Highly resolved measurements of atmospheric turbulence with the new 2d-Atmospheric Laser Cantilever Anemometer

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Abstract.

For the investigation of atmospheric turbulent flows on small scales a new anemometer was developed, the so-called 2d-Atmospheric Laser Cantilever Anemometer (2d-ALCA). It performs highly resolved measurements with a spatial resolution in millimeter range and temporal resolution in kHz range, thus detecting very small turbulent structures. The anemometer is a redesign of the successfully operating 2d-LCA for laboratory application. The new device was designed to withstand hostile operating environments (rain and saline, humid air).

In February 2012, the 2d-ALCA was used for the first time in a test field. The device was mounted in about 53 m above ground level on a lattice tower near the German North Sea coast. Wind speed was measured by the 2d-ALCA at 10 kHz sampling rate and by cup anemometers at 1 Hz. The instantaneous wind speed ranged from 8 m/s to 19 m/s at an average turbulence level of about 7%.

Wind field characteristics were analyzed based on cup anemometer as well as 2d-ALCA. The combination of both devices allowed the study of atmospheric turbulence over several magnitudes in turbulent scales.

1. Introduction

In wind turbine applications and site assessment, the wind velocities are measured by cup anemometers. These are well known and were intensively studied, even if disadvantages are accepted [1]. Their typical sampling rate is 1 Hz; this is sufficient to detect the turbulence on scales of a few meters according to Taylor’s frozen turbulence hypothesis. Ultrasonic anemometers typically have sampling rates of about 30 Hz and allow the detection of turbulent eddies with a size of a few decimeters. A new technology is currently emerging in site assessment; the light detection and ranging (LiDAR). It detects the speed of aerosol particles in the atmosphere. Typically, a LiDAR computes the average velocity in a large volume, so only large turbulent structures can be detected.

All these methods are limited to the detection of relatively large turbulent scales. In order to study the small scales of atmospheric turbulence on Taylor- or even on Kolmogorov-scale better...
resolving sensors are needed.

Until now, a hot wire anemometer was the only device that could detect the small scales. And it was used e.g. for measurements in the atmosphere by Sreenivasan and Dhruva at Brookhaven National Laboratory [2–4]. They used a hot wire and a ×-hot wire anemometer on their measurement mast. Time series of up to 41 minutes duration were measured with a sampling rate between 2 and 10 kHz. As far as known to the authors, these are the only other measurements that are comparable to the ones in this study.

However, a hot wire anemometer has several problems when used in a test field. Varying environmental parameters like temperature, pressure and humidity influence the measured signal and thus the resulting velocity. Moreover at the open sea or near the shore, where the air is saline and humid, corrosion destroys the hot wire fast.

In a previous attempt to measure small scale turbulence, a piezo electric pressure sensor was used. This sensor was able to withstand the hostile environment offshore, and sampling rates of 50 kHz were possible. But it only measures pressure fluctuations; and hence arises the problem of how to relate pressures and velocities. The discussion for an adequate relation is still ongoing [5–7].

In this study, the two-dimensional Atmospheric Laser Cantilever Anemometer is presented. It is a redesign of successfully applied laser cantilever anemometers (LCA) for laboratory use. The 2d-ALCA was specifically designed to withstand the robust offshore environment. It reacts less sensitive to temperature variations than a hot wire anemometer. The latter determines the speed by forced convection, which is directly dependent on the ambient temperature. The 2d-ALCA uses a cantilever that is insensitive to the temperature. Also, the 2d-ALCA can operate autonomously, which is important for use on unmanned offshore platforms. The working principle of the 2d-ALCA are explained in detail in section 2.

The 2d-ALCA was used for the first time at an onshore test field in February 2012 to demonstrate its applicability. The conditions for the test are explained in section 3. The gained results also allow a deeper insight in the statistics of atmospheric turbulence; the power spectrum and increments distributions are shown in section 4.

2. Sensor principle

The 2d-ALCA is a drag force-based sensor, whose measuring method is adopted from atomic force microscopes (AFM). In AFMs the deflection of a micro-structured cantilever is measured using a technique referred to as the laser pointer principle.

In the case of the 2d-ALCA the sensing element is a larger cantilever made of stainless steel. It measures 1.5 mm in length and 0.4 mm in width. Its thickness is about 35 µm. When exposed to airflow, the cantilever experiences a deformation due to the moving flow. This deformation is directly proportional to the drag force, which is acting upon it. The tip of the cantilever is equipped with a small mirror of size 0.3 x 0.3 mm. In order to detect the cantilevers deformation a laser beam is pointed onto that mirror and produces a light reflection. This spot moves according to the deflection of the cantilever. It is tracked using a position sensitive detector (PSD) (figure 1).

Depending on the inflow direction of the flow, the type of deformation can differ. For simple straight inflow the cantilever only bends, whereas for oblique inflows it also experiences some lateral forces and twists. Thus the total deformation of the cantilever is composed of two deformation modes, i.e. bending and twisting.

The total drag force that is experienced by the cantilever is given by:

\[ F_d = \frac{1}{2} c_d \rho A v^2 f(\alpha) \]  

1 apart from LDA (Laser-Doppler-Anemometers). We thank the referee for providing us this information.
with the air density $\rho$, the drag coefficient $c_d$, the area of the cantilever $A$ and the flow velocity $v$. The term $f(\alpha)$ describes the lateral force for angles of attack $\alpha$. Since the cantilever is very small, it implies small fluid inertia. If we assume a range of application $1 \leq v \leq 100 \text{ m/s}$ we may estimate the corresponding Reynolds number $15 \leq Re \leq 1500$. In that range we assume $c_d$ to be constant. $^2$ Hence $F_d$ is proportional to $v^2$ only.

The fact that the cantilever responds to different inflow directions is used for performing measurements in two dimensions. This is possible because the deflection of the reflecting spot due to bending is orthogonal to the deflection that corresponds to twisting. In order to track both deflections a two-dimensional PSD-element (2d-PSD) was installed. Its output signals are computed using analog operational amplifiers in order to determine a relative X- and Y-position of the spot along the active area. These X- and Y-positions serve as the measuring signal. The 2d-ALCA is capable of performing measurements in a circular section of about $80^\circ$ ($\pm 40^\circ$ relative to the cantilever).

The sensor design together with the implementation of the laser pointer principle is illustrated in figure 2. The cantilever is attached to the forefront of the sensor using a tiny boom. The laser module is located within the sensor housing. The laser beam is guided through a mirror and a cubic beam splitter before it hits the cantilever. The reflected beam again crosses the beam splitter and finally falls onto the active area of the 2d-PSD. By means of an adjustable mirror holder within the 2d-ALCA the laser beam can be aligned very precisely in order to hit the tiny mirror at the tip of the cantilever.

Since the 2d-ALCA was developed for operation under rough conditions, its housing was designed completely waterproofed. Besides it was made of anodized aluminum. For better corrosion resistivity the cantilever was coated with a gold layer of 100 nm. The resonance frequency of the cantilever, which at the same time is the limit for the temporal resolution, was estimated to be above 1 kHz.

3. Atmospheric Measurements

Germanischer Lloyd/Garrad Hassan (GL/GH) operates a test field in Kaiser-Wilhelm-Koog close to the German North Sea coast, approximately 85 km northwest of Hamburg. Here, the 2d-ALCA was used under real operating conditions for the first time on February 20th 2012. The test site provides a 60 m high lattice tower with various sensors for measuring atmospheric parameters (cup anemometers, vanes, temperature sensors, pressure sensors, rain detectors, etc.).

The 2d-ALCA was attached at the end of a boom in about 53 m above ground level (see

$^2$ This has to be proven. If we would use drag data from a sphere instead, $Re$ would vary from 2 down to 0.5.
Figure 3. Installation of the 2d-ALCA on the lattice tower in 53 m height at Kaiser-Wilhelm-Koog test site.

Figure 4. Sketch of tower, boom, 2d-ALCA; a compass rose for directions. Blue dashed lines are the acceptance angle of the 2d-ALCA, the blue arrow marks the average wind direction during measurements.

Figure 5 shows ten-minute-averages for wind speed and wind direction of cup anemometers and wind vanes. The error bars represent standard deviation; the thin red lines mark the minimum and maximum wind speed for each ten-minute-time-series. In the first 1.5 hours, the new sensor was tested by recording time series of ten minutes length. From 4:12 p.m. to 5:12 p.m. the first 60-minutes time series was taken by starting the measurement manually. After six o’clock in the evening the automatic measurement was started and continued until eight o’clock next morning.

The average turbulence level was about 7 %, while the instantaneous wind speed varied between 8 m/s to 19 m/s. The average wind speed was between 11 m/s in the evening and 14.5 m/s during night. For the following analysis of 2d-ALCA measurements, just the first time series of 60 minutes length from 4:12 p.m. until 5:12 p.m. is considered.

Figure 6 shows the calibration curve for the signals of the 2d-ALCA. The calibration curve was generated in the wind tunnel of the Carl von Ossietzky University in Oldenburg, Germany. For a given wind speed and direction, the X- and Y-signals of the 2d-ALCA were recorded and averaged over 50,000 samples. These X- and Y-signals are just the amplified 2d-PSD signals, which correspond to the reflected spot on the active area. The points are drawn in a diagram. When the points are connected, the results are lines of same wind speed (isokinetics) and lines of same angle (isogonals). Now, a combination of X- and Y-signal can be interpolated to a wind speed and an angle. As can be seen in figure 6, the interpolation is non-linear.
The black dots in figure 6 are the recorded signals of the first time series. All data points are close together and within the calibration area. The shape of the calibration plane mainly depends on the mechanical properties of the cantilever, and this is less sensitive to external influences. However, a change in density can also have an impact (see equation (1)). The greater influence on the calibration arises from little changes of the cantilever and laser alignment. This causes an offset shift in X- and Y-signals, which in our case has been corrected using measurement data from other sensors.

To verify the correct operation of the 2d-ALCA, the computed 2d-ALCA values for velocity and angle of attack were averaged and compared to the averaged data from the cup anemometers and vanes. The results are shown in table 1. The results of the 2d-ALCA are in agreement with the averages of cup anemometers and wind vanes.

Figure 7 shows the instantaneous values for velocity of cup anemometer (blue circles) and 2d-ALCA (red line). They are compared for a short period of 20 seconds. Both velocities agree well. The overall change of velocity is measured by both sensors, the cup anemometer and the 2d-ALCA. A few differences can be made out, but one has to keep in mind that cup anemometer and 2d-ALCA are about 3 m away of each other. Also, it can be seen that 2d-ALCA measurements are more detailed than the cup anemometer. The 2d-ALCA can measure turbulent fluctuations that are not covered by the cup anemometer.

This detail in figure 7 is exemplary for the entire time series. The wind speed from 2d-ALCA and cup anemometers were compared at random time intervals. The measured velocities agree

![Figure 5](image-url)

**Figure 5.** Ten minute averages of wind speed (cup anemometers, red) and wind direction (vanes, blue), with standard deviation as error bars. The continuous red lines are minimum and maximum wind speeds in a ten minute data set. The blue dashed lines are the lower and upper acceptance angle of the 2d-ALCA. No measurements were done between 5:12 p.m. and 6:35 p.m..

| Table 1. Averaged results for 2d-ALCA, cup anemometers and vanes in comparison |

| Series          | Length [min] | Wind speed [m/s] | Wind direction [°] | Wind speed [m/s] | Wind direction [°] |
|-----------------|--------------|-----------------|--------------------|-----------------|--------------------|
| 4:12 p.m. - 4:22 p.m. | 10           | 11.09 ± 0.31    | 230.70 ± 3.25      | 11.22 ± 0.28    | 230.27 ± 3.66      |
| 4:22 p.m. - 4:32 p.m.  | 10           | 11.01 ± 0.29    | 229.56 ± 3.17      | 11.01 ± 0.26    | 229.01 ± 6.09      |
well at each time interval.

4. Statistical Analysis
Now that the data from 2d-ALCA are verified, further statistical analysis can be done with the measured data. A power density spectrum was computed from both cup anemometer time series and 2d-ALCA time series. Both spectra were normalized in vertical direction to a relative power spectral density of one at $\nu=1$ Hz. They were plotted in the same diagram (figure 8). The blue triangles show the results for the cup anemometers; the red dots are the results for the 2d-ALCA; and the solid black line is the Kolmogorov power law, where spectral energy is proportional to the frequency by the power of $-5/3$.

The low frequencies are detected by both cup anemometer and 2d-ALCA. However, when the data of the 2d-ALCA are used to compute the spectrum at low frequencies, the results at higher frequencies are obscured by strong noise. To obtain a clear curve, the data must be filtered and the spectrum is calculated using different window sizes. On the other hand, figure 8 shows that the measurements of both cup anemometer and 2d-ALCA can be combined to cover a wide frequency range with little effort. The frequency range stretches from 0.001 Hz ($\approx$15 minutes

![Figure 6](image-url)

**Figure 6.** Calibration plane for the 2d-ALCA. Red lines are wind speed levels, blue lines are angle of attack levels, black dots mark recorded X/Y-signals for time series from 4:12 p.m. - 5:12 p.m.. Isokinetics separated in steps of $\Delta u=1$ m/s, isogones separated in steps of 5°.
or 10 km at 10 m/s) to 1000 Hz (≈1 millisecond or 10 mm at 10 m/s), when Taylor’s frozen turbulence hypothesis is assumed.

This wide range can be separated into three regions. For a very wide frequency range ($5 \cdot 10^{-2}$ Hz < $\nu$ < $2 \cdot 10^1$ Hz or $\approx$220 m to 0.5 m in spatial dimensions), the energy content of atmospheric turbulent structures are proportional to Kolmogorov power law.

At frequencies lower than $5 \cdot 10^{-2}$ Hz no $-5/3$ drop according to Kolmogorov can be observed. For frequencies that are larger than $2 \cdot 10^1$ Hz, the power of the turbulent eddies seems to be larger. The cause of that behavior is still subject of discussion. Finally, the peak at 1200 Hz is the first resonance frequency of the cantilever with mirror.

Next to the spectral analysis, the distribution of the velocity increments ($\Delta u = u(t + \Delta t) - u(t)$) were computed; they are shown in figure 9. The distributions were vertically shifted for better clarity; the shown time lags $\Delta t$ are 10 ms, 100 ms, 1 s, 10 s, 1 minute and 10 minutes for the 2d-ALCA data, and 10 s, 1, 5 and 10 minutes for the cup anemometer. The solid lines represent normal distributions with same standard deviations. The velocity increments $\Delta u$ on the x-axis were shifted by its average $\mu_{\Delta u}$ and its standard deviation $\sigma_{\Delta u}$. Anyway, the average

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**Figure 7.** Comparison of wind speed for cup anemometer (blue circles) and for 2d-ALCA (red line) of the time series from 4:12 p.m. - 5:12 p.m.; the data is from the first minute of measuring.

**Figure 8.** Power spectral density of 2d-ALCA (red) and cup anemometers (blue) for the time series 4:12 p.m. to 5:12 p.m.
Figure 9. Distribution of velocity increments $\Delta u$ for (a&b) one-hour time series of 2d-ALCA from 4:12 p.m. - 5:12 p.m. and (c) for cup anemometers for the time series from 6:35 p.m. until 7:35 a.m. (see also figure 5). Solid lines are normal distributions with same standard deviation $\sigma_{\Delta u}$.

$\mu_{\Delta u}$ is almost zero.

The increments distribution for the 2d-ALCA are shown in figures 9(a) and 9(b). They were computed from 36 million values that where recorded within one hour of measurement. Within an interval of $\pm 2\sigma_{\Delta u}$ the distributions are close to the normal distributions (solid lines) for all increment times. Outside that interval, more events were counted for the measurement than would be predicted by a normal distribution. This behavior is reported regularly for turbulent flows and is called intermittency.
The longer the time lag $\Delta t$ is, the narrower the distribution of the increments. For lag times $\Delta t \leq 100$ ms the increments distribution reaches up to $\pm 20\sigma_{\Delta u}$; and for lag times $\Delta t \geq 10$ seconds the range is less than $12\sigma_{\Delta u}$.

Figure 9(c) shows the increments distributions for the cup anemometer for four time lags. In the time interval from 4:12 p.m. until 5:12 p.m., the cup anemometer recorded 3600 values at 1 Hz. This is not sufficient for a meaningful increment statistic. For a period from 6:35 p.m. until 7:35 a.m., however, a continuous time series was recorded. The 46,800 values allow a basic statistical analysis. The data sets in figure 9 are not within the same time interval; however, statistics for cup anemometer and 2d-ALCA can be compared qualitatively.

For the cup anemometer the 13 hours of measurement resulted in a distribution of $\pm 6\sigma_{\Delta u}$ width. Also, the distribution is based on few values and is rather coarse. And the distributions show an onset of intermittency, but the distribution is still too coarse for clear evidence.

On the other hand are the increments distribution of the 2d-ALCA measurements. The distributions at 10 seconds and 1 minute are smoother and better resolved than those of the cup anemometer at the same $\Delta t$. Also the lag times can be very short ($\Delta t \approx 10$ ms). So, more detail of the turbulent characteristics can be investigated.

The distributions in figures 9(a) and 9(b) show that intermittency is prominently present for a wide range of time scales.

5. Conclusions
The first use of the 2d-ALCA in a test field was a success. The device collected data for hours at a high temporal resolution. The information from the new sensor is more detailed than from any other available anemometer used for wind energy applications. So, it provides important insight into the turbulent structures of the atmospheric boundary layer in the small turbulent scales, e.g. velocity increment distributions can be computed from 10 ms up to 1 minute for 2d-ALCA measurements. For easier evaluation, data from several sensors can be combined.

Also, the distributions of velocity increments show that even on the smallest resolved scales of about 10 ms ($\approx 10 \text{ cm at } 10 \text{ m/s}$) intermittent, turbulent structures are prominently present. This information is e.g. important for the inflow condition of a segment of a rotor blade.

In the meantime, the 2d-ALCA was tested under real offshore conditions on the FINO3 measurement platform.

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