# Project Plan: Dynamic shear profile modeling and validation with LiDAR data

**Written by:**
**Theodor B. Gilhøj (s203702)**
**10$^{\text{th}}$ of October 2024**

Danmarks
Tekniske
Universitet

**Bachelor Project Plan**
**Technical University of Denmark**

# Contents

# 1 Content and Learning Objectives of the Thesis

## 1.1 Learning Objectives

1. Develop a comprehensive understanding of wind doppler lidar technology.
2. Conduct a thorough literature review to assess the state of the art in lidar technologies.
3. Evaluate different lidar mounting configurations and their effect on the accuracy of wind measurements.
4. Identify and justify a research gap to demonstrate the relevance of the research area.
5. Analyze parametric models for wind shear profiles in the atmospheric boundary layer, including power law, polynomial, and logarithmic models.
6. Choose a suitable shear profile based on the reviewed literature and collected data.
7. Apply simulation and modeling techniques to estimate shear profile parameters from the collected lidar data.
8. Develop a method for estimating shear model parameters from the data and adapt the model to handle dynamic, continuous data.
9. Implement low-pass filters, data manipulation, and visualization techniques through programming for data analysis and model development.
10. Validate the developed model on new test cases, including different shear and time-varying profiles.
11. Evaluate the model's applicability in real-world wind energy applications.
12. Gain experience in structuring and managing large tasks, working independently, and adhering to project schedules.
13. Acquire and critically evaluate new knowledge independently
14. Communicate technical information, theory, and results in written, graphical, and oral formats.

## 1.2 Summary

This project develops a dynamic model for determining mean wind speed profiles based on lidar data. Various lidar technologies are reviewed, focusing on their strengths and weaknesses. Parametric models for shear profiles in atmospheric flow are described, to select a suitable model. The project uses simulations and/or existing data as the basis for developing the model. First, a method is developed to estimate model parameters from the collected data, and this estimation method is then extended to handle dynamic and continuous data. The validity of the developed model is assessed by validating it on new test cases, which include different shear profiles as well as time-varying profiles. Finally, the algorithm's applicability in real-world applications is evaluated.

# 2 Relevance of Research

## 2.1 Increasing demand

With an increase in demand for sustainable energy, the wind turbine sector is growing massively. It is growing domestically in Denmark, Europe, and the whole world, and the projected capacity in 2050 amounts to 13.4TW according to [1]. The capacity in 2022 was 906GW [2]. As the technology advances, the turbines are growing in size, with the largest commercially deployed at the time of writing being 222m in rotor diameter [3].

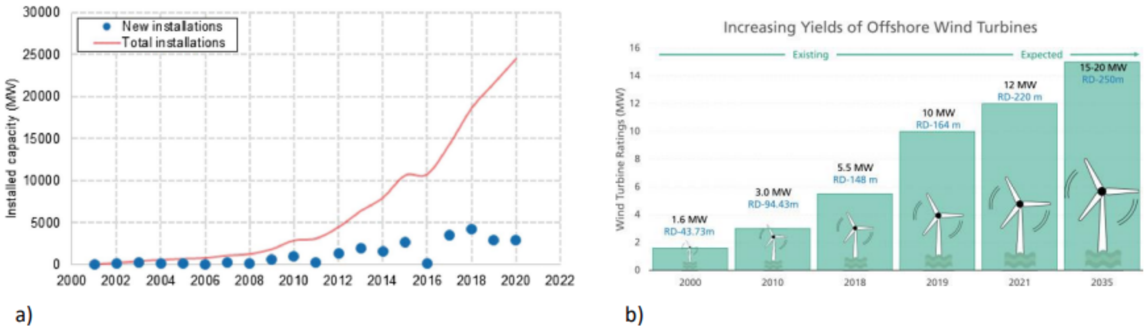


**Figure 1:** Turbine size development. a: Capacity Trend. Source:[4] b: Rotor Diameter Trend. Source: [5]

## 2.2 Wind shear and structural demands

Generally, the velocity of the wind scales with height above the surface. This relationship is not linear but can be modeled by logarithmic, power, and polynomial functions. Due to these effects, more energy can be extracted from the wind, as the available power to be generated scales with the wind speed cubed. This is the main driver for increasing the size of the wind turbines. However, the bending moment will also naturally increase, as the turbine is fixed to the ground, which increases the structural demands in the turbine.

## 2.3 Structural demands on blades

One thing is the structural capacity to withstand the rated windspeed, fluctuations around the mean wind speed, and stronger gusts, by the tower and the blades. Another thing is the shear forces inevitably being applied constantly along the extent of the turbine. The tower of the turbine is cylindrical, and therefore has a quite low drag factor, making the blades the main contributor to the torque applied at the base of the tower. However, as the rotor revolves around the hub, the blades also experience varied loads not only due to the gravitational force, that varies with the angle between the blade and the ground, but increasingly due to the differences in wind speed between the blades, due to the increasing size of the turbines, and on the blade itself. Over time, these effects tire out the blades, bearings, pitch system,

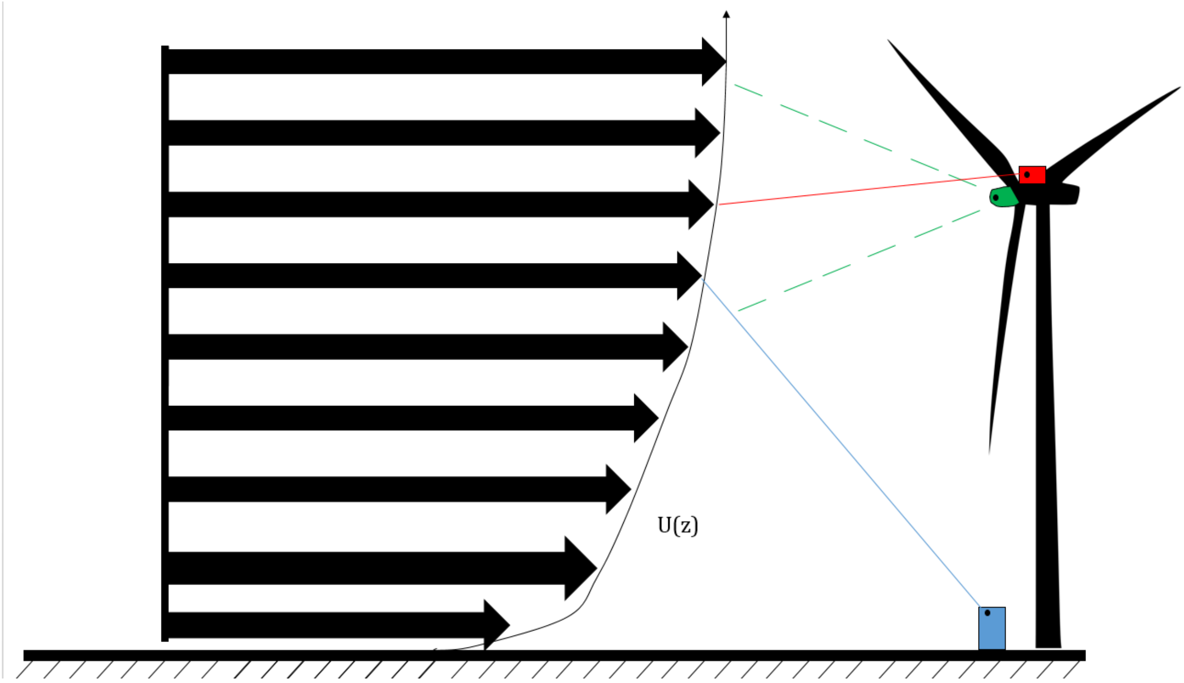


**Figure 2:** Project Principle Drawing: Incoming Wind Speed; Vertical Shear Profile

and tower base, which decreases the lifespan of the turbine. A quantification of this is difficult due to the complexity of the subject, but load reductions of up to 10% are claimed by [6], and described as *substantial* from nacelle lidar assisted control according to the company Windar Photonics [7].

## 2.4 Mitigation strategy: pitch control

Luckily, mitigation strategies have been developed for this already. By controlling the pitch of the blades and the yaw angle of the hub, shear and veer forces can be reduced. For the controller to adjust the blades ahead of the collision between the wind particles and the rotor, the controller needs an input. This input can be measurements of force by the blade itself [8] or in the hub, or it can be measurements of the incoming wind. It is exactly the measurement of the wind that is central to this project, as it has already shown great potential in mitigating shear loads and extending the lifetime of the turbines [9] [10] [11].

## 2.5 Anemometers

The wind can be measured in various ways, and the technology that has been used to do so has advanced greatly since meteorologists started trying to describe the wind. Perhaps the oldest wind measurement tool invented by humans is the wind vane, which can still be seen on farms, churches, etc. On bridges, wind socks indicate not only the direction but also the speed of the wind in a qualitative manner. Since then, quantitative anemometers have been developed, with cup anemometers being the most widespread tool, even today. Various other tools such as ultrasonic and acoustic resonance anemometers have also

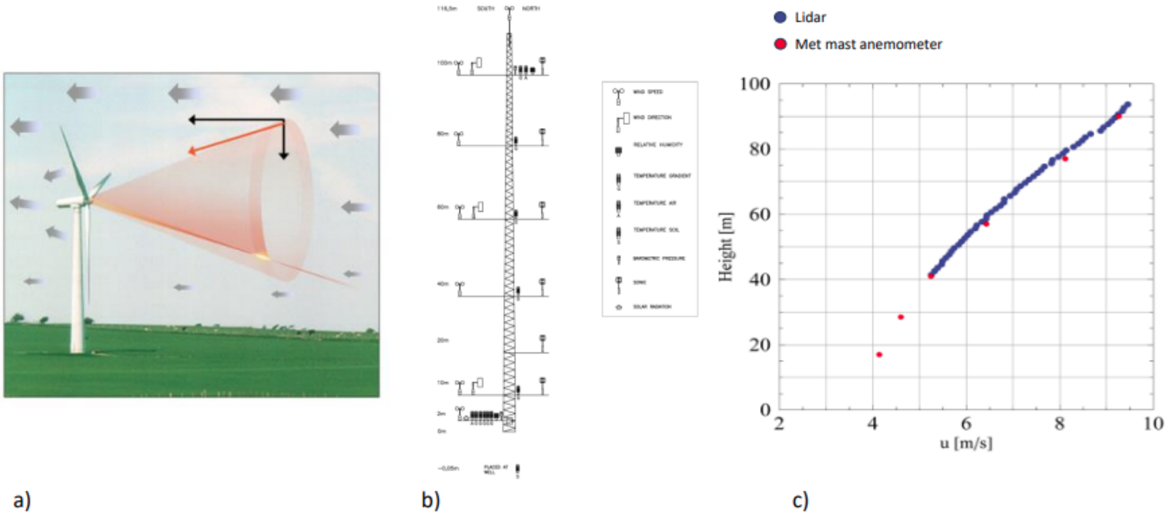


**Figure 3:** a: Principle measurement volume of a common lidar scan. b: example sketch of met mast showcasing wind speed measurements at seven discrete points. C: example of shear velocity profile measured with lidar (blue) and met mast anemometers (red). Sources: a:[11] b:[14] c:[11]

been developed. Nevertheless, for a multitude of reasons, the most promising anemometer type are laser doppler velocimetry systems. The acronym lidar is an acronym for a variety of word combinations, such as; Light Radar, Laser Imaging Detection and Ranging, or Light Detection and Ranging, which give a general idea of how it works, and is elaborated on in section 3.2

## 2.6 Lidar and advantages

Unlike meteorological masts, lidar systems do not cause any meaningful wake effects. The positioning of meteorological masts to avoid induction zone effects requires a distance of at least five rotor radii between the mast and the turbine [12]. With turbines increasing in size, this distance naturally increases as well. The inaccuracy of the measured incoming wind naturally also increases, the further away you measure it [13]. Furthermore, as turbines increase in size and are installed in mountainous areas and offshore, the installation of more expensive masts becomes necessary, if they can be installed at all. Lidar measurement ranges go all the way up to 2km, but measuring so far away is of course not advantageous, as just described. This just goes to say, that even when the lidar is positioned on the ground, it can measure as high as needed. Another big advantage to lidar is its' ability to measure a broad volume of velocities, as opposed to anemometers, which only measure a plane with a few discrete points. This is visualized in figure 3.

## 2.7 Historical Development and Applications of Lidar

The first lidar-like system was developed in 1961 [15] and was intended for satellite tracking [16]. It was introduced to wind measurements in the 1970's [17]. At the time, they were too large and expensive to be applied commercially [18]. However, due to the development of new technology such as optical fibres, the industry saw a dramatic change in the late 1990s with a CW lidar mounted on a turbine already in 2003[18]. Originally, it was used to evaluate the wind resource to assess the viability of installing a turbine at a certain location. It was therefore positioned at the ground. Since then it has been discovered to be useful for purposes of power curve assessment, and controller input.

## 2.8 Nacelle-Mounted Lidar

Since the emergence of these applications, Lidars have been installed on the turbine itself, to more accurately measure the incoming wind field. The use of nacelle-mounted Lidars is already being applied industrially, with promises of up to 10% load reductions in [6], and by unspecified amounts in [19], [7]. However, by placing the lidar on the nacelle, it is shaded by the blades as the rotor revolves. Therefore, it is currently researched to mount the lidar on the blades [20], or on the hub [11]. This project focuses on hub-mounted lidar.

## 2.9 Hub-Mounted Lidar and Research Gap

The first real-life implementation of hub-mounted lidars was seen in "LIDAR wind speed measurements from a rotating spinner (SpinnerEx 2009)" [21] and elaborated on in "A spinner-integrated wind lidar for enhanced wind turbine control" [11]. Among other things, it was able to measure the approaching wind and turbulence structures and yaw errors in real-time. Furthermore, vertical wind profiles as well as power curves were estimated. Since then, the idea of a hub-mounted lidar has been investigated through synthetic measurements, simulations, and experiments by various researchers around the world with a focus on Feed-forward pitch control[9], simulation with and without LES control applications[10], [22], induction zone effects [13], aero-elastic simulations for blade deformation [23], experimental applications [24], synthetic measurement modeling [25], and accuracy validation [26]. In [11], [27], [28] the need for more research in this particular area is underlined. Furthermore, the amount of scientific articles concerning hub-mounted lidars is quite limited, in the following areas at the time of writing (09/10/2024):

1. Feedback / Feedforward Control Systems,
2. Wind Field Estimation,
3. Synthetic Measurement Models,
4. Aeroelastic Response
5. Field Experiments
6. Industrial Applications

In addition to this, the technology is not yet mature for industrial use.

## 2.10 Characterizing the wind

A key element to commercial application is the ability to describe the wind field approaching the blades. This can be modeled in certain ways, for example, as a wind rose, a two- or three-dimensional vector field, a temporal mean wind speed, wind frequency distribution, or a shear profile, as seen in figure 4. Each representation has strengths and weaknesses, and the estimations of these performed by hub-mounted lidar are limited.

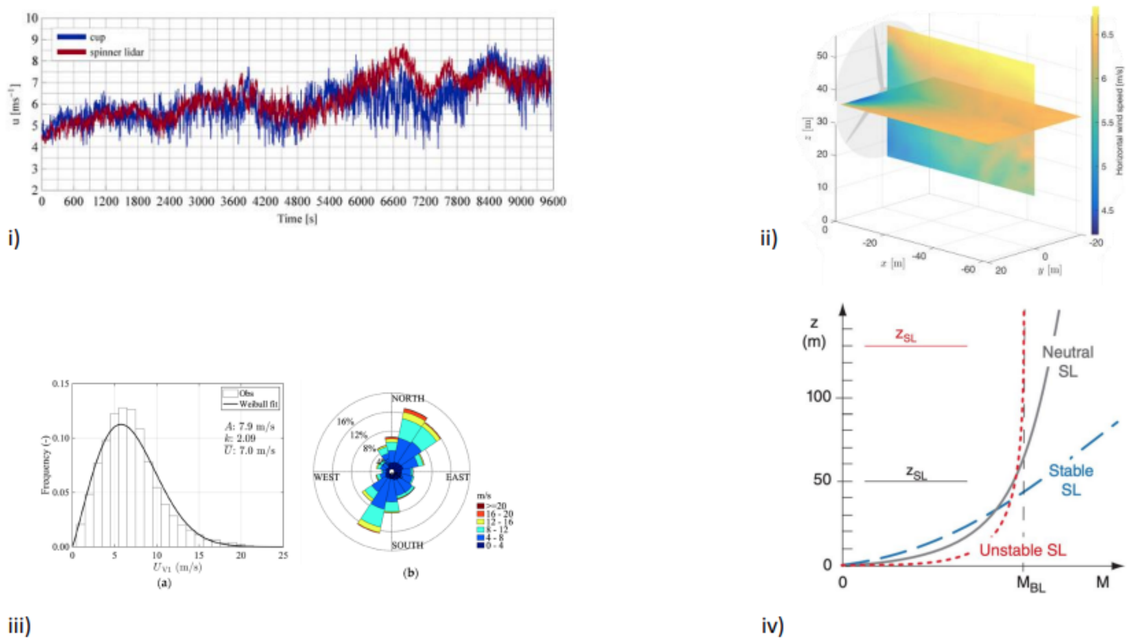


**Figure 4:** Wind models i: Temporal Mean Wind Speeds. Source[11] ii: Wind Field Vector Representation in Three Dimensions. Source:[13] iii: a: Wind Frequency Distribution and b: Wind Rose Depiction. Source: [29] iv: Shear Profiles in Stable, Unstable, and Neutral Conditions. Source: [30]

## 2.11 Relevance of Research

For control purposes, the shear profile is one of the best metrics for feed-forward input, since it describes the variation in wind speed with height in a simple manner, compared to a detailed three-dimensional vector field representation. It is the effect of exactly this phenomenon and the mitigation strategy with the controller through pitch regulation that is researched. This project aims to model the shear profile based on hub-mounted lidar synthetic measurements, to continuously describe the wind field, and feed it forward to the pitch controller. The relevance of this research is to extend the lifetime of the wind turbine, through reducing shear structural loads.

# 3 State of the Art

To understand the state of the art of vertical wind profiling based on doppler lidar technologies, it is useful to know the basics of boundary layer meteorology. That is, because the basic models are based on principles described by theories of that subject, and the functioning of the lidar anemometers is also to some extent easier to understand with a foundation in that field.

**Acknowledgements**
The following paragraphs on boundary layer theory, are mostly based on knowledge obtained from the books *An Introduction to Boundary Layer Meteorology.*[31] and *The Wind Energy Handbook* [32]. Much more details on the subjects can be found in those, particularly in chapters 1 and 2 in [31], and in chapter 2 in [32].

## 3.1 Boundary Layer Theory

### 3.1.1 Introduction to micrometeorology

The boundary layer concerns the part of the atmosphere wind turbines operate in, which makes it important to study, build, and optimize wind turbines and their operation. The available energy in the wind scales with the cube of the wind speed, which amplifies the significance of understanding how it behaves. This is relevant with respect to viability predictions for site selection, turbine design, details on electricity production in relation to the grid, etc. Most people know that the wind varies greatly both temporally and geographically and that it is difficult to predict anything about the wind in detail, especially when the time horizon expands. Micrometeorology is the study of wind phenomena with space scales smaller than 3km, and time scales shorter than about 1 hour, and the following chapter outlines the most basic knowledge within this area needed to understand the state of the art of doppler lidar technology.

### 3.1.2 Understanding the Boundary Layer

The atmosphere is theoretically divided into layers, the nearest to the earth being the troposphere. The troposphere is further divided into layers, and the boundary layer is the one closest to the ground. Formally, in the sense of micrometeorology, it is the part of the troposphere that is directly influenced by the presence of the earth's surface and responds to surface forcings with a timescale of about an hour or less. The rest of the troposphere is called the free atmosphere. The thickness of the boundary layer varies both in time and space, due to temperature, humidity, frictional drag, evaporation, transpiration, heat transfer, pollutant emissions, and terrain-induced flow modifications, to name a few. At the shortest, it extends about a few hundred meters, and a few kilometers at the tallest.

### 3.1.3 Solar Radiation Influence and Diurnal Variations

It is especially solar radiation causing warming and cooling of the ground, which alters the boundary layer. Therefore a diurnal cycle of temperature leads to a wind profile of the same type. This cycle is especially present on land, compared to oceans, which has implications for on- and offshore installations. This is due to the high mixing of water within the ocean, and the high heat capacity of water, compared to the surface of the earth. At low altitudes, the diurnal variations are high compared to higher altitudes, and in the free atmosphere, the diurnal variation is close to none.

### 3.1.4 Fundamentals of Wind characteristics

**Wind Formation**

From a completely basic point of view, the wind field is generated by the sun. The ground is heated by solar radiation, which in turn heats the air close to the ground, decreasing the density. This causes the warm air to rise, heating the surrounding air during transportation. This creates a flow of air in both directions, driven by temperature and density differences. Due to the constant rotation of the earth, Coriolis forces are applied creating a large-scale global circulation pattern. Because the surface of the earth is far from uniform, the circulation is highly disturbed. This creates a highly complex and non-linear flow.

**Wind Composition**

Even though the wind seems chaotic, it can be divided into signals superimposed on each other. The main signal can be seen as the mean wind speed, which changes on a large timescale, of about a few hours. On a smaller timescale waves are seen, changing on a minute scale. Even smaller yet, turbulence is seen, happening on a basis of less than a second, to a few seconds. Turbulence is often composed of more than one signal, which makes the description and prediction extremely difficult.

**Mean Wind**

The mean wind speed is responsible for rapid horizontal transport, also known as advection. Near the surface, humans experience between 2 and 10 m/s normally. Due to the friction between the earth and the wind, the mean wind is the slowest close to the ground. Waves are especially present during nighttime and are responsible for momentum and energy transport. It is generated by mean wind shear and obstacles, which will be described further in the section 3.1.5. Due to the complex composition of the wind, it often makes sense to divide the airflow into a mean and a perturbation part, the perturbation being turbulence and/or waves.

### 3.1.5 Stability Conditions

The boundary layer characteristics change temporally, and three main conditions arise under certain circumstances. The largest factors that influence stability conditions are the strength of the geostrophic wind, surface roughness, the Coriolis effect due to the rotation of the earth, and thermal effects. When the air rises due to surface heating and expands due to lower pressure, three situations can arise, when the air is cooled by the surrounding air.

**Unstable**
Unstable conditions occur when insufficient cooling does not cause thermal equilibrium with the surrounding air. This creates a thick boundary layer, with large-scale turbulent eddies, a high amount of vertical mixing and momentum transfer, and a small change of mean wind speed with height. Sudden gusts at a low level can occur.

**Stable**
If the cooling is sufficient to cause thermal equilibrium, vertical motion is suppressed, which typically happens on cold nights. Under these stable conditions, turbulence is dominated by friction, and wind shear is large, resulting in potentially significant asymmetric loads on turbines, and strong wind veer.

**Neutral**
A situation where the rising air is cooled at a rate where it is in equilibrium with the surrounding air without vertical suppression is called neutral stability. This results in strong winds, while the turbulence is caused by ground roughness which causes sufficient mixing. For wind energy, this condition is the most important, particularly regarding the turbulent loads, since they are larger in strong wind regimes.

#### 3.1.6 Temporal Wind Variation Patterns

It should be clear by now that the wind field in the boundary layer is highly transient in nature, which makes the description and forecasting of each individual eddy virtually impossible. The field of micrometeorology relies heavily on field experiments, which require a large array of sensors, are very costly, and in some cases simply are not feasible. Therefore numerical and laboratory simulations are becoming increasingly more relevant, as it is possible to approximate real-world scenarios with complex models, eg. the Mann model [33].

The temporal variations do not only happen on a short timescale but also annually and seasonally. These can be described by probability functions specifically known as Weibull distributions, and are caused by the tilt of the earth´s axis of rotation, which caused changes in insolation. The temporal variations relevant to this project are of the synoptic and diurnal sort.

#### 3.1.7 Turbulence

**Introduction**
Turbulence has now been mentioned in relation to stability conditions and temporal variations, but the perhaps most important contribution factor is frictional drag with the surface of the earth. Obstacles like trees and buildings also deflect the airflow, which causes turbulent wakes on the sides of, and downwind of the obstacle. Turbulence typically varies within a timescale of 10 minutes. For a pitch controller to respond, only a short lead time (¡ 1 second) is necessary. With a lidar measuring the incoming wind field several tens or even hundreds of meters out, it is very possible to respond in time. Turbulence does indeed seem quite random and unpredictable, and a deterministic description is extremely difficult.

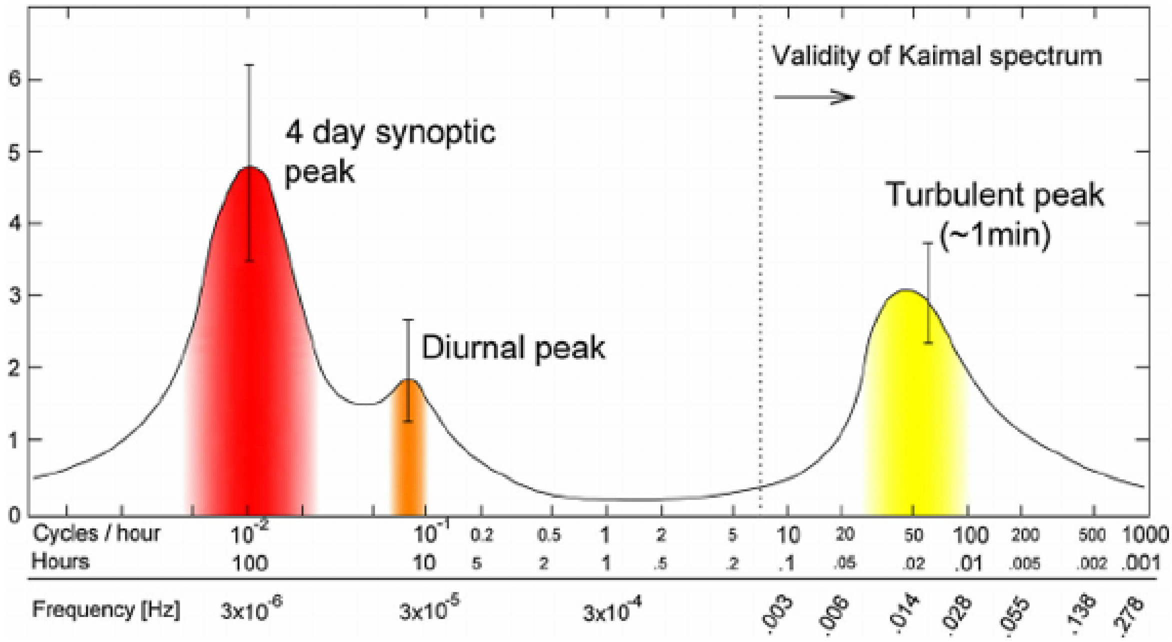


**Figure 5:** Van der Hoven spectrum

Nevertheless, statistical descriptions, theoretical knowledge, and mathematical models combined have shown to be useful for this purpose.

**Eddies and Spectra**

The mean wind speed only varies at an hourly rate, which suggests that turbulence is not completely random, although the pattern is highly irregular, which separates them from waves. As mentioned, turbulence is composed of multiple signals superimposed on each other. These signals can be idealized as eddies, which vary in size, and behave in a well-ordered manner when displayed on a spectrum.

In figure 5, a turbulence spectrum can be seen. If turbulence was completely random, these patterns would not be true in general. The relevance of this to the project is the spectral gap, which is the low density of turbulence between the diurnal peak and the turbulent peak, and the turbulent peak itself. The velocity variations in time periods between about 30 minutes and two hours are low. At a timescale of around 10 hours, at the diurnal peak, the mean flow variations are typically seen. Turbulent variations are as mentioned seen on a timescale of less than 10 minutes. Therefore vertical wind profiling is usually conducted on a timescale of more than 10 minutes, and less than 2 hours.

**Statistical Description of Turbulence**

Turbulent wind speed variations can generally be considered normally distributed, although the tails are non-Gaussian. Therefore, statistical descriptors like the standard deviation $\sigma$ and mean velocity $\bar{U}$ are useful. A measure of the intensity of turbulence is hence the standard deviation relative to the mean velocity:

$$I = \frac{\sigma}{\bar{U}} \tag{1}$$

Turbulence is naturally heavily dependent on surface roughness and decreases with height. As a general rule, the variance is approximately 2.5 times the frictional velocity close to the ground.

$$\sigma_u \approx 2.5u^* \tag{2}$$

Furthermore, the turbulence *u'*, can be separated from the mean wind speed through subtraction.

$$u' = U - \bar{U} \tag{3}$$

Hence the turbulence will be fluctuations around zero.

**Taylor's Frozen Turbulence hypothesis**
According to the theory on eddies of different sizes being superimposed on each other, different turbulence intensities of different timescales are expected. These can be translated into physical sizes of eddies. If the eddies advect undisturbed for a period of time, the turbulence can be considered 'frozen'. This is exactly *Taylor's frozen turbulence hypothesis*, which is relevant especially when turbulence is measured before interacting with a turbine. This simplification is useful, as long as the eddies evolve slower than the advection of the measurement volume. Even more so, when it evolves slower than the advection from the measurement point to the impact with the turbine. Numerically, it is assumed true when the standard deviation is less than half of the mean wind speed:

$$\sigma < \frac{1}{2} \cdot \bar{U} \rightarrow I < \frac{1}{2} \tag{4}$$

Taylor's hypothesis is central to the project, as the measurement of the incoming wind would be useless if it was completely changed during the advection from measurement to impact.

#### 3.1.8 Shear Profile Models

Mostly due to frictional effects, the wind speed varies nearly logarithmically with height in the surface layer. For many purposes, it has been useful to model the wind speed as a function of height, which is also central to this project. In general, two models are widely adopted by the industry; a logarithmic profile and a power law. The logarithmic profile takes arguments such as the friction velocity u*, the von Karman constant, approximately 0.4, the surface roughness, and a stability function Ψ.

$$\frac{u^\star}{\bar{U}(z)} = \kappa/(\ln\left(\frac{z}{z_0}\right) + \Psi \tag{5}$$

The sign and value of the stability function depend on the stability conditions, which are not elaborated further upon in this chapter.

The power law simply depends on a single factor $\alpha$, usually between 0.1-0.2, depending on terrain and wind conditions, like the logarithmic profile.

$$\bar{U}\,(z) \propto z^{\alpha} \tag{6}$$

Like all other functions, the profile can also be approximated by a polynomial function of n degrees, which might be useful in some cases.

#### 3.1.9 Structural Effects

If the amount of sheer is large, the loads on the turbine will naturally be asymmetric, unless a mitigation strategy is used. This decreases the lifespan of the turbine, which generates an incentive for research in the minimization of asymmetrical loads due to wind shear. The purpose of the project is to estimate a shear profile based on lidar measurements, to distribute the loads evenly on the turbine.

### 3.2 Wind Doppler Lidar Systems

The following paragraphs are based on *The Springer Handbook of Atmospheric Measurement* [34] and the article *Comparing Pulsed Doppler Lidar with SODAR and Direct Measurements for Wind Assessment* [35], which can be visited for further information.

#### 3.2.1 General Functioning and Methodology

In the context of wind velocity measurements, Laser Imaging, Detection, and Ranging, or simply *lidar*, works by targeting aerosols and particles in the atmosphere with a laser and measuring the time for the reflected light to return to the receiver. Because of the doppler shift, the frequency of the reflected light is different from the emitted light, which can be directly translated to a velocity, when the distance to the reflection point is known, and of course the speed of light. Generally, there are two types of lidars used for velocimetry, continuous wave, and pulsed lidars, which are described in sections 3.2.2 and 3.2.3.

#### 3.2.2 Continuous Wave (CW)

Continuous wave lidar works as the name suggests by emitting a continuous beam of light. The beam is focused at a certain radial distance, from which region the velocity is estimated. The focus region of the beam and the elevation angle must be varied to measure other distances. They typically scan an area conically, with a $360^o$ scan at each location. The measurements are done at a high frequency, and post-processed with a weighting function. In general, the distribution of the errors is considered random, with a variance scaling with the distance to the measurement point. This means that the weighting function looks more or less like a normal distribution, with a higher density around the mean wind speed at short ranges, compared to longer ranges. Effectively, this means that CW lidars are better at measuring wind speeds precisely near the system, with a high resolution. Additionally, CW lidars are a bit cheaper than pulsed lidars. CW lidars are used for wind profile estimation within a short range, which aids the wind energy industry.

### 3.2.3 Pulsed

Pulsed lidars emit regularly spaced emissions of light for a specified period of time. Along the beam, reflections of light returning after a given amount of time correspond to velocities measured at various distances, also known as range gates. Therefore the velocities are referred to as line of sight, or radial velocities along the path of the beam. Like CW, a weighting function is applied, however, the density of the function does not change with distance. Pulsed lidars excel at estimating 3-D flowfields, with conical and vertical scans. Therefore it is possible to derive a shear profile at a much greater vertical resolution, compared to an equivalent CW system. They are also used for horizontal wind and turbulence profiling. A limitation of pulsed lidars is, that the backscattered signals close to the system are weaker, and a higher general cost of investment, as well as higher energy consumption.

## 3.3 Lidar Mounting Configurations

For wind applications, lidar was initially installed on the ground, to assess the wind resource before turbine installation, and during operation. As turbines grow in size, it becomes increasingly difficult to build met masts tall enough to measure the wind coming into the turbine, but the lidars do not have this limitation with range. Using lidar for turbine control is not new at all, but hub and blade-mounted lidar is quite new. Nacelle-mounted lidar both up- and downwind has been researched quite thoroughly, and implemented commercially as well. However, when measuring upwind from the nacelle, the point of view is shaded not only by the nacelle itself, the further back on the nacelle the lidar system is installed, but also by the blades and the hub. This restricts the measurement space and ultimately decreases the accuracy of the incoming wind speed measurements. The system might be able to scan the entire plane coming into the rotor at a distance far away, but the turbulence might evolve between the advection from the measurement point and the rotor. Therefore blade and especially hub-mounted pulsed lidar presents an opportunity to assess the whole wind field accurately at relevant distances. The potential of this is described in section 2.

# 4 Objectives, Scope of the Project, and Research Questions

## 4.1 Objectives

1. Develop a robust dynamic shear profile model using hub-mounted lidar data.
2. Extend the model to handle dynamic and continuous data inputs.
3. Validate the model against real-world test cases.
4. Evaluate the model's applicability to wind energy production and turbine design.

## 4.2 Scope

- Focus on hub-mounted pulsed lidar systems for wind speed measurement and shear profile modeling.
- Analysis limited to two dimensional parametric models for vertical wind shear profiles in the atmospheric boundary layer.

## 4.3 Research Questions:

1. What is the current state of the art in Wind Doppler lidar technology?
2. What are the strengths and weaknesses of CW and pulsed doppler lidar systems for wind shear profiling?
3. How do different mounting platforms impact wind profile measurements?
4. Which parametric models are used to describe shear profiles in varying wind conditions in the boundary layer?
5. How can dynamic shear profiles be accurately modeled and validated using lidar data?
6. What are the existing research gaps in wind shear profile analysis with lidar systems?
7. How can simulation and modeling techniques be applied to estimate the wind shear profile?
8. How can the modeling technique be developed to respond to incoming data?
9. How can filters, averaging or some other data manipulation technique be applied to improve the accuracy of the model?
10. Can the developed shear profile models be validated on new data, and across different atmospheric conditions and varying temporal profiles?
11. How applicable are the developed models and methodologies in real-world wind energy projects, and what are the implications for future technology deployment?

# 5 Project Plan

To plan the project, initially, a Gantt chart was created, listing the most important tasks. These can be seen as the left-most column in figure 6. The few deadlines, such as the project plan hand-in, the tentative work report, and the project hand-in date are inserted to provide a sort of overview. The duration of the tasks was hard to estimate, so they have been iteratively updated for the first 4 weeks of the project work and will likely be continuously updated after the submission of this document, to keep track of progress. The percentage of completion is a quantitative assessment based on a qualitative list of assignments related to each task, kept in separate text documents.

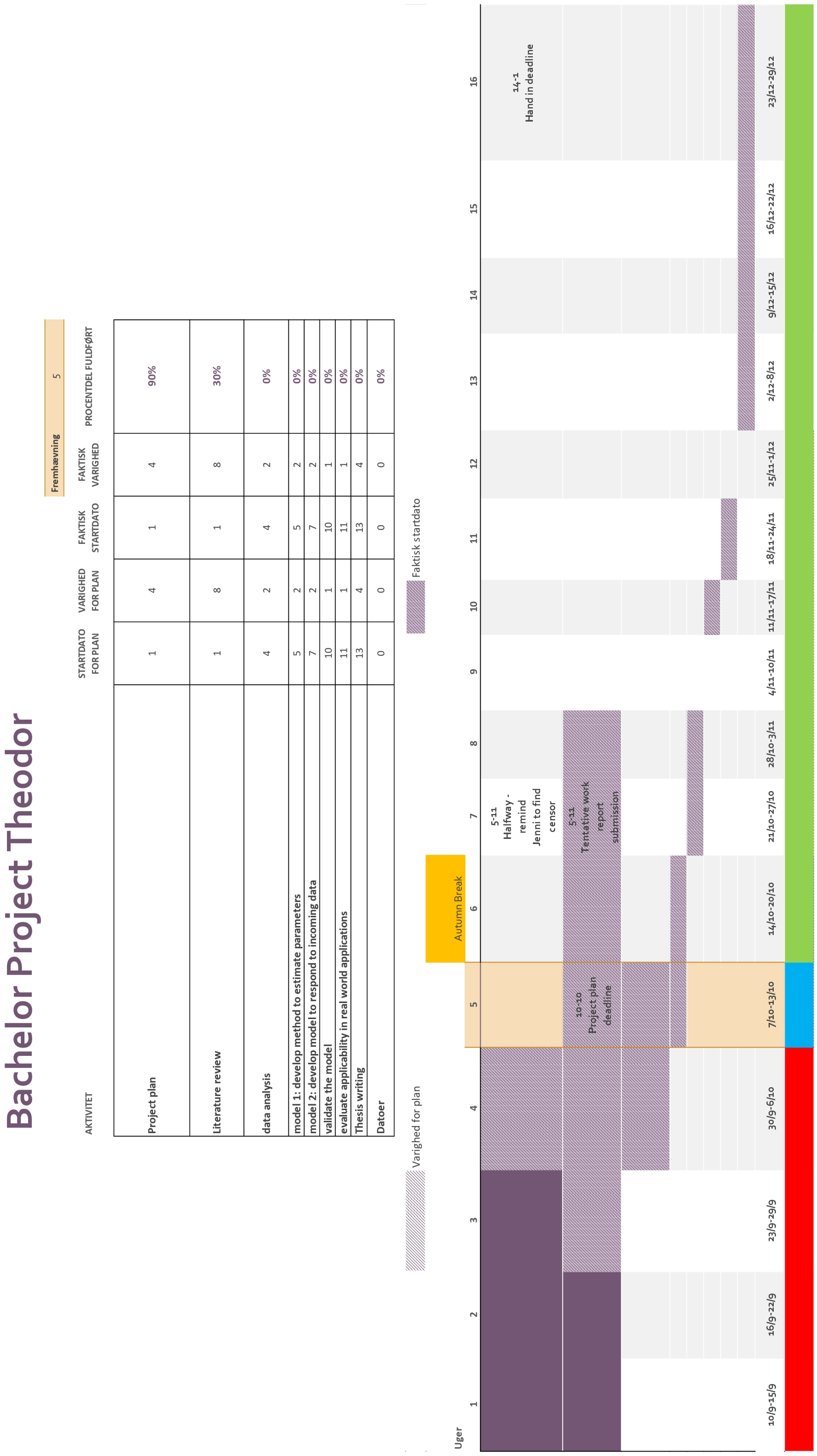


**Figure 6:** Gantt Chart Project Plan Timeline

# References


[1] David Severin Ryberg et al. "The future of European onshore wind energy potential: Detailed distribution and simulation of advanced turbine designs". In: *Energy* 182 (2019), pp. 1222–1238. ISSN: 0360-5442. DOI: https://doi.org/10.1016/j.energy.2019.06.052. URL: https://www.sciencedirect.com/science/article/pii/S0360544219311818.

[2] Global Wind Energy Council. *Global Wind Report 2023*. Tech. rep. Global Wind Energy Council, 2023.

[3] Siemens Gamesa. *SG 14-222 DD Wind Turbine*. https://www.siemensgamesa.com/global/en/home/products-and-services/offshore/wind-turbine-sg-14-222-dd.html. Accessed: [09/10/2024]. 2024.

[4] M. Bilgili, H. Alphan, and A. Ilhan. "Potential visibility, growth, and technological innovation in offshore wind turbines installed in Europe". In: *Environmental Science and Pollution Research* 30 (2023), pp. 27208–27226. DOI: 10.1007/s11356-022-24142-x. URL: https://doi.org/10.1007/s11356-022-24142-x.

[5] Muhammad Omer Siddiqui et al. "Wind turbine nacelle testing: State-of-the-art and development trends". In: *Renewable and Sustainable Energy Reviews* 188 (2023), p. 113767. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2023.113767. URL: https://www.sciencedirect.com/science/article/pii/S136403212300624X.

[6] Move Laser. *Nacelle-Based Wind Lidar for Wind Turbine Control and Wind Monitoring*. https://www.movelaser.eu/en/remote-sensing-wind-lidars-for-wind-monitoring/nacelle-base-wind-lidar-wind-turbine-control-wind-monitoring/. Accessed: [09/10/2024]. 2024.

[7] Windar Photonics. *Brochures and Articles*. https://www.windarphotonics.com/brochures-articles. Accessed: [09/10/2024]. 2024.

[8] Vasilis Pettas et al. "Investigation on the potential of individual blade control for lifetime extension". In: *Journal of Physics: Conference Series* 1037.3 (2018), p. 032006. DOI: 10.1088/1742-6596/1037/3/032006. URL: https://dx.doi.org/10.1088/1742-6596/1037/3/032006.

[9] W. Fu et al. "Feedforward pitch control for a 15 MW wind turbine using a spinner-mounted single-beam lidar". In: *Wind Energy Science* 8.12 (2023), pp. 1893–1907. DOI: 10.5194/wes-8-1893-2023. URL: https://wes.copernicus.org/articles/8/1893/2023/.

[10] Eric Simley, Lucy Pao, and Edward Patton. "SIMULATION OF LIDAR WIND SPEED MEASUREMENTS FOR WIND TURBINE CONTROL APPLICATIONS IN AN EVOLVING LES WIND FIELD". In: *Dept. of Electrical, Computer, and Energy Engineering, University of Colorado* (2015).

[11] T. Mikkelsen et al. "A Spinner-integrated Wind Lidar for Enhanced Wind Turbine Control". In: *Wind Energy* 16.4 (2013), pp. 625–643. DOI: 10.1002/we.1564. URL: https://doi.org/10.1002/we.1564.

[12] *IEC 61400-12-1: Wind Turbines - Part 12-1: Power Performance Measurements of Electricity Producing Wind Turbines*. Accessed: [Insert Date of Access]. 2005. URL: https://webstore.iec.ch/en/publication/5429.

[13] Alexander Raul Meyer Forsting. "Modelling Wind Turbine Inflow: The Induction Zone". English. PhD thesis. Denmark, 2017. DOI: 10.11581/DTU:00000022.

[14] A. Peña, R. Floors, A. Sathe, et al. "Ten Years of Boundary-Layer and Wind-Power Meteorology at Høvsøre, Denmark". In: *Boundary-Layer Meteorology* 158 (2016), pp. 1–26. DOI: 10.1007/s10546-015-0079-8. URL: https://doi.org/10.1007/s10546-015-0079-8.

[15] Odessa American. "New Radar System". In: *Odessa American* (1961).

[16] Frank Macomber. "Space Experts Seek Harness for Powerful LASER Light". In: *Bakersfield Californian* 5 (1963). Copley News Service. Retrieved 11 July 2019. URL: https://newspaperarchive.com/bakersfield-californian-jun-03-1963-p-5/.

[17] A.V. Jelalian. *Laser Radar Systems*. Artech House radar library. Artech House, 1992. ISBN: 9780890065549. URL: https://books.google.dk/books?id=TEdqQgAACAAJ.

[18] Chris Slinger and Michael Harris. *Introduction to Continuous-Wave Doppler Lidar*. 2012.

[19] Vaisala. *Wind Energy - WindCube Nacelle*. https://www.vaisala.com/en/products/wind-energy-windcube-nacelle. Accessed: [09/10/2024]. 2024.

[20] R. Ungurán et al. "Uncertainty identification of blade-mounted lidar-based inflow wind speed measurements for robust feedback–feedforward control synthesis". In: *Wind Energy Science* 4.4 (2019), pp. 677–692. DOI: 10.5194/wes-4-677-2019. URL: https://wes.copernicus.org/articles/4/677/2019/.

[21] Nikolas Angelou et al. *Lidar Wind Speed Measurements from a Rotating Spinner: 'Spinner¿Ex 2009'*. 2009.

[22] Eric Simley et al. "LIDAR Wind Speed Measurements of Evolving Wind Fields". In: 2012. DOI: 10.2514/6.2012-656.

[23] S. Lehnhoff et al. "Full Scale Rotor Blade Deformation Measurements in Comparison with Aeroelastic Simulations Based on Measured High-Resolution Wind Fields". In: *Journal of Physics: Conference Series* 1618.5 (2020), p. 052036. DOI: 10.1088/1742-6596/1618/5/052036. URL: https://doi.org/10.1088/1742-6596/1618/5/052036.

[24] Daniel Houck et al. "A Hub-Mounted SpinnerLidar for the RAAW Experiment". In: *Proposed for Presentation at the NAWEA*. US DOE, 2022. DOI: 10.2172/2004730. URL: https://doi.org/10.2172/2004730.

[25] Esperanza Andrea Soto Sagredo, Jennifer Marie Rinker, and Rasmus Sode Lund. *Verification of Numerical Lidars in HAWC2: Analysis of Nacelle- and Hub-Mounted Lidars*. Report. DTU Wind Energy, 2023. DOI: 10.11581/DTU.00000302. URL: https://doi.org/10.11581/DTU.00000302.

[26] Alfredo Peña, Jakob Mann, and Gunhild Rolighed Thorsen. *SpinnerLidar measurements for the CCAV52*. English. Vol. 0177. DTU Wind Energy E. Denmark: DTU Wind Energy, 2019. ISBN: 978-87-93549-45-6.

[27] Eric Simley et al. "Analysis of light detection and ranging wind speed measurements for wind turbine control". In: *Wind Energy* 17.3 (2014), pp. 413–433. DOI: https://doi.org/10.1002/we.1584. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/we.1584. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/we.1584.

[28] Alfredo Pena Diaz. "Sensing the wind profile". English. Risø-PhD-45(EN). PhD thesis. DTU, 2009. ISBN: 978-87-550-3709-0.

[29] Susumu Shimada et al. "Coastal Wind Measurements Using a Single Scanning LiDAR". In: *Remote Sensing* 12.8 (2020). ISSN: 2072-4292. DOI: 10.3390/rs12081347. URL: https://www.mdpi.com/2072-4292/12/8/1347.

[30] Julie K. Lundquist. "Wind Shear and Wind Veer Effects on Wind Turbines". In: *Handbook of Wind Energy Aerodynamics*. Ed. by Bernhard Stoevesandt et al. Cham: Springer International Publishing, 2020, pp. 1–22. ISBN: 978-3-030-05455-7. DOI: 10.1007/978-3-030-05455-7_44-1. URL: https://doi.org/10.1007/978-3-030-05455-7_44-1.

[31] Roland B. Stull. *An Introduction to Boundary Layer Meteorology*. Springer Science & Business Media, 1988, p. 670.

[32] Tony Burton et al. "The Wind Energy Handbook". In: vol. 1. Jan. 2001. DOI: 10.1002/0470846062.

[33] J. Mann. "Wind field simulation". In: *Probabilistic Engineering Mechanics* 13.4 (1998), pp. 269–282. DOI: 10.1016/S0266-8920(97)00036-2. URL: https://doi.org/10.1016/S0266-8920(97)00036-2.

[34] Thomas Foken, ed. *Springer Handbook of Atmospheric Measurements*. 1st ed. Springer Handbooks. Bayreuth, Germany: Springer Cham, 2021, pp. LVIII, 1748. ISBN: 978-3-030-52170-7. DOI: 10.1007/978-3-030-52171-4.

[35] Neil Kelley et al. "Comparing Pulsed Doppler LIDAR with SODAR and Direct Measurements for Wind Assessment". In: (Jan. 2007).