Master of Science (MSc) in Wind Power Project Management

- Spring Semester – Master Thesis –

Turbine-Mounted Lidar:
The pulsed lidar as a reliable alternative.

Author: Isaac Braña

- Wind Energy Department -

Supervisor: Richard Koehler
Examiner: Bahri Uzunoglu
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Acknowledgements

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Abstract

Expectations for turbine-mounted lidar are increasing. The installation of lidars in wind turbine nacelles for measuring incoming winds, preventing wind gusts and increasing energy productions is after recently studies, technically and economically feasible.

Among available lidar types, the most studied were continuous wave lidars because they were the most reliable apparatus when this initiative began. However, after studying technical considerations and checking commercial lidars, it was found that pulsed lidars lead this technology due to their promising results.

The purpose of this report is to fill the gap between the interest in this technology and the absence of any academic papers that analyzes continuous-wave and pulsed lidars for the mounted lidar concept. Hence, this report discusses the importance of turbine-mounted lidars for wind power industry, different possible configurations and explains why specifically pulsed lidars are becoming more important for the mounted lidar market.

Key words:

Wind power, doppler lidar, pulsed lidar, continuous-wave lidar, power control system, wind turbine-mounted lidar.

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Background Description

This project was as part of the Master's of Science programme in Wind Power Project Management (60 ECTS) offered by Gotland University, Sweden, for 2010-2011. The starting date of this research was on 01st April 2011 under the supervision of. Richard Koehler, and the final submission on 03rd June 2011 following the approval of Dr. Bahri Uzunoglu.

The master program was divided into nine modules. The fall semester (30 ETCS) was characterized by the introduction to the technology and the wind energy concepts such as wind resources assessment, advanced energy estimations, turbine efficiency and grid integration. The the spring semester is focused on the management module (spatial planning, management of wind farms projects, and wind site optimization) with 15 ECTS, and the final research thesis (15 ETCS).

Thesis Timeline

1st April 2011: Starting of the project.
4th May 2011: First draft of theory and methodology sections.
16th May 2011: Supervisor – Examiner review draft – full thesis document.
23rd May 2011: Final draft for opposition review and final corrections.
17th June 2011: Finished thesis – final form for record.
30th July 2011: Report improved after the examiner' comments.
08th December 2011: References 22 and 29 updated.
03rd January 2012: References on Fig. 3, 5, and 11 were modified.

Theory and Methodology

Turbine-mounted lidar is a recently concept based on the installation of a lidar unit in the wind turbine nacelle. The first academic paper that mentions this term was written by NREL (National Renewable Energy Laboratory) in the USA in 2006 and shortly afterwards other research centers as DTU in Denmark or University of Stuttgart (Germany) developed an interest in this concept.

However, the investigated alternatives were dissimilar. Whereas NREL and DTU decided to examine continuous wave (cw) lidars, the German institution choose pulsed lidars. After the first investigations, when pulsed lidars were less developed, everything indicated that pulsed lidars do not have any opportunity for installation on turbines. However, nowadays it is different.

After investigating technical the technical principles involved in both types of lidar, and analyzing the market positions of private companies, the indication are that pulsed lidars are at the same level or even better positioned than cw lidars for leading this promising market.

Chapter I explains the importance of this technology for the wind power industry and which solutions the turbine-mounted lidar could provide. Chapter II analyzes different configurations and alternatives related to this concept. Additionally, this section includes is mentioned some of challenges and improvements that lidar devices must cope with. In Chapter III, the main differences between cw and pulsed lidars are studied. Furthermore, it will be explained the advantages of each type and we will conclude that pulsed lidars do not have any technical obstacles to further market penetration. Chapter IV will focuses on the commercial perspectives. This report describes the companies involved in this technology, recently joint-ventures and future projects.

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Nomenclature

Ψ Azimuth Angle [rad].

c   Speed of light [m s-1]

V_{los} Velocity measured along the line-of-sight [m s-1].

ν Frequency of emitted signal [Hz].

σ Frequency of backscattered signal [Hz].

λ Wavelength of emitted signal [m].

δ Wavelength of backscattered signal [m].

$\delta\nu$ Frequency difference between emitted and backscattered signal [Hz].

u, v, w   Components of wind directions for the x, y and z respectively [m s-1].

θ Angle between laser beam and x axis [rad].

φ Angle between V_{los} and horizontal wind [rad].

F   Length from optical fibre to lens [m].

$F^{'}$ Focus distance [m].

F_l Focal length of lens [m].

Z_R Rayleigh length [m].

$2 Z_R^{'}$ Volume depth of laser beams [m].

W_O Minimum radio of laser beam in the optical fibre [m].

W_{OUT} Focus volume radius [m].

ΔZ Radial sounding volume size for pulsed lidars [m].

Δr Spatial longitude of pulsed laser beams [m].

Δp Distance between pulsed beams [m].

PRF   Pulse Repetition Frequency [Hz].

τ Time between pulsed beams [s^{-1}].

Erf   Gauss error function.

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t_p Time of pulse duration [s].

β Angle between emitted laser beams [rad].

α Angle between emitted laser beams [rad].

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Chapter I – Scope

Introduction

From the first wind turbines erected at the end of the nineteenth century, the size of these machines has continuously increased. Currently, there are 7 MW turbines being developed and it seems that the trend towards bigger turbines is likely to continue. [1]
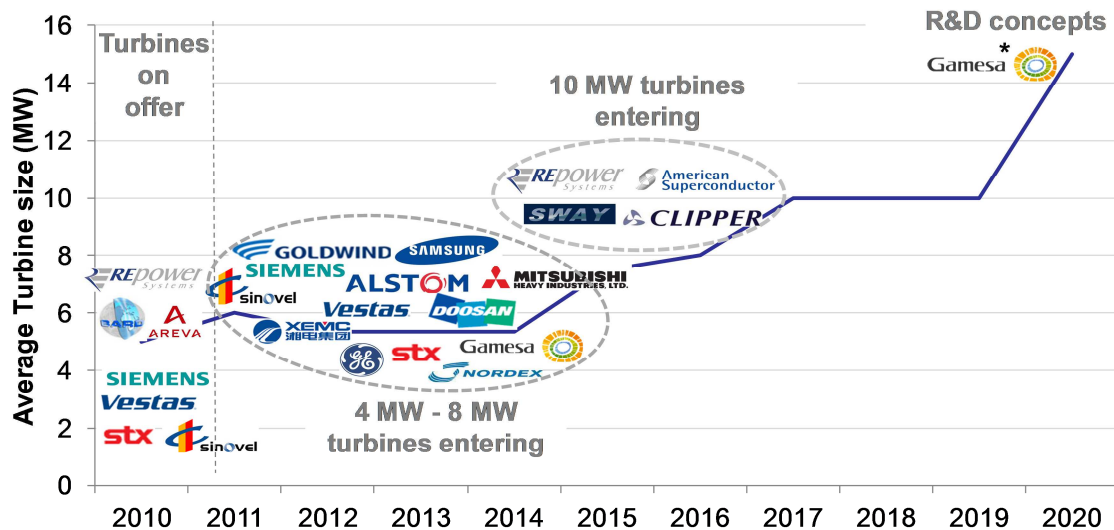

Fig. 1.1: The size of wind turbines is continually increasing. The main wind turbine manufacturers are working to offer to the market higher and more powerful machines due to the possibility to harness higher wind resources. Note: *Gamesa leads a R&D consortium for developing the 15 MW Azimut Turbine.[2]

The reasons for such big structures can be explained by the possibility of harnessing higher wind resources. Placing fewer and more powerful wind turbines have some important advantages such as less visual impact to local people, and projects more profitable. However, costs for operating those wind farms (especially, O&M) are an important factor that slows down the growth of such structures.

To meet these challenges, new technologies must be developed for reducing costs and prolonging the expected life of turbines. Techniques that seemed not economically viable are being considered under this new framework of higher turbines and less accessibility to maintenance tasks.

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Defining the problem: Wind Gusts

One of the most important considerations for increasing the life and reducing breakdowns in wind turbines would be a system to protect them against wind gusts. This wind behavior is very harmful for the whole wind turbine but especially to root blades, tower bases and hubs.

The typical behavior of wind gusts is represented by the figure called the "Mexican Hat" (see continuous line in the upper graph on Fig. 2). The wind keeps steady until it decreases slightly, then and suddenly, wind speed increases up to unsafe conditions for wind turbines. Though technology and endurance of wind turbines has improved considerably over the past decades, wind gusts provoke many problems to the equipment and currently there is not any definitive solution in the market for preventing the negative effects of wind gusts and avoiding damage in wind turbines.

One of the alternatives that scientists are considering to minimize the wind gusts' consequences is the called *Artifical Neural Networks* (ANN). This solution is based on interconnecting wind turbines and controlling them by an algorithm that forecast wind gusts. However, wakes in wind farms and errors on wind gusts' predictions make this technique difficult to realize. [3]

Another solution is installing a lidar device in the nacelle of each individual wind turbine for measuring the incoming winds and integrating it into the control system. This technique, called *Turbine-Mounted Lidar*, has more advantages in comparison with the ANN for preventing damages from wind gusts. Turbine-mounted lidar is technically feasible because lidar apparatuses have greatly improved in recent years and their costs are decreased as well. One of the advantages is because reliability does not only depend on hypothetical situations foreseen by algorithms. Secondly, by knowing in advance incoming winds, it is possible to adapt the pitch of the blades and the yaw angle. Hence, this technique makes possible optimizing the power control of wind turbines under stochastic winds, and thus it increases the output power.
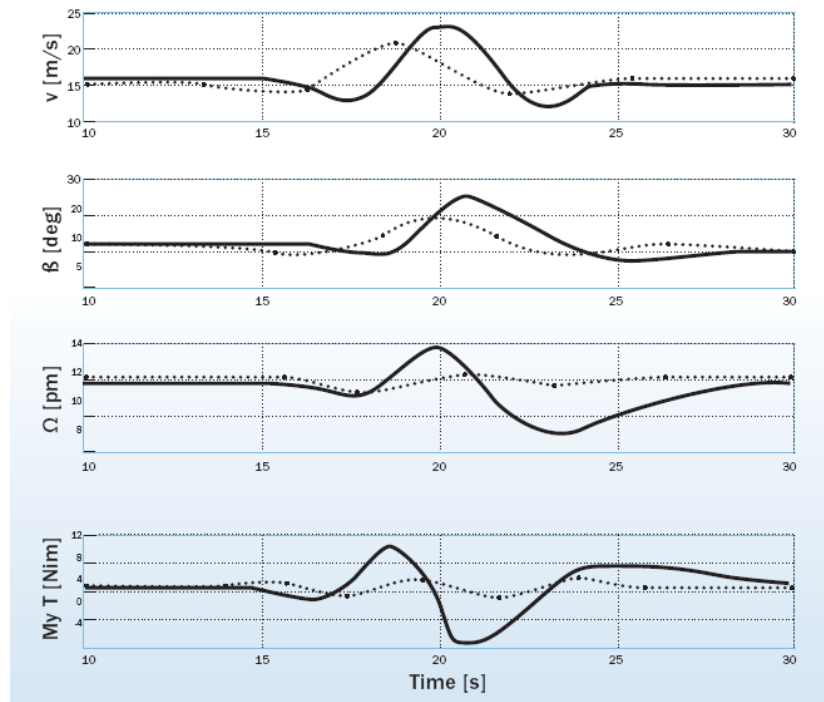
Fig. 2: Under computer simulations (Bladed), the European project FP6 can predict the consequences of integrating a lidar into the power control of wind turbines. The upper graph shows the real wind with the continuous line ("Mexican Hat") and the measurement by the lidar with the dotted line. The next second, third and fourth graph illustrate the behavior of pitch angles, rotor speeds and tower bending moments (respectively) by preventing the power system with lidar measurements (dotted lines) and without it (continuous lines). It is easy to understand the importance of integrating lidar measurements in order to avoid fatigues and maintenances during the life of wind turbines.[4]

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Types of Remote Wind Measurements. Why Lidar?

Lidar is not the only technology that provides remote measurements of fluids. These techniques have a wide spectrum of uses and they are employed for determining gas compositions, military applications, turbulence and wake measurements at airports, and so on. However, lidar is the only apparatus that has a suitable application for wind measurements for the wind industry. Nevertheless, it is interesting to review briefly the different available techniques and explain why lidar is the most suitable for developing turbine-mounted lidars.

Sodar: Though it has been used in the wind industry with success, it is not suitable for installing in hubs/nacelles. Noise disturbances from the turbines make it impossible to obtain accurate measurements. In addition, the emitted sound beam will be interfered by the blades, the ground, and so on. Furthermore, the sensitivity of these devices is much lower than lidars.

Laser Doppler Anemometry (LDA) or Laser Doppler Velocimetry (LDV): With the intersection of two laser beams at the point required, it measures the frequency of the created fringe. It is only possible to use it for short distances and therefore, its applications are few. (See Annex A).

Particle Imaging Velocimetry (PIV): By taking snapshots of particles with a digital camera, it is possible to determine the speed and related properties of fluids. Nevertheless, it is not suitable for atmospheric conditions because it is necessary previously to add small particles to fluids. [5]

Doppler Global Velocimetry (DGV): DGV detects frequencies of backscattered signals according to the Doppler Effect and thus, it is able to determine speeds of fluids. The return signal is transmitted through an iodine cell which has a strong absorption line. Unfortunately, neither this technique is the most suitable for the wind industry because their extremely complexity of these devices make possible to use them for laboratory applications. [6]

Incoherent (or direct detection) Doppler lidar: As coherent doppler lidar does, they measure the frequency of scattering signals. Two techniques are being used: the double-edge Fabry-Perot interferometer (FPI) and the iodine vapor filter (IVF). [7] Since the late 1990's, the interest on these devices has increased due to the fast development of opt-electronics techniques. However, the size, cost, and complexity of this equipment are not appropriated for installing in nacelles of wind turbines. [8]

Coherent Doppler Ladar (CDL), Coherent Laser Radar (CLR), Ladar, or simply LiDAR: From the first trials in the late of 1960s for remote wind measurements, technology of these devices has improved a lot thanks to components of fiber-optic telecommunication that make possible to transmit information from one place to another one by sending pulses of light through an optical fiber. Therefore, lidars can be used for measuring wind profiles, distributions, directions, shears and veers. Its accuracy is well proven from independent studies, [9] and its cost has been reduced in recent years. This

has led to increased popularity of this technology in the wind industry. Hence, lidar apparatuses seems to be the most suitable solution for measuring incoming winds.

Lidar solutions

LIDAR technology can be a breakthrough to mitigate the effects of wind gusts because the improvements reached from fiber telecommunication are making it possible to produce devices more reliable and less costly. LIDAR (LIght Detection and Ranging) is a device that allows measuring wind speeds and wind directions by using laser beams.

Its basic contributions to the wind power industry is that it is ideal for complementing traditional meteorological masts. By collecting wind data from the ground, and after correlating the values with cup and sonic anemometers, measurements provided by the lidar make possible to determine accurate wind data for determining good locations for new wind farms or studying wakes interactions.

However, wind power professionals go further. New research demonstrates that is technically feasible to mount a LIDAR device in the nacelle for measuring incoming winds and combining it with the power control of wind turbines. [10] In this way, knowing in advance the stochastic wind speeds and wind directions makes it possible to better adjust blades pitch, revolutions per minute (rpm) of the rotor, and yaw systems. In other words, higher performance and fewer loads (fatigue and extreme loads) can be achieved.

Evolution

It is interesting to observe the fast evolution of laser technology and more specifically, the progresses and milestones made in the adaptation of laser technology into the turbine-mounted lidar concept.

The first person to describe the laser fundamentals was Albert Einstein and after him, five Nobel Prizes were given to scientists for their researches related the laser technology. This demonstration of laser technology is still very interesting for many applications and it is still under new scientific researches.

In 1960, Theodore Maiman built the first laser, called "ruby laser" which was based on strong pulses of red light. In addition, NASA agency, in the middle of the Cold War when they had high financial support, also played a crucial role in this field by developing the first Coherent Doppler Lidar for measuring wind speeds. [11]

Commercial lidars came in the first decade of this century. Firstly, the continuous-wave (CW) lidar appeared in 2003 and later, thanks to the development of fiber telecommunications in the late of 90's, the pulsed lidars emerged to the market in 2006 (WindCube) and in 2008 (Galion). At the same time that these commercial lidars were unveiled, interest on turbine-mounted lidars started.

After the experience of mounting a cw lidar in a 2,5 MW Nordex wind turbine in Germany in 2003, the first report that mentioned the possibility to adapt a lidar unit into the power control of wind turbines appeared in 2006. This paper was written by a professional involved in a company which develops cw lidars and people related to the National Renewable Energy (Colorado, US). Though it has many remarkable facts, it failed in its prediction, which suggest that it is not possible develop a turbine-mounted lidar with pulsed lidars.

Following the trend that cw lidars are better prepared for challenging environments as nacelles are, the technical research centre of Denmark, DTU, started testing these lidars in 2009. They mounted them on the top of the nacelle of a 225 kW wind turbine and into the hub of a 2,5 MW for analyzing the collected wind measurements.

However, the Universität of Stuttgart (Germany) decided in the same year testing the pulsed lidar in a 5 MW wind turbine. This experiment could be considered as the first evidence that pulsed lidars are reliable enough to develop turbine-mounted lidars.

On the other hand, the signs that turbine-mounted lidars are economically profitable are founded on the fast progress reached by private companies such as Catch The Wind Inc. (CTW). This American firm, in collaboration with several research centers, demonstrated that is possible to increase the annual energy output of a turbine by more than 10% by using this technology. Hence, this extra energy would be a reason enough for recovering the economical investment that lidars need.

Furthermore, recently there have been some collaborations and partnerships among important private firms in order to accelerate their market positioning in the wind power industry. One example would be the development of a blade with a lidar integrated by the Danish company LM Wind power, the largest blade manufacturer in the world. This and other joint ventures will be analyzed in the last section of this report.

Finally, it must be emphasized the rapidity and of events. In less than ten years, it has been possible to develop commercial wind lidars and and installing them in nacelles.
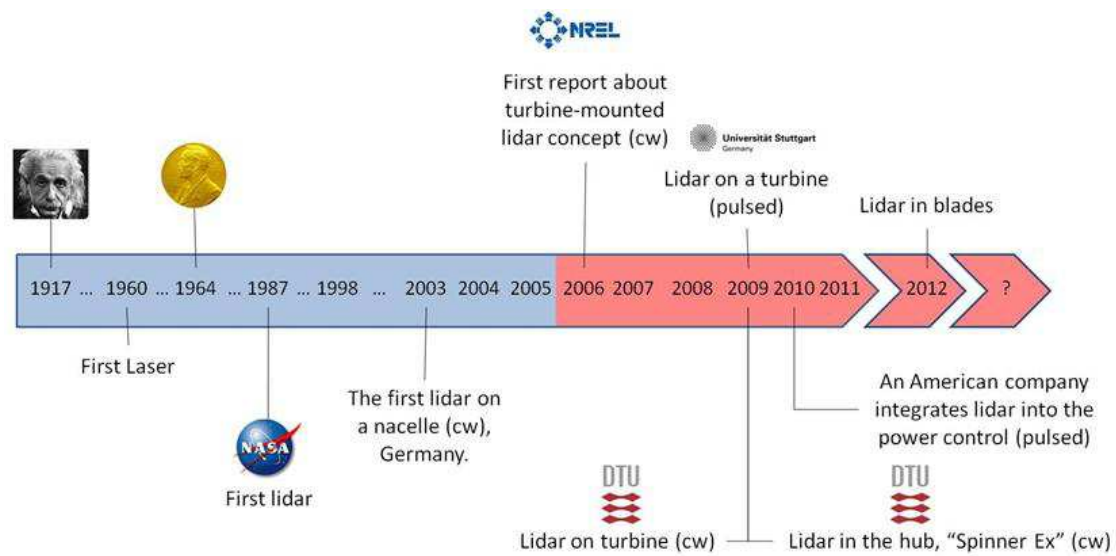
Fig. 3: The evolution of laser, lidar and turbine-mounted lidar is closely related. Laser investigations are having enormous repercussions on our daily lives and further research is in progress. NASA developed the lidar equipment but its price was prohibitive for commercial purposes. After the progress reached, the continuous wave lidar was the technology chosen for the development of turbine-mounted lidar. However, pulsed lidars could displace them.[Source: By author].

Chapter II – The Turbine-Mounted LIDAR concept

Before going further, it is necessary to describe how the turbine-mounted lidar works.

Turbine-mounted lidar: Concepts

Mounting a lidar in the nacelle for measuring incoming winds is a new technique that is still under development by private companies and public research centers. By knowing the wind measurements ahead of the rotor, control system of wind turbines can adjust the pitch, rpm and yaw systems in order to have smooth conditions, thus, reducing loads and increasing energy output.

However, lidar units must be adapted to the challenging environment as nacelles are. Among other considerations, lidars at that locations must cope with vibrating conditions for long times, avoid electrical interference from the generator, and different configurations and alternatives must be evaluated.

Nevertheless, the basic configuration is easily understandable. Firstly, lidar measures the wind speed at the predetermined distance. This distance cannot be too far because winds evolve by themselves and previous measurements at that range could not valid after the wind evolution. Specifically, after considering that control system of wind turbines requires only short preview times to adapt the wind turbine to new wind conditions.[i] One solution would be measuring far winds from turbines and the wind evolution model keeps this information until it is necessary to apply it.

The design for adapting the mounted lidar in the nacelle to the control system of wind turbines is shown in Fig 4. The measurement provided by the lidar unit is integrated to the wind evolution model and later, into the control system of wind turbines. Control system, and more specifically pitch control, combines this information with the collective pitch feedback controller to control the rated generator speed. Thus, the Feedback Loop that wind turbines have at this moment might be integrated with extra information that lidar provides, the Feedforward Loop.

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[i] Some authors argue that the optimal preview time for adapting a 600 kW wind turbine for winds up to 18 m/s is only 0,45 sec (around 8,1 meters in front of the turbine).

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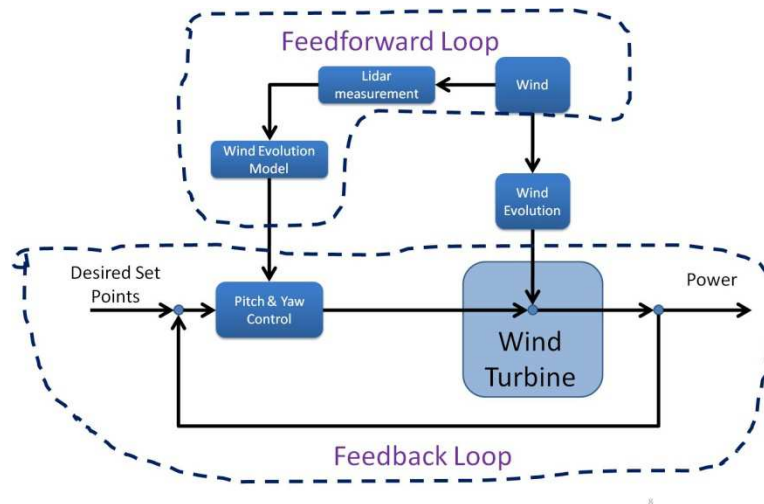July 30, 2011   Page 21

Fig. 4: At this moment, commercial turbines are equipped only with the Feedback Loop configuration. Cup anemometers (or ultrasonic anemometers) on the top of nacelles register the wind shears and veers. However, this system does not protect to turbines from wind gusts. The additional Feedforward Loop reached by the lidar technology makes possible to measure incoming winds, and therefore, optimize turbines by the yaw and pitch controls, and the rpm of rotors.[12]

Lidar mounting

Among the different alternatives for installing lidar apparatuses in nacelles, the most studied option by companies and research centers is fixing it to the top of the nacelle. However, other choices must be commented as well.

1. **Nacelle mounting:** Fixing the lidar on the top of nacelle is the easiest version and the most studied for build the turbine-mounted lidar concept. However, from the Nordex experience in 2003, only 60% of measurements can be obtained due to the blocking of blade rotations to laser beams and backscattered signals. [13]

2. **Hub mounting:** When installing the lidar in the hub, the blades do not block the laser beams and therefore, collected data by lidar receptors from backscattered signal are more constant and reliable. Another important advantage of this alternative is that the conical rotation of hubs can be used to provide to lidars the conical movements that they need for spatial scans. Hence, additional hardware would not be necessary and it would possibly simplify lidar units. Nevertheless, this configuration is more complicated.

3. **Including lidar units in blades:** This alternative is been developed by an important blade manufacturer. Although it is obviously the most expensive because it uses three lidar units instead of only one, the "Cyclops Dilemma" would be solved as it will be explained further. [14]
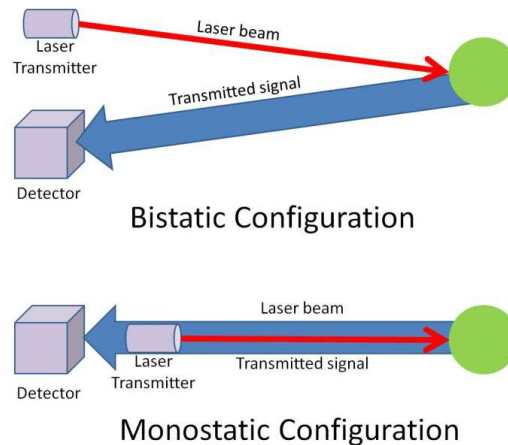

Fig. 5: a) Mounting the lidar on the top of the nacelle is the easiest one and for this reason, it is the most studied. b) The DTU's university installed a wind turbine in the hub for avoiding the blocking of blades. c) Though installing one lidar in each blade is an alternative under development, at this moment there is not any published report.[15]

Configuration of LIDARS

At this moment lidar is the most unique remote measuring apparatus in the market with enough reliability and endurance to be installed in a vibrating environment. However, from the available lidar configurations, it must be selected as the most appropriate and some features might be improved in order to work properly.

Laser Waveband: Projected laser beams can belong to the visible, near-infrared or far-infrared spectrum. However, due to safety reasons, especially the eye's retina, and precision on measurements, an alternative is the near-IR. This technology uses wavelengths in the range of 1,5 – 2 μm.

Bistatic and Monostatic: Coherent Doppler Lidars can be developed by using a bistatic design. This configuration was tested from ground levels for having accurate wake measurements in wind farms. However, the simplicity of monostatic configuration makes this alternative the most suitable for developing turbine-mounted lidar purposes. (Fig. 6).

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Fig. 6: When the transmitted and received signals share the same axis, it is called monostatic configuration. The simplicity of this alternative is the reason that lidars use it. (Source: By author).

Durability: The durability of lidars is being considered. At this moment, companies that provide these apparatuses only warrant their products for short times (WindCube is only for one year). This feature should be solved in order to accomplish the challenge of providing turbines more reliable and with less O&M tasks. [16]

Robustness: Lidar uses rotating parts to direct laser beams. These components are quite sensible and more robust lidar configurations should be studied. One alternative used by the company, Catch the Wind Inc, is duplicating the telescope but results from this configuration have been still evaluated.

Software: Some lidar (as ZephIR) saves the measurement data in flash disks that is filled in short times (days). Therefore, this aspect must be improved as well. Alternatives could come from saving only indispensable information, compressing it in a better way, or sending the information to data centers. [17]

Continuous Wave (cw) and Pulsed Lidars: There are two types of coherent Doppler lidars. Their main difference is they use different techniques to calculate the distance of target range; cw lidars concentrates the laser beam by using optical lens and by knowing the physical characteristics of this lens, the target range can be calculated. On the other hand, pulsed lidars calculates the range by calculating the time for sending and receiving the laser beam, and by knowing the speed of the laser beam. Though it could be a trivial differentiation, fact it is not. A further explanation is explained in the next chapter.

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Chapter III - LIDAR physics

At this point, it is necessary to describe how lidar technology works and what its limitations are. As other remote sensing appliances do, lidar must determine two basic parameters; reliable values for wind speeds and locations of those measurements.

Wind Speed:

The first assumption that lidar is based on is that wind speed has the same value as the small particles in the air, called aerosols. Pollen, droplets, smoke, and particles of dust form these particles. In order to determine their velocity, lidar emits laser beams to the targeted distance, and detector measures the scatted lights that aerosols produce by the heterodyne principle. The frequency of the backscattered signal depends on wind speed of the aerosols according to the Doppler principle.

The Austrian physic, Christian Andreas Doppler, demonstrated in 1842 the *Doppler Effect*. He argued that wave frequency depends on the relative speed between receiver and transmitter. Hence, in the case that the receiver does not have any speed, (such as the lidar unit does), frequency of scattered signals depend only on the speed of aerosol particles, and hence wind speeds can be calculated. When aerosol particles move fast, the frequency of backscattered signals (Doppler Shift) provoked by the laser beams are higher and vice versa. Hence, by measuring the frequencies of backscattered signals it is possible to determine wind speeds.
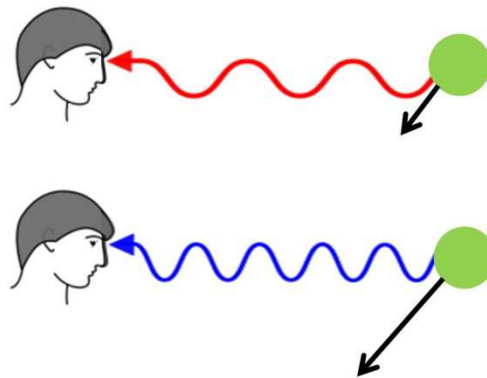
Fig. 7: According to the Doppler Effect, the frequency of scattered signals is proportional to the speed of particles of the air (aerosols). Lidar apparatus use this effect in order to measure their speed. (Source: By author).

Mathematically, the variation of the frequency in the targeted point is calculated according to the formula:

$$|\delta v| = \frac{2V_{los}}{c} \; v = \frac{2V_{los}}{\lambda} \tag{1}$$

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Where:

c: Speed of light.
V_{los}: Velocity measured along the line-of-sight.
ν: Laser frequency.
λ: Laser wavelength.

The next figure (Fig. 8) represents the basic configuration of lidar. The emitter sends a laser beam and the Local Oscillator (LO) divides it into two identical beams. One of them, the transmitted light, is sent to the target point in order to induce return signals from aerosol particles called scattered signals. The other beam is sent by the local oscillator directly to the detector thanks to the local oscillator, in order to compare its frequency with the backscattered light. This lidar configuration allows for avoiding periodic calibrations as cup-anemometers need.
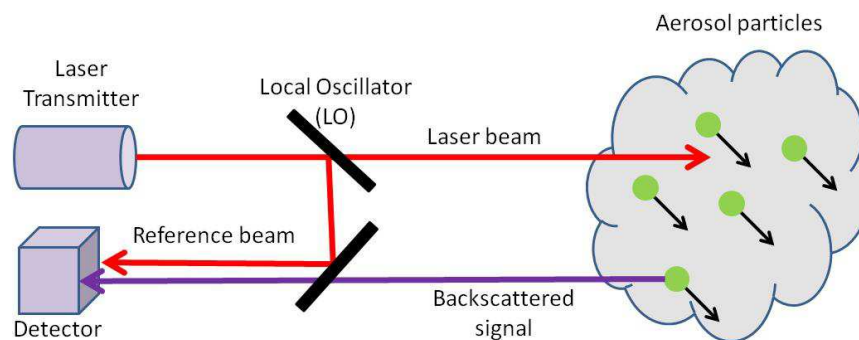
Fig. 8: The Local Oscillator (LO) divides the laser beam in two. One of them provokes the scattered signal at the target point, and the other one provides a comparison. By evaluating both frequencies, it is possible to determine the wind speed thanks to the Doppler Effect.[18]

After receiving the analog scattered signal in lidar's detector, it creates an average from several measurements in order to reduce measurement errors and it transforms it into a digital signal (by using a Fast Fourier Transform, FFT). Thus, it is easier to compare frequencies between the received signal and the reference laser beam. After knowing the difference on frequencies, wind veers and shears can be determined.
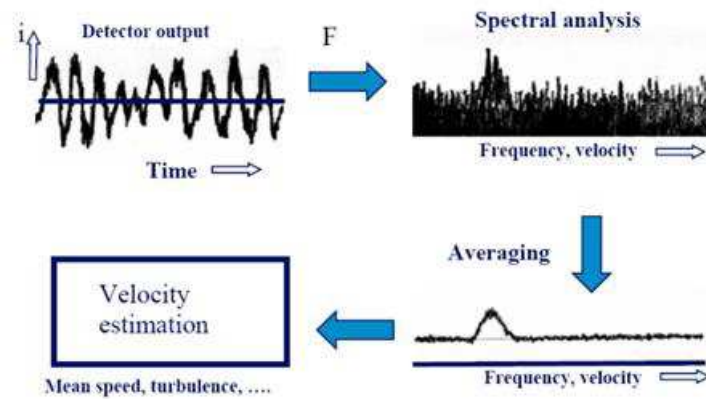
Fig. 9: The signal processing is similar for all lidars. The analog signal is transformed into a digital one. After averaging some measurements to avoid discrepancies, the velocity of aerosols is calculated by comparing the frequency of the scattered signal. [18]

Further Considerations:

Atmospheric conditions and wake interactions:

Lidar devices have a tendency to provide wrong measurements under unfavorable atmospheric conditions such as rain, hail or snowflakes. Furthermore, turbine-mounted lidars have some problems with yaw alignments and wind measurements under wake interactions from other turbines or on complex terrains. For these considerations and other ones, see Lindelöw-Marsden. [19]

Cyclops Dilemma:

Wind speed has three crucial parameters that define the 3D vector for the infinite directions that it can take; u, v and w (see continuous black arrows on Fig. 10). However, a simple lidar unit cannot calculate all of them. After mounting lidar units in nacelles, they assume a predominant wind direction (u>> v and w) and therefore, v and w are equal to zero. Hence, these remote sensing devices neglect two dimensions of wind speeds and only measure wind speeds in the direction of the velocity along line-of-sight (V_{los}) (red dotted arrows on Fig. 10).

In order to have real 3D vectors, it would be necessary to use three interconnected lidars that would provide measurements from three lines-of-sights (V_{los}). To solve this dilemma with only one unit, a lidar can be adjusted in two different ways in order to make two different assumptions and/or neglect some wind components. [20]
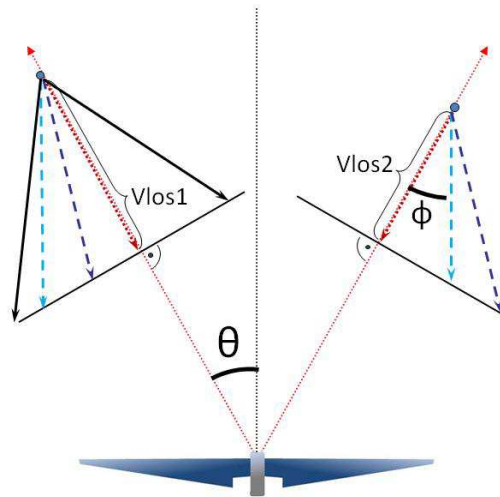
Fig. 10: Lidar only can measure the wind speeds in the direction of the laser beams directions (or in other words, in the V_{los} direction). However, it is possible to determine the wind shear and veer by making some assumptions: Wind always flows perpendicular to the rotor (light blue lines) or in homogeneous flows (dark blue lines).[21]

Not vertical and horizontal wind components

The spotted light-blue lines on the Fig. 10 represent the alternative that incorporates only u wind components (with v and w equal to zero). After installing the lidar equipment in the nacelle, it measures the wind speed along the line-of-sight and it assumes wind is always flowing with an angle φ equal to θ. Hence, wind direction is always perpendicular to rotors of wind turbines and thus, wind vector can be determined.

However, this assumption is an ideal situation because wind flows in other directions and φ is rarely equal to θ, especially in complex terrains. Furthermore, at higher values of θ, the u wind speed component is very sensitive to disparities between θ and φ, which it leads to an increase in the number of measurement errors.

The next figure (Fig. 11) shows the relation between the angle θ from the x axis with the wind speed measured. After increasing the angle θ for same wind speeds (blue lines), the collected data contains severe errors. After evaluating the lidar at different angles, it is possible to conclude for angles greater than 45 degrees wind measurements should be regarded with caution due to the high frequency of errors.
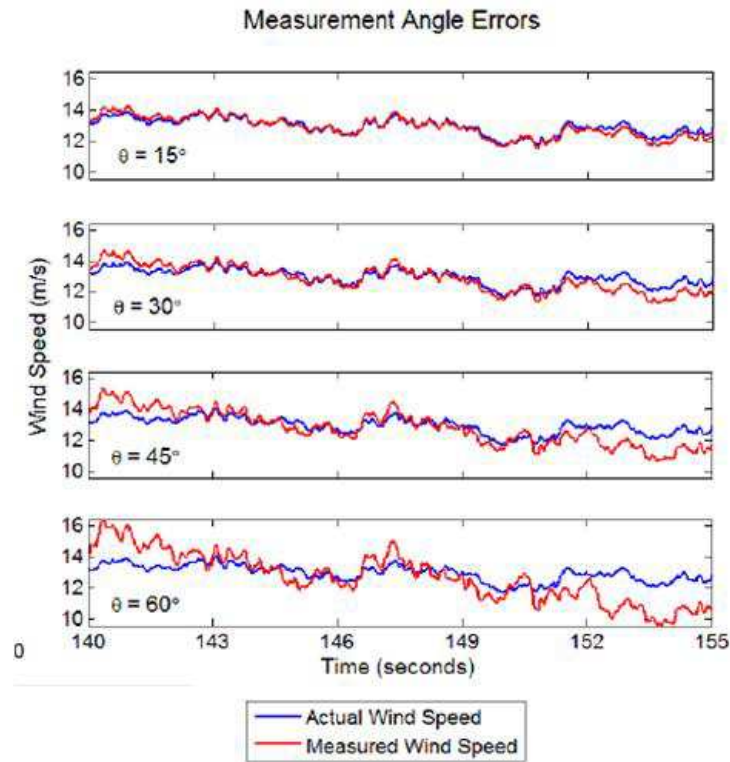
Fig. 11: For values of θ higher than 45 degrees, measurements are not reliable enough. It is demonstrated that the best angles are between 15 and 30 degrees. [12]

Nevertheless, this configuration is very convenient for pitch control because it determine wind shears and therefore, the most effective angle of attack for the blades can be determined and set. This allows higher energy productions from the generator but, more importantly, load reductions for the components of wind turbines.

Not vertical component and homogenous flow:

Under this assumption, (spotted dark-blue arrows on the Fig. 10) lidar interprets homogeneous flows along the spatial resolution (same wind shear). By measuring winds along the lines-of-signs and under the assumption that there is a uniform wind speed, it is possible to determine the angle between the V_{los} and the horizontal wind (φ). Hence, lidar obtains the wind direction or veer. This premise of neglecting wind shears is the best one for calculating direction changes and thus, aligning the yaw control is possible.

However, this assumption that wind flows constantly along the entire scanned area can be considered only reliable when there are not many wake interactions or under small wind shear conditions. In addition, it must be noticed that wind speed is usually affected by height and therefore, the real wind speed at the higher point of the scanned areas is generally stronger than at lower points.

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In order to mitigate this error, the scanned areas can be divided into several layers, and then, assuming constant wind flows (see Fig. 12). [22]
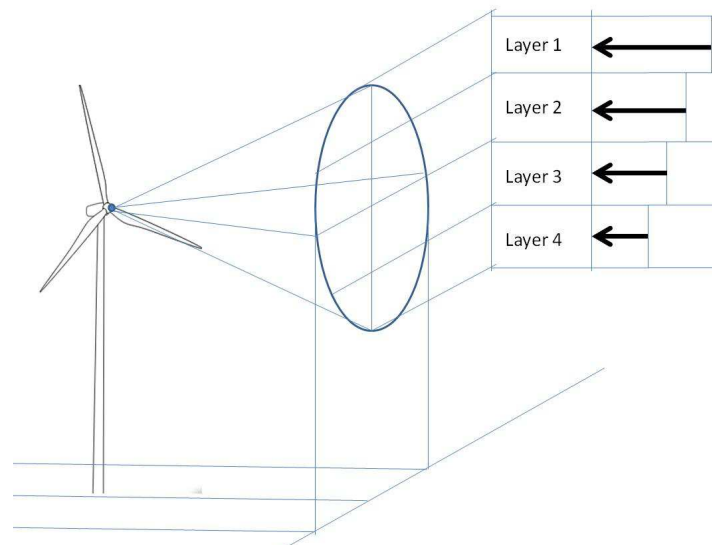
Fig. 12: Wind is related to height. In order to make more realistic assumptions, the scanned area is divided into several layers where it is supposed there are homogeneous flows in order to determine the yaw misalignment (φ). (Source: By author).

These assumptions for measuring wind shears and changes in the wind direction, though different, are not exclusive. Turbine-mounted lidars can be adjusted as a combination of both interpretations and they can determine wind shears at high frequencies for the pitch control, and changes in the wind direction at low frequencies for misalignments of rotor blades. Hence, only one lidar unit can optimize either pitch or yaw control of wind turbines.

On other words, using high frequencies for determining wind shears means most of the time is employed for that purpose. On the other hand, changes in the wind direction are determined by using the lidar device at low frequencies or short intervals of time. This configuration is brilliant since lidar is predominant adjusted for calculating wind shears and hence, the consequences of wind gusts are minimized.

Location of wind measurements:

As it has been mentioned before, the second value for reliable measurements of remote sensing appliances consists on determining the location of aerosol particles. There are two ways: by focusing laser beams by optical principles (cw lidars), and by multiplying the time of the back-scattered signal times the speed of light in order to calculate the distance of the targeted area (pulsed lidars).

Continuous Wave Wind Lidar (cw lidar)

As its name indicates, cw lidars project a continuous laser beam to the targeted distance and makes complete rotations in order to collect wind speeds at different angles. Thus, lidar is continuously emitting and receiving signals, and more than one hundred data can be collected per revolution. This spatial configuration for cw lidars is called Velocity Azimuth Display (VAD).
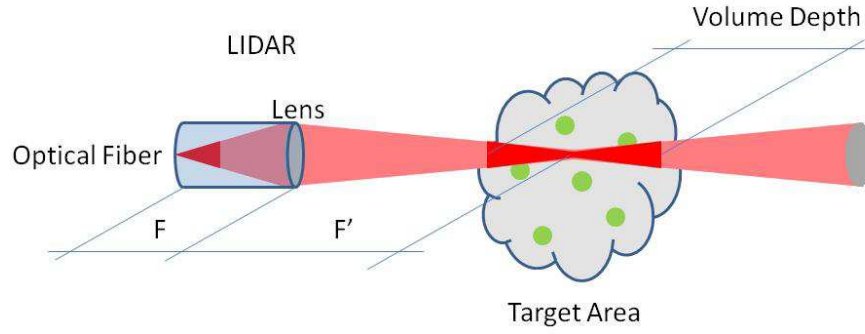
Another important singularity of cw lidars is that they use optical lens to focus the laser beam at the target area. By physic-optic principles, lens of cw lidars adjust the distance where the laser beam is concentrated according to the formula (2). This equation shows the relation among the distances where beam is focused and the focal length of lens (f_l).

$$\frac{1}{F'} - \frac{1}{F} = \frac{1}{f_l} \qquad (2)$$

In accordance with the Lorentzian distribution, the Rayleigh length (Z_R) characterizes the dimensions of the laser beam called Full Width Half Maximum (FWHM). Hence, for the ideal cw lidar, it is demonstrated the longitude is $2Z_R$ at the point of the optical fiber. Rayleigh length (Z_R) is calculated by the formula (3), where W_0 is the smallest radio of the laser beam in the optical fiber and λ is the wavelength of the emitted laser beam.

$$Z_R = \frac{\pi \, W_0^2}{\lambda} \qquad (3)$$

However, laser beam must be amplified by the optical lens in order to reach the target area. The reliability of cw lidars depends on the range weighting. Thus, for longer distances, the laser beam will be concentrated in a space called, "Volume Depth", and its dimension will be affected by the focal point (F').

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Fig. 13: Lens of cw lidars concentrates the laser beam at the target point with the optical lens. At that range, F' is much bigger than F (F' >> F), and Volume Depth is defined by the mathematical equations called Full Width Half maximum (FWHM).[23]

At that point, the Rayleigh length is $2Z_R'$ and it is defined by the formula (4). Where M is the "magnification" of the laser beam and W_{out} is the radio of the laser beam at the target point. Equations (5) and (6).

$$2Z_R' = M^2 \cdot 2Z_R \tag{4}$$

$$M = \frac{f}{\sqrt{(F-f)^2 + Z_R^2}} \tag{5}$$

$$W_{OUT}(F') = M \cdot W_O \tag{6}$$

In the target area, the laser beam is concentrated. In the Fig. 14 is represented the dimensions of the volume depth. When the target area is very far away, the size of the volume depth increases exponentially and data collected are not reliable enough.

Volume Depth
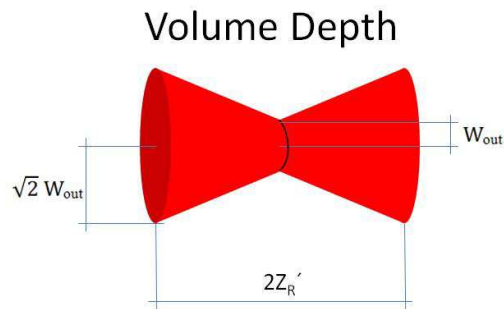
Fig. 14: FWHM for cw lidars at the target point is $2Z'_R$. In this place, the laser induces a backscattered signal produced by the aerosol particles. Measuring the change in the frequency due to the Doppler Effect is possible to determine the speed in the line-of-sight (V_{los}). [25]

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As it was mentioned, dimensions of volume depth depend on the longitude of focal point (F'). Hence, if laser beam is focused far away (F'), subsequently the "Volume Depth" is too big, and wind profile would vary too much for achieving reliable measurements.

To illustrate how this error is related to wind measurements is shown the Fig. 15. For same actual wind speeds (the blue line), lidar device collets different wind speeds depending of the focal distance (F) of lens. For higher focus distances, data measured are much rough, that it means higher errors. Hence, the minimum and maximum distance for cw lidars is around 10 and 200 meters respectively.
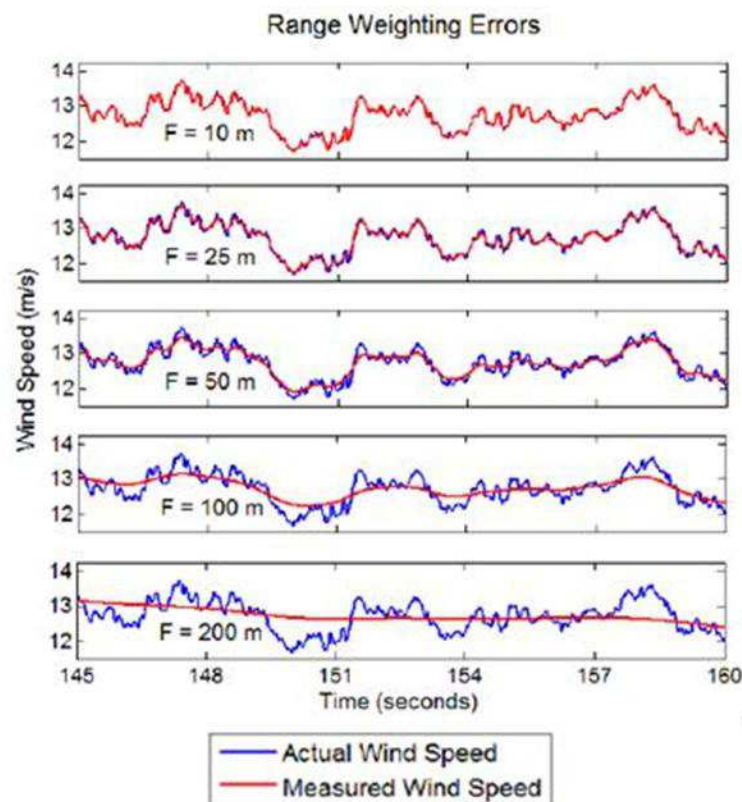
Fig. 15: For cw lidars, errors in measurements are related to the distance of the focal distance. When the focal distance is short, cw lidar is very accurate. However, when it is increased the range weight to hundred meters, the reliability of these devices is very poor. [12]

Furthermore, under low clouds conditions (even if clouds are far above of the focus distance), laser beams are susceptible to converge in other additional points which contaminate the "authentic" backscattered signal. For this reason, cw lidars use an algorithm to solve this difficulty by using background measurements. [24]

Combining both imperfections

Though the range weighting and the "Cyclops dylema" for wind lidars can be measured separately, in reality measurements of cw lidars contain a combination of both errors. Nevertheless, for high θ angles the angular error is the predominant. On the other hand, for small θ angles and large focal distances, the range weighting is the major consideration for the collected information.

Fig. 16 shows the importance of θ value for four different focal distances (F = ΔZ / sin θ) of lidar lens. For high θ angles, the geometrical error is much bigger than range weighting and vice versa.
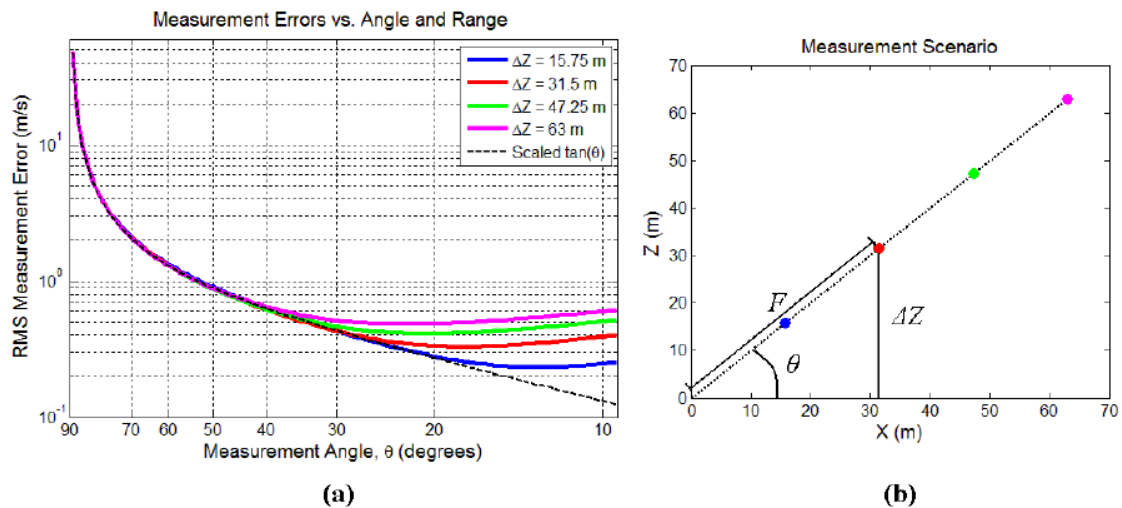

Fig. 16: The combination of the Cyclops Dilemma and range weighting is shown. For high focal distances and low angles, the predominant error is the first. [12]

Pulsed Wind Lidar

After the improvements on the fiber laser technology in the late of 1990's, modern pulsed lidars did not use any more the solid-state laser's technology that was less reliable, higher power consumption, bigger and weightier. Fiber lidars utilizes fiber amplifiers to augment low power pulses, and one of the most interesting features of them that they are easily adjustable and more reliable in a vibrating environment such as wind turbines' nacelle are.

The principle of the pulsed wind lidar is simple. They transmit a rhythmical coherent laser beams called pulses. The total resolution of these devices depends on the spatial longitude of the laser beam Δr [m] and on the distance between beams Δp [m] (Fig. 18). The Pulse Repetition Frequency (PRF) should be as high as possible, but it cannot exceed a maximum in order to avoid ambiguity between backscattered signals. This maximum value is depending on the time that the signal needs (1/PRF) for travelling a round trip from the lidar to the target point. Therefore, for far away distance ranges, it should be necessary fewer pulsed repetition frequencies.

Thus, after sending a pulse, laser beam provokes backscattered signals that lidar's detector receives. By associating the beam emitted, the signal received, and the time-of-flight of the laser pulsed, it is possible to determine the target distance.
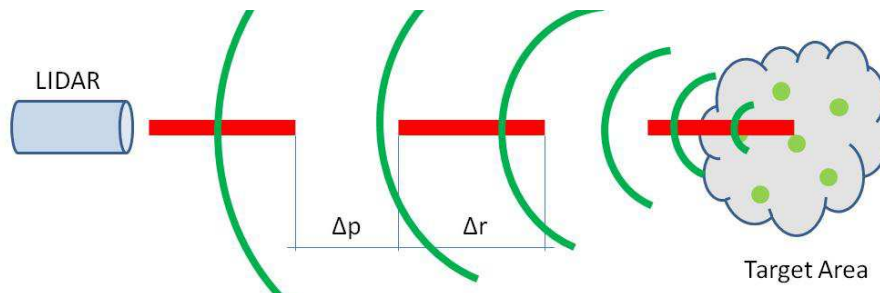
Fig. 17: Pulsed lidars send rhythmical laser beams to induce a backscattered signal of the particles at the target area. After receiving the return signal in a few microseconds, lidar emits another pulse. Due to velocity of signals (velocity of light), frequency is high enough for having reliable measurements. (Source: By author).

Once it has sent the sequence of beams, the prism of lidar rotates (usually an azimuth angle of 90º) and starts again emitting new stream pulses. A full rotation takes more time than cw lidars (approximately 6 seconds). This spatial configuration typical of pulsed lidars is called Doppler Beam Swinging (DBS).

By mathematical and physic principles, it is possible to determine the Full Width Half Maximum (FWHM) for pulsed lidars. Some authors have demonstrated that this value is 0.95*ΔZ, where ΔZ is the effective radial sounding volume size (see eq. (7)). This space combines the beam pulse length and the distance between pulses, but it does not depend on the range distance between target area and lidar. Hence, measurement errors are constant along the range distance. [25]

$$\Delta Z = \frac{\frac{c \cdot \tau}{2}}{Erf\left(\frac{\tau}{2t_p}\right)}$$
(7)

Where:

c: Speed of light.
τ: Time between beams.
Erf: Gauss error function.
t_p: Time of pulse duration.

The operations of these devices make them very singular for the wind power industry with longer ranges. The range distance of second generations of pulsed lidar is several kilometers (much higher than the 200 meters of cw lidars). In addition, due to the spatial configuration that pulsed lidars are based, it is possible to determine simultaneously wind speeds at different distances. Thus, pulsed lidars can measure wind speeds either near points or far away distances.

However, due to pulsed lidar's principle, the minimum distance for accurate measurements is limited by the spatial longitude of the laser beam Δr (m) (around 40 meters). Furthermore, the frequency resolution related to the pulsed lidars is not the best appropriate for calculating wind distribution width.
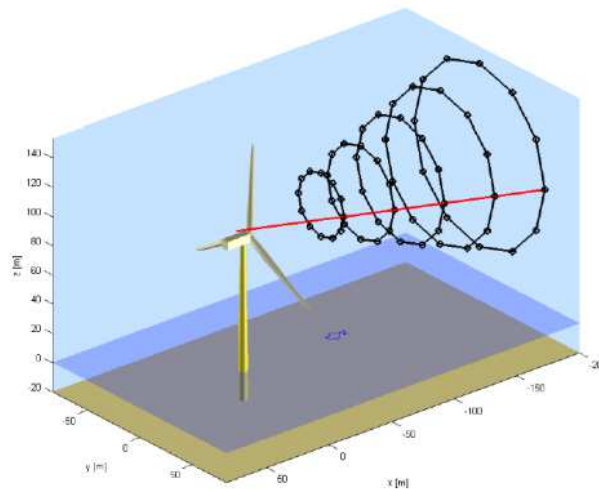
Fig. 18: Pulsed lidars send stream of laser pulses, wait for the backscattered signal and then the prism rotates 90 degrees for sending another set of beams. Furthermore, this configuration makes possible measuring wind speeds at different distances. This feature is very convenient for measuring wind evolutions. [26]

After describing the physical principles that pulsed lidars are based on, it is important to emphasize there are not any technical obstacle to dismiss them for accomplishing a turbine-mounted lidar purposes. Furthermore, the possibility of having simultaneous

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range measurements could be a significant competitive advantage to induce better technical solutions. [27]

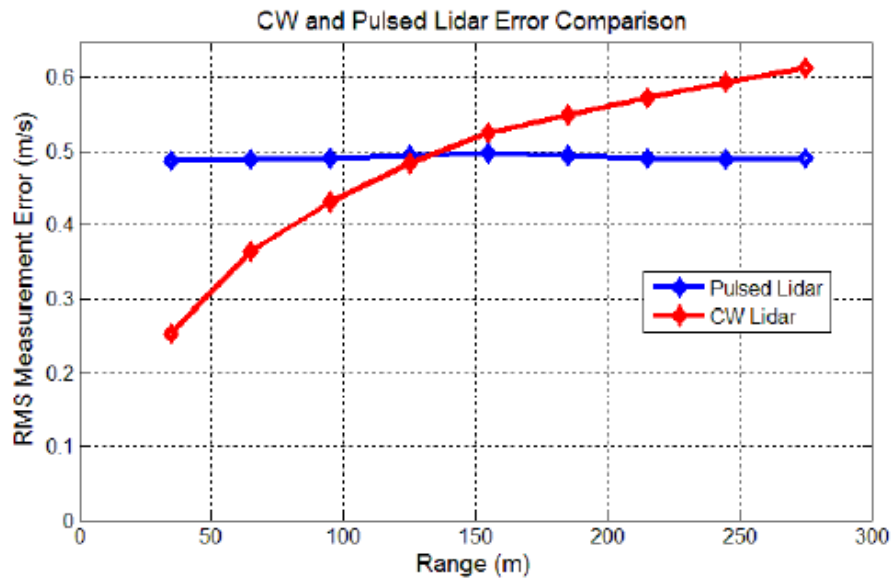**Continuous Wave Vs Pulsed Lidars**

Though the commercial Doppler wind lidars are based on similar physic principles, cw and pulsed lidars have remarkable differences as below table shows:

	CW LIDAR	PULSED LIDAR
Principle	Optical convergence of laser beams.	Measuring the time-of-flight of the backscattered signal.
Limitations	Limited by the hyperfocal distance of lens.	Limited by Δr and the power of the laser.
Range distance	From 10 to few hundred meters.	From 40 to 2.000 meters.
Simultaneous range measurements	One.	Up to 10 or more.
Low clouds	Measurements are susceptible under low clouds or mist weather conditions.	Not applicable.
Scanning configuration	VAD	DBS

Table 1: The differences between cw lidars and pulsed lidars. (Source: By author).

A comparison between the performances of CW and pulsed lidar can be represented on Fig. 19. Latest is not dependent of the distance (the small variations of the blue line are due to simulation imperfections). On the other hand, the measurement errors of CW lidars increase with the range due to focus distance is farther as it was explained before. It is possible to observe also that for an approximate range of 135 meters, the Root Mean Square (RMS) measurement error for cw lidar (ZephIr) and pulsed lidar (Windcube) is the same. Therefore, at that range both lidar devices have the same error.

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Fig 19: Errors in cw lidars depends on the distance between the lidar and the focal distance (range). However, pulsed lidars are not affected and they can measure wind speeds at far distances. [12]

One of the most remarkable differences between both apparatus is the possibility that pulsed lidars have for collecting wind measurements at different ranges. Thus, the algorithm for controlling the wind evolution would be a priori more reliable.

Chapter IV- Commercial lidars available

Reliability of cw lidars reached in the past years and their sooner development meant many of prestigious research centers (for instance, Risø National Laboratory or NREL) started to investigate them. Thus, the first reports related to turbine-mounted lidars and wind measurements from nacelles employed pulsed lidars.

Nevertheless, pulsed lidars started having good performance and the paradigm that "they are not suitable to operate in nacelles" started to be questioned. Companies from Europe and America began to develop pulsed lidars and public research centers validated their results. The Stuttgart University (Germany) carried out one of the most interesting projects but it was not the only one. Research centers that had tried continuous technology started to focus on pulsed beams as well.

Due to this new trend, and the singularity that at this moment there are more pulsed than continuous lidars, could be the starting of a tendency of using pulsed technology for turbine-mounted lidars. Before making any conclusion, it is indispensable to review the available commercial lidars.

The next table summarizes the commercial lidars available in the market. It must be emphasized most of them are based on pulsed continuous lidars. In addition, only a few of them were of them were designed specifically for the wind power industry (WindCube, Galion, Vindicator and ZephIR) and it seems these ones are better positioned to accomplish the requirements of turbine-mounted lidars.

Company	Country	LIDAR	Technology	Range (m)
Lidar Wind Technologies	USA and France	WindCube	Pulsed	40 - 200
SgurrEnergy	UK	Galion Lidar	Pulsed	40 -250 or 80-4.000
Catch The Wind Inc.	USA	Vindicator	Pulsed	50 - 300
Natural Power	UK	QinetiQ ZephIR	CW	10-200/300
Lockheed Martin	USA	WindTracer	Pulsed	500-5000
Mitsubishi Electrics	Japan	LR-05FC series	Pulsed	30 - 1500
Michigan Aerospace Corp.	USA	N/A	Pulsed	40 -20.000
Pentalum Technologies	Israel	SpiDAR	Pulsed	N/A

Table 2: The first trials for developing a turbine-mounted lidar were made by using the cw lidar, QinetiQ ZephIR. However, currently many researches are proving the pulsed lidar. (Source: By author).

Lidar Wind Technologies

NRG Systems and Leosphere are partners to commercialize this pulsed lidar, called Windcube. Leosphere (France) developed this lidar thanks to the collaboration of ONERA (Office National d'Etudes et Recherches Aérospatiales). On the other hand, NRG Systems (USA) is a company that was focused on wind measurements and equipment for turbine control.

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This lidar is one of the most used by the European universities (University of Stuttgart, Technical University of Denmark) for research purposes. There are available seven versions with different characteristics depending on the range distances, number measurements heights, or data frequency. Its prize is around 180.000 $. [28] [29] [30] [31]

Sgurr Energy

After a joint-venture in 2010, SgurrEnergy is the renewable brand of a large energy engineering company called Wood Group. SgurrEnergy was founded in 2002 and it is headquartered in Glasgow (Scotland). Currently, they hold offices in India, China, Europe and America.

Their star product is the Galion Lidar launched in 2008. This pulsed lidar is presented to the market as "second generation lidar" which means larger range distances and more number of measurement heights (up to 100). Recently, it has been tested by DTU as well and its price is around 150.000 €. [32] [33]

Catch The Wind Inc.

Catch The Wind (CWL) is an American company established in 2008 being a subsidiary of Optical Air Data Systems (OADS), a high-tech company in fiber-optic lasers. CWL is responsible for commercialize the pulsed lidar, Vindicator. Their lidar, Vindicator, is expected to cost around $95,000. [34]

This lidar unit has been used for wind measurement from ground levels, from nacelles of wind turbines and recently, from buoys for offshore locations thank to their collaboration with AXYS Technology Inc. [35]

Among other partnerships with other companies and private research centers, it should be emphasized their relationship with the National Renewable Energy Laboratory (NREL) in 2009 to investigate lidar applications, and their collaborative research with Gamesa for improving the turbine-mounted lidar concept. [36] [37]

Furthermore, they have been pioneers on integrating lidar units into the control system of wind turbines. In the summer and in December 2010, they incorporated the lidar into the power system of a V82 turbine (Nebraska, US) and a Nordex N-60 (Alberta, Canada) respectively. By faster yawing to the veer winds, they argue it is possible to increase the energy around 14% and up 83% load reductions. [38] [39]

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Natural Power Group

This Scottish renewable energy consultancy is a holding that includes several subsidiaries such as; SeaRoc for the offshore renewable energy field, and re-consult for site prospecting projects. Natural Power purchased in 2007 an exclusive license to market the lidar developed by QinetiQ, a British high-tech company for the defense field.

This ZephIR lidar is based on the continuous-wave technology and it was designed to fill the needs of the wind industry. It was the first commercial lidar available in the market, and this advantageous position made possible that it was the first unit for the turbine-mounted concept. However, after the launch of pulsed lidars, it is having many competitors. Its prize is very similar to the other ones and it is around 125.000 €.

Others

Lockheed Martin

This firm arose in 1995 after the merging between Lockheed Corporation and Martin Marietta Corporation, two important technologies companies. At this moment, their portfolio is a wide combination of products and services related to radars systems, defense, energy, air traffic, or space exploration.

Their pulsed lidar is WindTracer, and it is used for measuring wakes at airports, wind resource assessments for industrial application on wind industry and meteorological researches.

Mitsubishi Electric

Mitsubishi Electric was established in 1921 in Kobe, Japan, for manufacturing electric motors for vessels. Their growth is linked to the development of Japan, and currently the firm offers a wide gamma of technologic products in 35 countries thanks to their 100.000 employees.

In 2005, Mitsubishi manufactured the LR-05FC lidar series. They are based on fiber optical components and their capability for measuring winds speeds could have additional applications in the automotive industry.

Michigan Aerospace Corp. (MAC)

Engineering company that provides optical and opto-mechanical products, related to wind measurements. The firm was created in 1996 to commercialize the technology developed in the University of Michigan. Recently, they have opened offices in Los Angeles, Phoenix, and Berkeley.

Furthermore, they support two ground LIDAR in Hawaii and New Hampshire. Their products are specialized for industries such as spacecraft, aircraft, high-altitude balloon platforms and marine environments.

Pentalum Technologies

According to their website, this Israeli company provides a pulsed lidar called SpiDAR. In December 2010, ABB (Asea Brown Boveri) announced an investment on the firm to exploit the pending patent to remote sensing of wind. However, the information available at this moment is very few. [40] [41]

Chapter V - Conclusions

In the beginning of the twenty-first century, the interest of building turbine-mounted lidars has considerably increased because lidar technology has greatly improved and it has been possible to reduce its costs. From an economical perspective, this concept is having much acceptation because the possibility of reducing loads in the turbines and producing higher energy output make this concept very interesting for the wind industry.

The first researches on this field only considered continuous wave lidars because they were the most developed apparatus and it seemed pulsed lidars could not accomplish the requirements for installing them in nacelles. However, pulsed lidars have considerably improved and even they could take this promising market.

One evidence of these conclusions can be founded in the market. Currently, most of the commercial coherent doppler lidars use the pulsed technology. Furthermore, the research centers that investigated only continuous-wave lidars have starting to develop turbine-mounted lidars by testing pulsed lidars.

From the technical perspective, pulsed lidars have not the typical limitations of cw lidars, such as limited ranges or only one measurement sets. The singularity of pulsed lidars converts them more appropriate for longer distances and furthermore, for collecting measurements at different levels.

However, there are many works ahead. The market of turbine-mounted lidar needs apparatuses more robustness and autonomous, better configurations to integrate them into to the power control, and algorithms more reliable.

It is hard to predict the future. However, it looks clear it will necessary to build wind turbines with better performances and lidars integrated into the power control, and more specifically pulsed lidars, could be fill this need.

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Annex A

Laser Doppler Anemometry (LDA) – Heterodyne Principle.

The basic functionality of the Laser Doppler Anemometry (also known as Laser Doppler Velocimetry (LCV)) is represented in the Fig. 21. The laser beam is generated by the emitter (1) and is split it in two beams (2) of equal intensity.

The beams converge at the target area (7) thanks to the optical lens (6). The light deflected backwards from target area (7) from the airborne particles (aerosols) due to the heterodyne principle. The backscattered signal crosses the lens (6) onto the inclined mirrors (8) and (9). Then, the light crosses the lens (10) and it is converged to a tiny aperture (11) where the photo-detector (12) analyzes the information received.
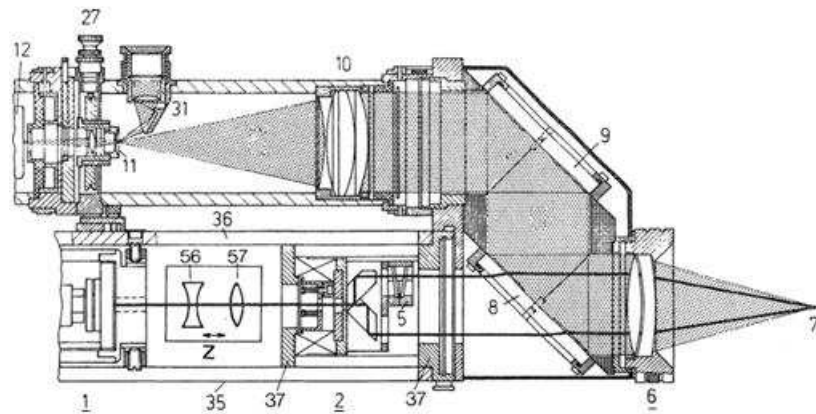
Fig. 20: A sectional perspective of a Laser Doppler Anemometry (LDA). The laser beam is divided in two equals and they converge in a point in order to create a backscattered signal by the Heterodyne Principle.

The technique that combines two frequencies in order to produce a new frequency is called the heterodyne principle. The two split laser beams intersect at the point (7) with an angle (β) with a wavelength (ν). According to the Doppler Effect, the wavelength of the scattered light (δ) depends on the relative wind speed at that point. (Fig. 21).

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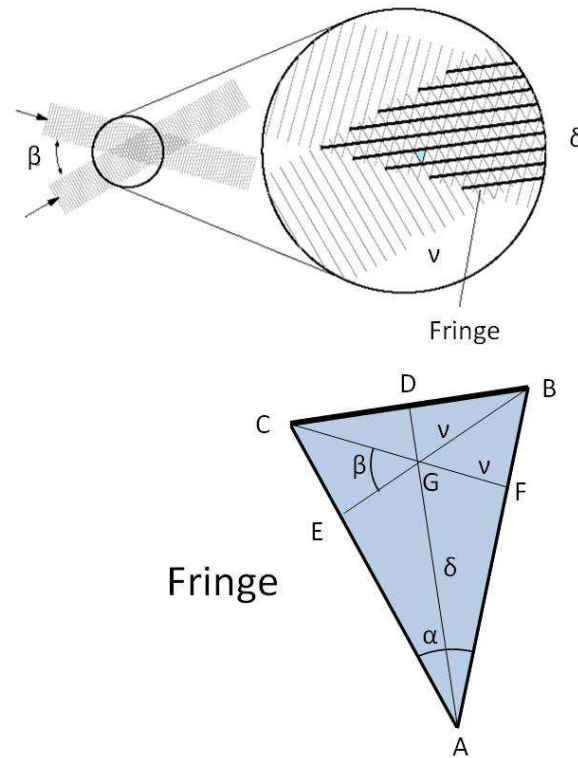Department of Wind Energy
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Fig. 22: The two beams focus on the target point and make up a triangle. Knowing the parameters; ν and α (equal to β), by trigonometric principles, it is possible to determine the wavelength of the scattered light (δ).

Therefore, the wavelength of the scattered light (δ) can be calculated by trigonometric principles and the result is;

$$\delta = \frac{\nu}{2 \sin(\beta/2)} \qquad (8)$$

Therefore, in order to calculate the speed of the fluid at that point (V_{los}), it is necessary to multiply the frequency of the backscattered signal (σ) times the wavelength of that light (δ).

$$V_{los} = \sigma \cdot \delta = \frac{\sigma \cdot \nu}{2 \sin(\beta/2)} \qquad (9)$$

It must be noticed the similarity of this formula with the principles used in the continuous wave lidars. Furthermore, as lidars do, it is only possible to determine the wind speed in only one point and it is necessary to combine several measurements in order to have 3D wind speeds. [41]

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