Combined wind & aerosol/cloud measurements with coherent Doppler LIDARs for operational networks

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Key specifications of Doppler LIDARs

Figure of Merit:
- Allows to compare different lidars or different configurations. It allows to classify LIDAR sensitivities, independently of atmospheric parameters.
- \( \text{WINDCUBE7v2} \sim 5.6 \times 10^{-12} \)
- \( \text{WINDCUBE200S} \sim 3.39 \times 10^{-10} \)

\[ FOM = \eta E T_p A \sqrt{f_{PRF}} \]

- Range resolution
- Maximum operational range
Key specifications of Doppler LIDARs

- **Range resolution:**
  - Is defined as the Full Width Half Maximum (FWHM) of the averaging kernel
  - For pulses and weighted range gates
    - Squared

\[ \Delta R = \frac{c}{2} \sqrt{\tau^2 + tm^2} \]
Data processing chain

Level 0
Temporal data

Level 1
Spectra
Signal to Noise Ratio
Radial windspeed
Dispersion

Level 2
Horizontal wind speed
Wind direction
Turbulence
Windshear
Aerosol/cloud related data
Numerous validations at reference independent sites (DTU, DEWI, Deutsche WindGuard...) against cup anemometers

Accuracy is 0.1 m/s on windspeed and 2° on wind direction
New aerosol/cloud features

- Aerosol/cloud layer detection and discrimination
- Planetary Boundary Layer height detection
- Attenuated backscatter coefficient retrieval
- Mass concentration estimation (still in progress)
Aerosol/cloud layer detection
Detection of layers using CNR gradients

Step 1: filtering and gradient calculation

Step 2: Automatic gradient segmentation (iterative OTSU method 1979)

Step 3: Base and top detection

Aerosol/cloud layers detection

Principle
Aerosol/cloud layers detection

Validation

Comparison with a reference database

\[ CSI = \frac{\text{good detection}}{\text{good detection} + \text{misdetection} + \text{false alarm}} \]

Reference Algorithm results
73% with less than 10% relative error
Detection capabilities

Need to adjust SNR thresholds defined for wind measurements for clouds/aerosols detection

Scenario | ds | dt
---|---|---
LOS | 50m | 1s

CNR without filtering

CNR threshold = -27dB

CNR threshold = -28dB

CNR threshold = -29dB

CNR threshold = -30dB

CNR threshold = -31dB
PBL detection

- Free troposphere
- Residual layer
- Convective layer
- Stable layer

Sunset - Sunrise
Planetary boundary layer height

Principle of the detection

Residual layer
- Signal reflectivity
- Gradient
- Gradient mask
- Residual layer detection

Mixing layer
- Vertical wind speed
- Variance of the vertical wind speed
- Binarisation of the variance image
- Mixing layer height

Threshold 0.2 m/s
[Bianco et al, 2013]
PBL height detection

Validation

Comparison with database from various campaigns

Vertical pointing measurements ($\Delta z = 25\text{m}$, $\Delta t=2\text{min}$)

PBL height detection with a relative error <20%:
- 94% for the residual layer
- 78% for the mixing layer
Attenuated backscatter coefficient
Attenuated backscatter coefficient

Principle

Carrier-to-Noise Ratio (CNR)

Relative attenuated backscatter coefficient

\[ CNR(z) = K \cdot F(z) \cdot \beta(z) e^{-2 \int_0^z \alpha(r)dr} \]

\[ \beta_{rel,att}(z) = K \cdot \beta(z) e^{-2 \int_0^z \alpha(r)dr} \]

Automatic calibration is performed with low elevation PPI

Lorentzian shape with 4 parameters:

\[ F(z) = y_0 + \frac{2A}{\pi} \cdot \frac{w}{4(z-z_0)^2 + w^2} \]
Comparison of WINDCUBE200S attenuated backscatter coefficient @1540nm with R-MAN510 absolute backscatter coefficient @ 355nm

Relative attenuated backscatter @ 1540 nm WINDCUBE200S \([\log_{10}(m^{-1}.sr^{-1})]\)

Absolute backscatter @ 355 nm R-Man\(_{510}\) \([\log_{10}(m^{-1}.sr^{-1})]\)
Building networks of Doppler LIDARs
Why building networks of LIDARs?

Enhance observation networks with Doppler LIDARs

1. To improve the « weather » monitoring

Wind hazards: Severe weather, Wind Shears,
Aerosol hazards (plumes dispersion): Air pollution, Mining,
industrial risks
Why building networks of LIDARs?

Enhance observation networks with Doppler LIDARs

2. To improve weather nowcasts / forecasts

- Area of interest?
  - Surface / Ekman Layers (up to 200m / 500m)
  - Boundary Layer (up to 1 – 2km)
  - Troposphere (up to XX km)?

- Spatial and temporal Scales of the met phenomena
  - 10’, 2’?

- Quantities to measure?
  - Averaged Wind Speed / Direction
  - Turbulence (tke?)
  - Detection of Cloud / Aerosol layers ?
  - Backscatter profiles?

- Data of interest for the models?
  - Define accuracy, resolution of required observations
Technical constraints for the LIDARs in networks

- Reliable (MTBF, MTTR)
- Design to maintenance / to cost
- Tracability of the system during its entire life

Calibration / verification process → Consistency of the data for each system
- Determine accurately noise level
- Calibrate frequency offset
- Calibrate the correspondence between temporal signal and range gates
- Verify the accuracy of wind speed against a reference LIDAR
UFO Project: Assimilation of LIDAR data into HARMONIE Model

- Set-up of Harmonie model domain for Toulouse
  - 1km resolution: 500 x 500 grid points
  - Calculation of Model background error Characteristics
  - observations assimilation (area 400x400 grid points)
  - Preprocessing set up for UFO observations
    - Radar/Lidar Scanners and Profilers
    - TUBS aircraft data and Mode-S EHS data
- Mode S EHS & MRAR versus HIRLAM

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<thead>
<tr>
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<th>Nestor</th>
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<tbody>
<tr>
<td>Grid</td>
<td>200x200 5km</td>
<td>500x500 1km</td>
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<tr>
<td>Cycle</td>
<td>3 hours</td>
<td>1 hour</td>
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<tr>
<td>Lateral boundaries</td>
<td>ECMWF hourly</td>
<td>Nestor 15 min</td>
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<tr>
<td>Observations</td>
<td>Temp/aircraft/ synop</td>
<td>Temp/aircraft/ synop</td>
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<tr>
<td>Assimilation</td>
<td>3DVAR 3 hour window</td>
<td>3DVAR 1 hour window</td>
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</tbody>
</table>

Courtesy of S. De Haan / KNMI
UFO Project: Assimilation of LIDAR data into HARMONIE Model

Experiments

Conventional obs MF: coMFhr
+ Mode-S MRAR : mra
+ LeoSphere WindcubeV2: vlmr
+ LeoSphere 3D wind observations

Requires additional QC

Comparison with WindCubeV2

![Wind speed comparison chart]

Wind speed bias is reduced in the first 2 hours

Wind speed bias: best performance
Positive impact on wind speed standard deviation in the first hour

Contribution of S. De Haan / KNMI
Weather monitoring and forecasting

LIDAR networks

http://www.nysmesonet.org/

125 standard sites
15 sites equipped with LIDAR Profilers & RADIOMETERS

> 100 000 km² - PBL profilers < 5 000 km² - covering typically a Megapole area -

Long range scanning LIDARs

Weather monitoring and forecasting

LIDAR networks

~1700 LIDARs needed!
Conclusion / Perspectives

- Coherent doppler lidars are used operationnally in many applications:
  - Wind energy, aviation weather, air quality, weather & climate...

- Proven accuracy of the radial and reconstructed wind measurements (like in DBS mode)

- Aerosol / cloud features can be retrieved from Doppler LIDARs
  - Should be evaluated within TOPROF research working group: cloud base, backscatter; PBL

- Long term assimilation of Doppler LIDAR data should be performed in TOPROF to evaluate the improvements of local weather forecasts
Current LIDAR products
Questions ?
Backup slides
A suite of atmospheric parameters

Wind
Radial Wind Speed
Vertical wind speed
Horizontal wind speed
Wind direction

Turbulence
Turbulence intensity (TI)
Turbulent Kinetic Energy (TKE)

Aerosol/Clouds
Structures
Backscatter profile
Choice of the wavelength of 1.5µm (NIR)

At 1.5µm:
- Availability of reliable laser sources
- High power Lidars are eye safety
- Transmission of lidar signal in atmosphere is very efficiency
Benefits of fiber technology

Why are we using fibers?

- For guiding the light: avoid disalignment
- For amplifying the light: low consumption and reliable laser diodes

- Used of reliable optronic components of mainstream telecommunication market ➔ Low cost, reliable and compact architecture
- Flexible architecture that allows to adjust
  - Pulse Repetition Frequency (ie. Power) ➔ Measurement Range
  - Pulse length ➔ Spatial resolution
Long Range Scanning LIDARs

- A 6 months trial has been performed in Palaiseau, France in 2014
  - Determine ranges for clear air conditions (visibility >10km, no rain) following the recommendations of ISO working groups on Doppler LIDARs
  - Assess the impact of weather conditions on range

Measurements performed with a Scanning LIDAR
  - WINDCUBE400S

<table>
<thead>
<tr>
<th>Availability</th>
<th>Availability</th>
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<tbody>
<tr>
<td>80%</td>
<td>50%</td>
</tr>
<tr>
<td>Range</td>
<td>9km</td>
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Long Range Scanning LIDARs

- LIDARs measure at nominal performances in clear air conditions, i.e., above 10km of visibility and with no rain.
- For an all weather observations system, LIDAR must be coupled with RADAR.
Short range LIDAR profiler

- Operations in DBS Mode
- One sequence performed every 4s
- Worldwide 500 units are deployed

<table>
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<th>Measurements</th>
<th>Performances</th>
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<tr>
<td>Range</td>
<td>40 to 290m</td>
</tr>
<tr>
<td>Number of heights</td>
<td>12</td>
</tr>
<tr>
<td>Data sampling rate</td>
<td>1s</td>
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<tr>
<td>Speed range</td>
<td>0 to 60 m/s</td>
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3 wind components (u,v,w)
Range resolution

\[ D = \frac{c \cdot t_1}{2} \]

Distance

\[ \frac{c \cdot t_1}{2} \]

\[ D = c \cdot t \]

\[ D = -c \cdot t \]

Time

0

t_1
Range resolution

If pulse is very short, spatial resolution is

\[ \Delta R = \frac{c \cdot tm}{2} \]
Range resolution

If pulse is square, range resolution becomes:

\[ \Delta R = \frac{c}{2} \sqrt{\tau^2 + tm^2} \]
Long Range Scanning LIDARs

- Deployment during 3 months of a WINDCUBE200S at the certification test site in Denmark
- Objectives: To evaluate accuracy (mean difference) and precision (RMSE) of radial wind speeds and horizontal wind speeds

\[ y = 0.99x - 0.18 \]
\[ R^2 = 99.7\% \]

\[ \mu = 0.09 \text{ m/s} \quad \text{RMSE} = 0.27 \text{ m/s} \]
Why building networks of LIDARs?

Source ON THE KINETIC ENERGY SPECTRUM NEAR THE GROUND, A. OORT and A. TAYLOR, MONTHLY WEATHER REVIEW, VOLUME 97, NUMBER 9, SEPTEMBER 1969