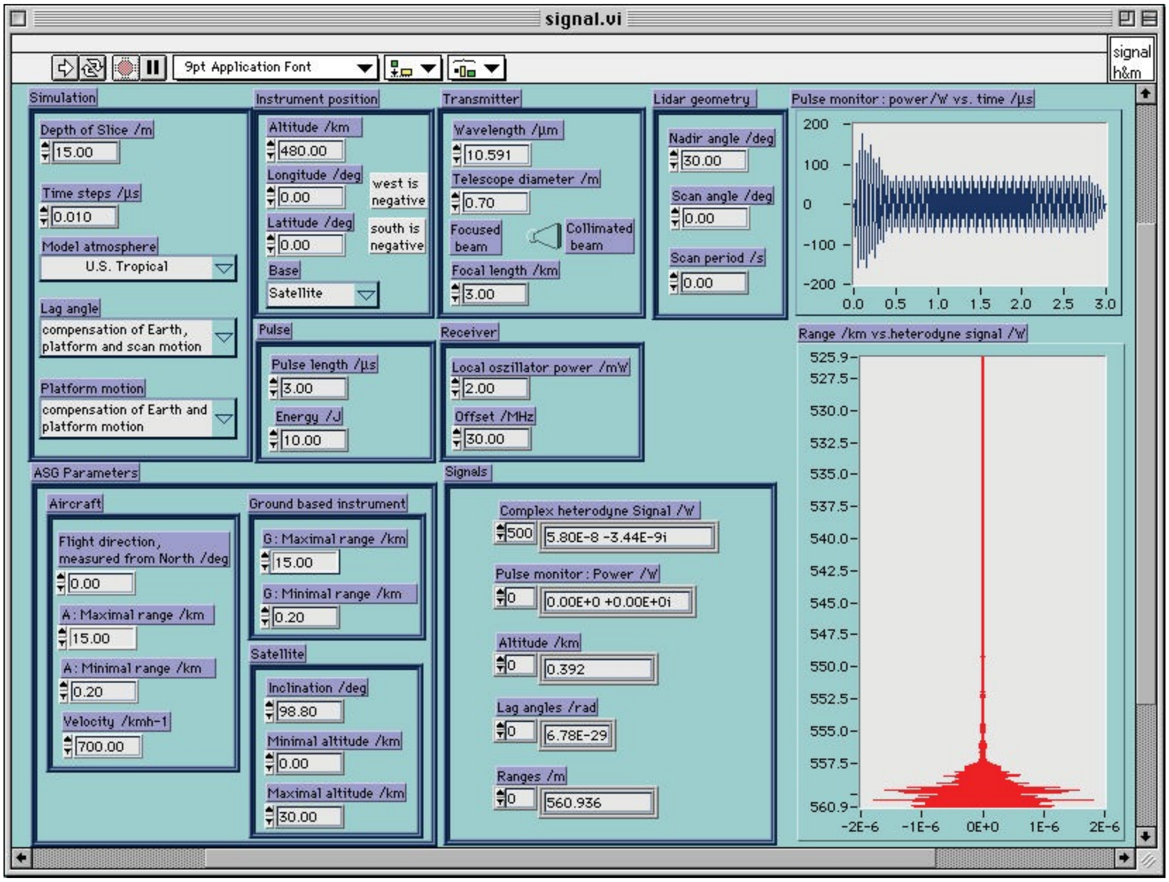


Fig. 3: Scheme of the virtual instrument simulation program ALIENS for coherent detection (left column) and IALIENS for direct detection (right column).

A lidar system is defined with its laser wavelength, pulse shape and power, transceiver characteristics etc. A platform like the aircraft, a satellite or a ground based station can be chosen with its parameters (see for example figure 4). The atmosphere is acting as source (wind, clouds, molecule and aerosol parameters) and as passive part for its role in extincting and scattering the optical beam. Different shots into the same atmosphere lead to different return signals based on the random distribution of the scatterers. The atmosphere is divided into slices of height intervals (1.5 m as lowest value). In contrast to previous lidar simulation tools which provide deterministic return signals, the current software package generates a stochastic signal. That means, two shots into the same atmosphere lead to different return signals due to the random distribution of the scatterers.

The theory behind our program is based on an atmospheric model that divides the atmosphere into small horizontal layers. Such a layer can be regarded as a rough surface, producing a signal modelled via joint-Gaussian random variables. The standard deviation of this Gaussian random variable is determined by the atmospheric backscatter coefficient, the atmospheric transmission, the depth of the

layer, the wavelength and the telescope diameter. The result is a signal involving temporal speckles due to interference and changing from shot to shot even through the same atmosphere.
The optical signal is specular. Speckle result from destructive and constructive interference of waves, scattered by randomly distributed particles. Due to the stochastic simulation, temporal and spatial speckles appear in the signal.



Simulation
Depth of Slice /m 15.00
Time steps /µs 0.010
Model atmosphere U.S. Tropical
Lag angle compensation of Earth, platform and scan motion
Platform motion compensation of Earth and platform motion

Instrument position
Altitude /km 480.00
Longitude /deg 0.00 west is negative
Latitude /deg 0.00 south is negative
Base Satellite

Transmitter
Wavelength /µm 10.591
Telescope diameter /m 0.70
Focused beam Collimated beam
Focal length /km 3.00

Lidar geometry
Nadir angle /deg 30.00
Scan angle /deg 0.00
Scan period /s 0.00

Pulse
Pulse length /µs 3.00
Energy /J 10.00

Receiver
Local oszillator power /mW 2.00
Offset /MHz 30.00

ASG Parameters
Aircraft
Flight direction, measured from North /deg 0.00
A: Maximal range /km 15.00
A: Minimal range /km 0.20
Velocity /kmh-1 700.00
Ground based instrument
G: Maximal range /km 15.00
G: Minimal range /km 0.20
Satellite
Inclination /deg 98.80
Minimal altitude /km 0.00
Maximal altitude /km 30.00

Signals
Complex heterodyne Signal /W 500 5.80E-8 -3.44E-9i
Pulse monitor : Power /W 0 0.00E+0 +0.00E+0i
Altitude /km 0 0.392
Lag angles /rad 0 6.78E-29
Ranges /m 0 560.936

Fig. 4: Front panel of signal. vi, computing the return signal.

Figure 4 shows the front panel with the input and output parameters grouped together in boxes of common relation. The two graphs on the right show the pulse monitor (top, blue), that is the signal of the laser source, and the atmospheric return signal (bottom, red) both in units of optical power versus time or range both modulated in the intermediate frequency band.

For the coherent instrument, the signal field generation is followed by optical mixing with the local oscillator field on the detector. This was performed by the module AGNA (additive Gaussian noise approximation) which has been formerly developed by the TU Vienna [Winz 97]. The next specs are digitisation and signal processing. A number of different estimators like Pulse Pair (PP) or Maximum Likelihood (ML) can be selected. The result of the simulation is the comparison of calculated wind profile with the input wind field.
The direct detection virtual instrument works on two techniques: double edge technique [Chan 89] for the detection of the molecular signal and multichannel Fizeau receiver for the aerosol signal. A detector chain (CCD array) with the relevant errors follows and after that accumulation and wind speed estimation.

The tool further includes:
- satellite/airborne/ground geometry calculations (position, scan pattern)
- arbitrary atmospheric conditions (wind field, backscatter profiles, clouds)
- arbitrary laser source (pulse shape and frequency)

A dynamic version of ALIENS produces signals for a given flight path or satellite track. Special versions exist for multiple telescopes or for an array detector.

4 - COMPARISON WITH EXPERIMENTAL DATA

WIND developed within a common project by CNRS-CNES/DLR is an airborne coherent infrared Doppler lidar for wind velocity measurement. The system is based on pulsed CO_2 laser technology, heterodyne detection and a conical scanning system. Tests and validation measurements of the WIND instrument were done on the ground before integration on aircraft. During December 1998 and April/ May 1999 several field tests totalling several hours of experiments were made at Palaiseau (near Paris) with several weather conditions like clear air, snow and rain. The objective was to retrieve the wind field and to check the instrument performance.

The WIND instrument consists of a transceiver unit and three racks with electronics. Figure 18 shows the drawing of the transceiver. Laser, telescope and scanner are mounted on different frames. These frames were connected via shock absorbers on the seat rails of the aircraft (figure 5).

First technical flights were performed with the DLR Falcon aircraft in June and August 1999. The system was able to measure ground return signal over land and clouds and aerosol signals under various conditions

Routines for correcting flight attitude data from GPS (Global Positioning System) and IRS (Inertial Reference Systeme) with ground return from lidar are currently tested. The aircraft vibrations were successfully damped by the mechanical structure.

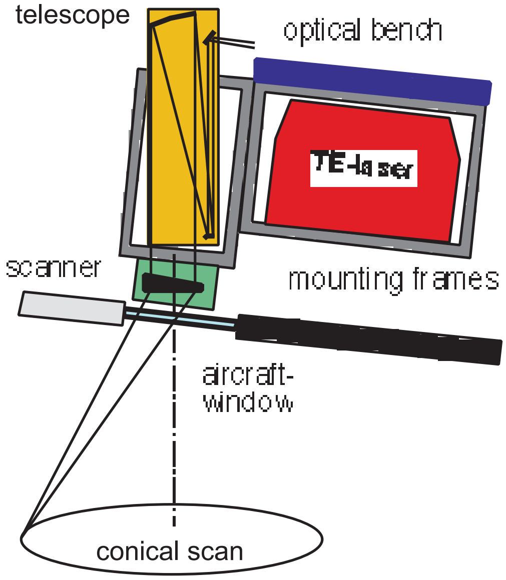


Fig. 5: Installation of the CO_2 Doppler lidar WIND in the Falcon research aircraft.

The validation was performed using the Windprofiler of the Meteorological Observatory Lindenberg and with the forecast model (LM) of the German Weather Service. The flight was performed on October 12, 1999 at 13.30 UTC.

Figure 6 shows the flight path over the Berlin area with Lindenberg.

The local model (LM) of the German Weather Service produced data for all the levels in the atmosphere with the same information as for the global model within a finer grid. Figure 7 shows an example of the wind speed for the level at 8935 m.

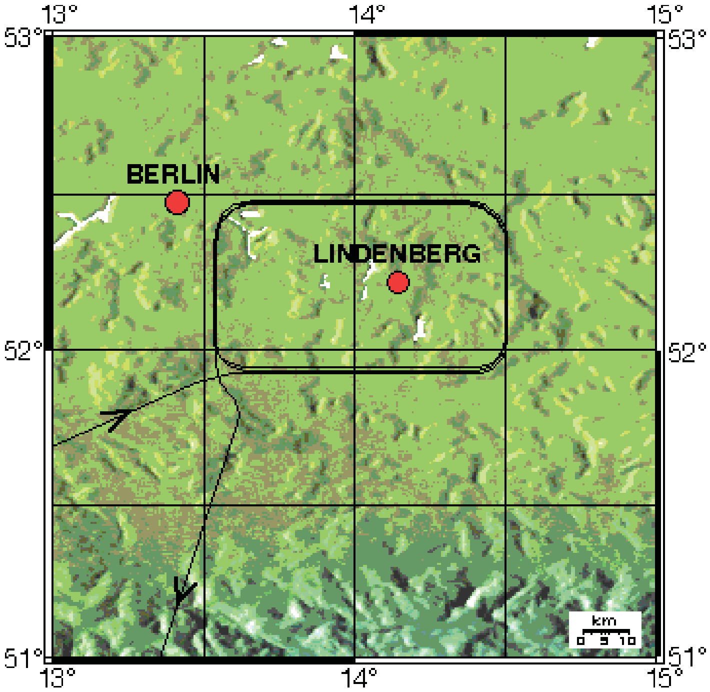


Fig. 6: Flight track over Lindenberg.

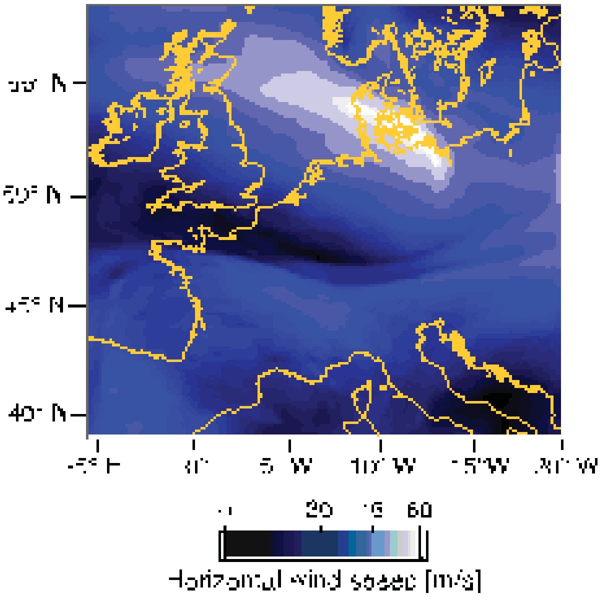


Fig. 7: Wind speed in color scale over Europe from the local model of the German Weather Service for October 12, 13.30 UTC, 8935 m altitude.

For the flight path shown in figure 6 a very strong wind appears in the flight level. The virtual instrument is attached to the local wind field and produce data like in the global case. The flying virtual instrument scans as a real Doppler lidar with all the parameters like chirp and aerosol content. One can compare simulated signals with the measured signals.

Figure 8 shows the result. The WIND data are as full squares. The WIND data are profiles of the horizontal wind accumulated over 5 conical scans (i.e. over 100 seconds measurement time or 10* 50 km grid size close to the ground). The solid curve with the open squares are the virtual data using the profile of the German Weather Service local model (LM) for 13.30 UTC.

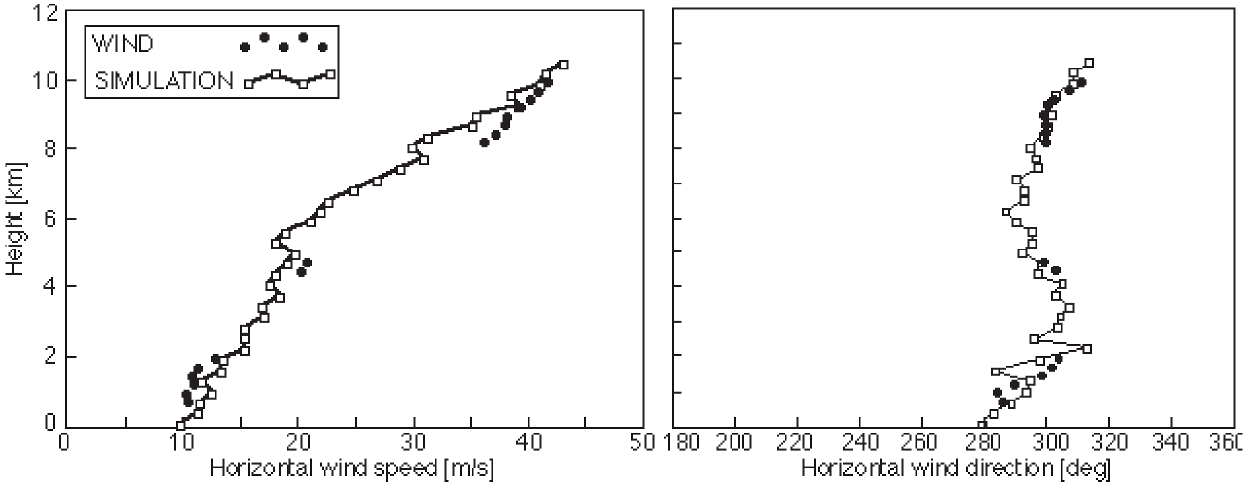


Fig. 8: Comparison of WIND profiles measured with the airborne Doppler lidar WIND with the simulated data using the Local Modelof the weather service.

Figure 9 shows the local model profiles of the wind direction and wind speed for the regions 1 and 2 from figure 6. These profiles are similar to the measurements shown in figure 8. The example shows the very good agreement of model output and measurements. Airborne Doppler lidar systems have to meet at least the same specifications in horizontal resolution and accuracy as the state-of-the-art numerical models.

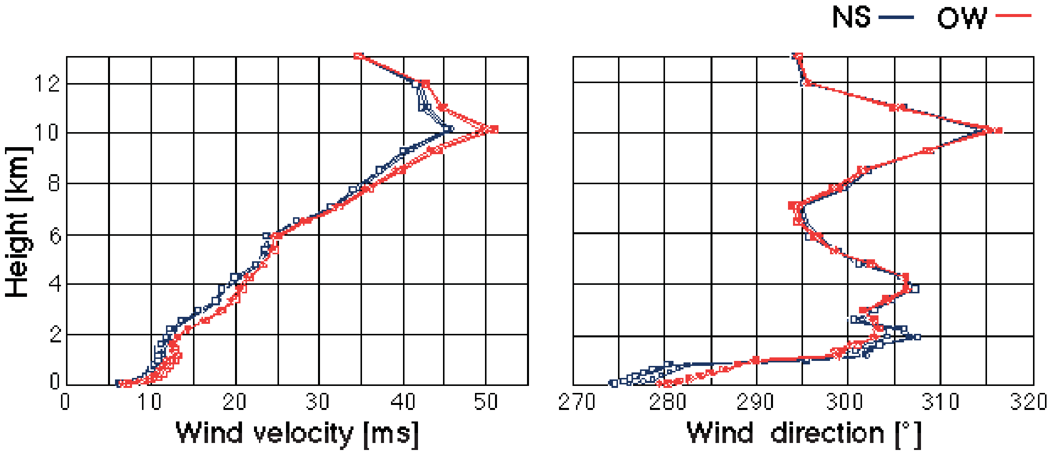


Fig. 9: Local Model wind profiles (wind direction and wind speed) for the regions 1 and 2 from figure 6.

5 - SUMMARY

The new software package provides a powerful and convenient tool for Doppler lidar simulation. All the instrument parameters can be set individually. This software tool can be used to find the optimal lidar parameters for the envisaged application or to interpret lidar results. The single units of the software package, like the processing unit, can even be used separately, for example to process measured Doppler lidar data. The model assumptions of the simulation have been validated comparing real Doppler lidar data from the airborne WIND system, ground observations and local model of the German Weather Service.

An airborne Doppler lidar was developed jointly by CNRS/CNES in France and DLR in Germany. The WIND instrument is a modular and flexible unit to perform airborne measurements of mesoscalic wind phenomena. The accuracy is 1 m/s for the horizontal wind within a volume pixel size of 10 km x 50 km x 250 m in the boundary layer.

By further improvement a resolution of10 km x 10 km x 250 m is envisaged. Also other scanning or non-scanning procedures can be performed for example to deliver single line-of-sight components to simulate a spaceborne Doppler lidar.
A demo version can be found at **http://kraftwerk.oe.op.dlr.de** either for Macintosh PowerPC (aliens.sit.bin) or Windows 95/NT (aliens.zip) operating system.

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