1. Introduction

Renewable energies, their production, transportation and storage are one of todays most important technical and scientific fields, especially in Germany, after the decision to exit nuclear energy was made. Nuclear energy is intended to be replaced by renewable energy such as photovoltaic, biomass, hydroelectric, geothermal and wind energy of which the latter is one of the most promising in Germany, due to its climatic, geological and geographical properties. As still in Germany the sources for renewable energy that provide high yield are limited, to satisfy the increasing demand for energy it is an important and promising strategy to optimize the efficiency. For wind energy this can be done by optimizing the design of wind power plant with respect to mechanics, flow mechanics and electrics. For maximum electrical power output and to reduce mechanical peak loads that could damage the plant, the controlling of the dynamical behavior has to be optimized as well, e.g. the orientation of the nacelle and especially the orientation of the blades according to the current wind situation.

Information on wind speed is obtained by real time wind measurement, usually by means of a mechanical anemometer placed on the nacelle of the turbine. This is a simple, cost-efficient and reliable method, but the measured quantities can become unreliable as the flow of the wind can be disturbed by turbulences caused by the mast, nacelle or its blades. Furthermore only the speed of the wind speed can be measured that has already hit the rotor. Changes in wind speed will be detected only after they have reached the plant. During this time the plant may suffer from higher mechanical load or suboptimal adjustment. The former can lead to higher costs for maintenance, shorter lifetime or even damage, the latter to suboptimal energy-output.

Forecast measurements of wind speed changes with a leadtime of in the order of tens of seconds can help reduce these issues. This can be done by measuring the wind speed at a distance of several 100 m in front of the rotor plane. From a measurement at this location the wind speed change at the plant can be derived with a certain lead time, allowing for an accurately timed optimal adjustment of the parameters of the plant to the wind situation in order to avoid the problems mentioned above.

One way of getting forecast information on wind speed is to install tall measurement masts about as high as the wind power plant itself. This approach is rather expensive and lacks versatility if the wind direction changes, or requires multiple masts in different directions.

A different approach is using lidar (light detection and ranging) systems for remote sensing of the wind speed at distances up to a few 100 m in front of the wind turbine as an alternative or complement to tall measurement masts.

First lidar systems have been known for atmospheric remote sensing since the 1930s [1]. The rapid development and spread of modern systems, however, started with the invention of lasers [2, 3]. Classical applications are the range resolved measurement of quantities such as temperature, pressure, humidity, concentration of trace gases and aerosols in the atmosphere or wind speeds using various techniques such as the Raman effect, differential absorption, polarization or frequency analysis [4]. Recently the measuring and surveying of wind fields has opened a new field of application for lidar systems [5, 6], in particular in the field of wind energy [7].

Lidar measurements of the wind speed rely on the fact that the emitted light is scattered by particles and aerosols that are moved along with the air. Scattering by moving particles makes the scattered light undergo a frequency shift compared to the incident light, the familiar Doppler shift. As this frequency shift is proportional to the line-of-sight (LOS) speed of the scattering particle a frequency analysis can reveal the speed. Based on this effect, wind lidar systems are known as Doppler-lidar systems.

A single measurement can only yield a single speed component of the wind velocity vector, which usually is the line-of-sight, if emitter and receiver are located at the same position. Before surveying a whole wind field, the first task is to determine the velocity component along the line-of-sight, preferably in real time. After that, different lines of sight can be chosen from which the remaining components of the wind velocity vector can be determined. Scanning techniques for determining the whole wind vectors are e.g. velocity-azimuth display (VAD)[8, 9] or the reduced variant Doppler beam swinging (DBS) [10] also referred to as wind profiler. Eventually the wind velocity distribution of the whole wind field can be measured.

Lidar systems are not only suitable for being installed in already existent wind power plants, but also the related task of site surveys of potential wind farms.

1.1. Lidar

Lidar systems can be divided into two groups: pulsed lidar systems and continuous-wave (cw) lidar systems. The former provide inherent spatial resolution by sending out short pulses of laser light the duration of which (i.e. the distance between the leading and the trailing edge of the pulse) defines the range resolution of the system. The measurement distance of such systems is set by choosing a certain time gate, corresponding to the round trip time of the laser pulse from the lidar system to the location of interest and back to the system. The length of this time gate corresponds to the pulse duration. Typical values for the range resolution of such systems lie in the range of meters, corresponding to time gates in the order of 10 ns. The spatial resolution of such a system can easily be changed by altering the pulse duration. When used for frequency measurements, as in the case of Doppler lidar systems, this type of lidar suffers from the uncertainty relationship of simultaneously measuring frequency and time, as the region of interest is illuminated only for a short period of time. Furthermore, pulsed lidar systems have rather complex setup.

Compared to pulsed systems, cw lidar systems exhibit a simpler setup. They obtain their range resolution from focusing the laser beam on a certain location in the atmosphere since the close-to-focus-range contributes primarily to the received signal [11–13]. Thus the resolution is determined by the length of the focal zone, i.e. the Rayleigh range if the laser beam is Gaussian. This prohibits independent adjustment of measurement range and range resolution without severe intervention into the mechanical setup. A typical range resolution for this type of system is in the order of 10 m for a measurement distance of 100 m. The range resolution for cw lidar systems deteriorates approximately to the square of the distance and, moreover, the boundaries of the resolution zone are poorly defined.

This rather inflexible procedure of establishing range resolution makes changing the measurement range and range resolution more tedious than it is with pulsed systems. For a modification of the measurement range cw systems require mechanical refocusing of the laser beam and the measurement has to be repeated afterwards. A change of the spatial resolution at a certain location, i.e. the change of the Rayleigh range, is even harder to achieve, as this would require a different telescope or a different beam radius at the telescope.

In remote wind sensing for wind power plants there is a strong interest in eye-safe, affordable and compact systems. This requirement can be met by using components of optical communication technology for wavelengths around 1550 nm, in particular semiconductor laser diodes, semiconductor photodiodes, quartz glass fibers and erbium fiber amplifiers. Inside the system the light is routed through optical fibers, creating an all-fiber lidar, that leads to simple setup and alignment, increased robustness and low cost. These components are already commercially available in high quality. Together with a small transmitting telescope they represent the basic components typical wind sensing lidar systems are built of. Both types of lidar systems for remote wind sensing are commercially available, pulsed systems e.g. from Leosphere (Windcube) or Catch the Wind (Vindicator) as well as cw systems e.g. from Natural Power (ZephIR).

1.2. Optical Low Coherence Lidar

The lidar system presented in this thesis [14–18] addresses the disadvantages of conventional cw lidar systems: vulnerability to strong out of focus scattering and tedious change of measurement distance, poor and poorly changeable range resolution and the need for repeated measurements will be avoided by translation of the optical low-coherence reflectometry (OLCR) [19–24] principle to lidar systems in combination with a newly developed synthetic broadband laser source.

The OLCR principle (also known as optical coherence domain reflectometry, OCDR) is well known from characterization and inspection of waveguides and integrated components as well as in optical coherence tomography in medical applications. Instead of the very low range resolution of a few µm that classical OLCR system can provide, we focus on a range resolution in the order of meters. As Doppler lidar systems rely on the detection of light scattered by airborne particles, the received signal from the atmosphere will be very small. Even with nearly quantum-limited detection [25] a certain number of particles is required which is not given if the range resolution is set too small (e.g. a few µm). To obtain a range resolution in the meter range in an OLCR system a laser source with a bandwidth of a few MHz is needed. Basically this goal can be achieved by installing a telecom laser diode with an appropriate bandwidth. A change of range resolution in this case is only possible by switching between different laser diodes with different bandwidths, but the problem of changing the measurement position persists. As we are aiming at distances and distance changes in the order of about 100 m, moving a mirror as in classical OLCR measurements is not a feasible approach. Changing the reference arm length by switching between different lengths of fibers is possible but cumbersome and does not yield continuous range scanning. Moreover it requires multiple measurements.

For the optical low coherence lidar system (OLCL) we therefore use a broadband light source with an adjustable bandwidth. Light from a narrowband laser diode is properly phase modulated to generate a specific power spectral density (PSD). The bandwidth of the spectrum defines the spatial resolution whereas the spectral shape defines the confinement of the resolution range by the corresponding coherence function which is the Fourier transform of the power spectral density. Since the PSD can be shaped arbitrarily, the output spectrum is not limited to the Lorentzian shape of natural laser diodes, but a more advantageous shape can be chosen, a Gaussian shape in this case, which offers a better confined range resolution. A change of the spatial resolution becomes easily possible for cw lidar systems, as it is only necessary to select a different phase modulation. Besides, since the phase evolution of the electric field of this source is known, it opens up the possibility of numerical range scanning after the measurement has been taken. Thus the wind velocity information along the line of sight can be determined from a single measurement without repetition. A side effect of a setup that allows for range scanning without the need of refocusing is that the system no longer comprises any moving parts, which could pose a source of errors and higher costs from the setup itself as well as from maintenance.

In the following a general cw Doppler lidar system and its components will be described in chapter 2, since cw lidar presents the principle OLCL is based upon. Examples of hardware components and numerical quantity values that are given in this chapter are taken from from the OLCL system that is presented in the following chapter 3. Here, the theoretical background will be investigated and simulation and experimental results will be presented. Besides the remote measurement of wind speeds, OLCL is also useful in other applications, two of which will be explained in chapter 4. Section 4.1 details the application as a range resolving vibrometer for remote monitoring of the movement of surfaces. Section 4.2 shows how the OLCL system can be extended to work as a differential absorption lidar (DIAL) with the ability to measure the range resolved concentration of trace gases.

2. Doppler Wind Lidar

The phenomenon of a change in observed frequency of a wave in case of a moving emitter or a moving receiver due to actual or perceived stretching or compression of the wavefronts is referred to as the familiar Doppler effect. It was named after the Austrian physicist Christian Doppler (1803-1853) who was the first to investigate this effect for acoustic waves.

Since the frequency shift depends on the speed difference between emitter and observer, this phenomenon allows for a speed measurement if the group velocity of the wave is known. A well known example for the acoustic Doppler effect in daily life can be experienced by listening e.g. to the sirens from emergency vehicles, the perceived frequency of which alters when the vehicle is passing by. Technical applications using the acoustic Doppler effect today are for example diagnostic sonography, echocardiography or sonar.

In the classical description of the acoustical Doppler effect, the cases of moving emitter and/or moving observer have to be distinguished as depicted in fig. 2.1. When emitting a signal at frequency f_0 in the case of a moving observer with speed v the perceived frequency at the observer is

$$f_{\mathrm{obs}} = f_0 \left(1 + \frac{v}{c}\right). \tag{2.1}$$

In the case of a moving emitter at the same speed the frequency detected by a stationary observer is

$$f_{\mathrm{obs}} = \frac{f_0}{1 - \frac{v}{c}}. \tag{2.2}$$

Here, the emitter and the observer are assumed to move straight towards one another.

The following sections in this chapter deal with the optical Doppler shift in 2.1, techniques for detection of movement perpendicular to the line of sight are presented in 2.1.3. Since OLCL is based upon already well-known cw lidar, sections 2.2, 2.3 and the appendix A will give an overview of cw lidar systems and the techniques that are commonly implemented for detection of wind speed.

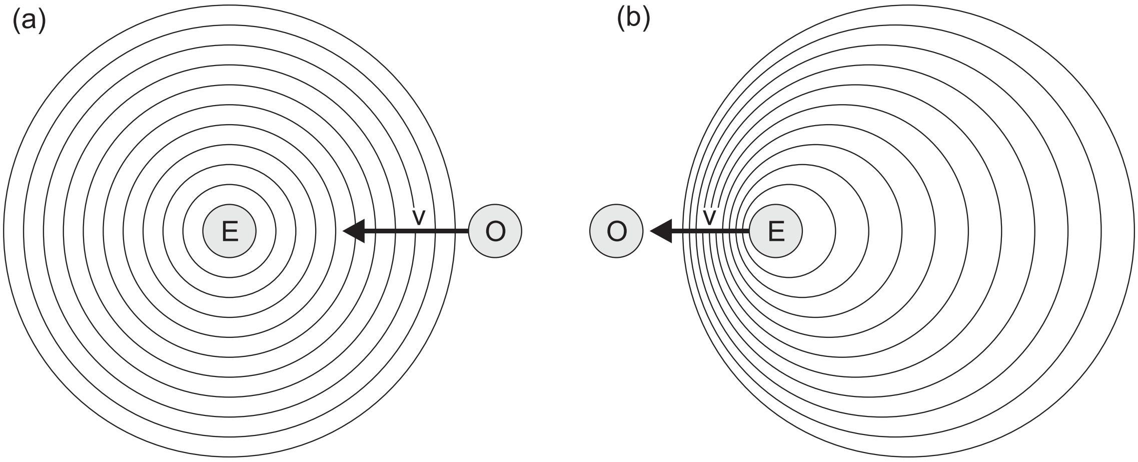

Figure 2.1.: (a) Wave field from stationary emitter (E), frequency perceived by a moving observer (O) corresponds to eq. 2.1; (b) wave field of a moving emitter (E), frequency experienced by a stationary observer (O) corresponds to cp. eq. 2.1

2.1. The Optical Doppler Effect

The Doppler effect applies not only to acoustic waves and related phenomena that require a medium for the propagation of waves. Electromagnetic waves propagate without the need of a medium at the speed light c_0. In this case the relativistic Doppler effect has to be considered, which differs from the classical Doppler effect: Time dilation from special relativity has to be included in the equations and, since the choice of inertial frame of reference is arbitrary, only the relative speed between emitter and observer is relevant. Considering a relative movement between emitter and observer, only the line of sight (LOS) component of the velocity-vector yields a frequency shift, cp. fig. 2.2. The transverse Doppler effect describing the frequency shift due movement perpendicular to the line of sight can be neglected due to the low velocities involved. Emission of radiation with a wavelength of λ_0 or the frequency $f_0 = c_0/\lambda_0$, respectively, and a relative speed v_{LOS} between emitter and observer results in the detection of the frequency

$$f_{\text{obs}} = f_0 \sqrt{\frac{c + v_{\text{LOS}}}{c - v_{\text{LOS}}}}. \tag{2.3}$$

Here, the movement of emitter and observer towards each other is defined as positive. In the case of low speed differences $v_{\text{LOS}} \ll c_0$ eq. 2.3 simplifies to

$$f_{\text{obs}} = f_0 \left(1 + \frac{v_{\text{LOS}}}{c_0}\right). \tag{2.4}$$

Since the speed of light is known with high accuracy, electromagnetic radiation is well suited for remote measurements of speeds. Applications are found e.g. in radar, laser-Doppler-vibrometry, lidar and satellite communications. A famous astronomical example for the application of the Doppler effect was the discovery of the redshift of light emitted from distant stars and galaxies, leading to today's assumption of an expanding universe.

2.1.1. The Optical Doppler Effect in Doppler Lidar

In lidar measurements in most cases the object of interest does not emit radiation, hence a common way of performing measurements using the Doppler effect is to illuminate the target with radiation. In wind lidar systems, aerosols and airborne particles, such as dust, water, smoke, etc. serve as scattering particles that provide a signal. Thus wind lidar systems actually measure the speed of theses particles, but due to their small mass, the assumption can be made, that they accurately follow the movement of the air.

The light perceived on the moving particles appears Doppler shifted as explained in the previous section in eq. 2.4. Subsequently the light is reflected, scattered or reemitted, causing a second shift in frequency, this time the particle is acting as as a moving emitter. Again, the frequency is shifted according to eq. 2.4. After applying the Doppler shift twice the reflected light that propagates back to the detector has a frequency

$$f \approx f_0 + f_0 \frac{2v_{\mathrm{LOS}}}{c_0}. \tag{2.5}$$

The second term denotes the Doppler frequency shift which is defined as

$$f_{\mathrm{D}} = f_0 \frac{2v_{\mathrm{LOS}}}{c_0}. \tag{2.6}$$

Here, the Doppler effect can be described by the simplified version as in eq. 2.4, since the wind speed is much smaller compared to the speed of light.

A frequency analysis of the detected reflected light directly reveals the Doppler frequency shift f_{D} which is proportional to the speed to be determined. Using light in the near infrared region as it is generally used in optical communications, with e.g. $\lambda = 1550\,\mathrm{nm}$ or $f = 193.5\,\mathrm{THz}$ a movement of $v_{\mathrm{LOS}} = 1\,\mathrm{m/s}$ causes a Doppler frequency shift $f_{\mathrm{D}} = 1.29\,\mathrm{MHz}$.

Scattering by air molecules is present as well but this signal is not used in wind sensing lidar, as it will be strongly Doppler broadened, as will be explained in sec. 2.1.2.

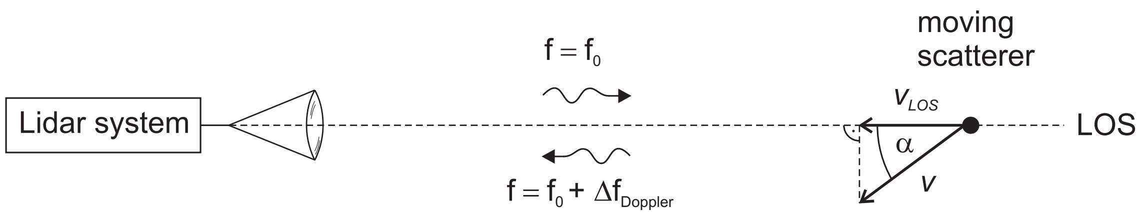

Figure 2.2.: Doppler effect arising from scatterer with velocity component in LOS-direction

2.1.2. Doppler Broadening

A side effect of measuring the speed of a distributed target such as particles in air is Doppler broadening. Even with a homogenous flow of air, molecules and particles undergo a random individual thermal movement which causes spectral broadening of the received signal. Air molecules with low mass move at comparatively high speeds causing a thermal Doppler broadening with a full width at half maximum (FWHM) bandwidth in the 100 MHz or GHz range[26]. As this is several orders of magnitude larger than the typical wind-induced frequency shift, the resulting spectrum is not well suited for determining the frequency shift because the ratio of frequency shift to bandwidth is low. Particles on the other hand, like dust, soot, smoke or water vapour possess a much higher mass and move at a much lower thermal velocity, so the Doppler broadening is less severe. The FWHM in this case is typically in the kHz range [4], which makes the signal component from aerosols suitable to detect the wind induced Doppler shift. As both processes, scattering from molecules and particles, are occurring in the atmosphere simultaneously, acquiring the pure aerosol signal may require proper filtering.

2.1.3. Detection of Transverse Wind Speed Components

Techniques to measure the speed of objects moving along a path perpendicular to the line of sight, in particular of distributed targets like particles moved with the air are also available [27]. Laser Time-of-Flight velocimetry (LTV) [28–30] focuses 2 separate laser beams very closely spaced in the atmosphere. Particles crossing both foci will produce 2 impulses of scattered light which can be detected. From the time difference