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QinetiQ Lidar Availability Report

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Abstract: This report summarises the factors that affect availability of lidar systems for wind measurements worldwide. The main factors are environmental tolerances, weather obscurants (cloud/rain/fog/snow), and aerosol backscatter.

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STATUS, CONFIDENTIALITY AND ACCESSIBILITY									
Status				**Confidentiality**				**Accessibility**	
S0	Approved/Released	**x**		**R0**	General public			Private web site	**x**
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1. Introduction

In order to reduce costs associated with the siting of tall masts, the wind energy industry needs methods such as sodar and lidar for remotely obtaining accurate wind profiles. However, widespread acceptance by the industry requires that these techniques be extensively validated for a wide variety of terrain and atmospheric conditions. One of the main objectives of Work Package 6 (“Remote Sensing”) is the evaluation of new wind lidar technologies with a view to gaining greater acceptance of these methods in the wind energy industry. It is a further aim, ultimately, to achieve formal certification of lidar methods and their introduction into existing standards.

This report addresses the limitations of lidar availability: Are lidars reliable for use worldwide? How frequent are data dropouts? We have surveyed some of the available statistics, including aerosol backscatter and weather limitations.

There are several ways to define “availability” [1], [2]. For example, the acceptance criterion used in NORSEWInD documents [2] is familiar to UpWind partners: “Data availability – defined as number of valid data points returned as compared to maximum number of possible points that can be acquired during the test”. This criterion is “distinct from system availability” – i.e. in NORSEWInD the periods when the system is broken or otherwise offline, and unable to acquire data points (valid or invalid), do not count towards data nonavailability.

When quoting percentage values for ZephIR availability or nonavailability below, we consider specifically the acquisition of **ten-minute-averaged wind data**. We define availability at a given height as the number of ten-minute periods during which the lidar measures a horizontal wind speed that is deemed by the system to be correct and reliable, divided by the total number of ten-minute periods during which the system was switched on and attempting to gather data. This is a simple and useful definition. It relates to the most important output parameter (V_H) and is consistent with the established industry standards.

The vertical wind component (V_V) will be more prone to error during rain, and its “availability” (in the same sense) will be correspondingly reduced because ZephIR’s self-checking will recognise the risk of error and reject some of the measurements. The “availability” of wind bearing data should be very similar to that of horizontal wind speed data. The performance is likely to differ slightly for measurement at different heights, so it is useful to consider each height separately.

Section 2 describes the main influences on availability of coherent lidar sensors, with emphasis on ZephIR but also some comments on pulsed lidars such as WindCubes and Galion. We estimate, roughly but instructively, the availability expected for ZephIR in typical UK conditions. Section 3 summarises field experience for the three lidars, as reported in the literature (where various definitions apply), and Section 4 lists some of the easily accessible databases of aerosol properties, including backscatter at common lidar wavelengths. This is a fast-changing field of research and exploitation, and the present report offers only a short overview and some rough estimates – sufficient to give confidence that wind lidars already work with high availability, and that they will perform well at “almost all” potential wind farm sites.

2. Lidar measurement issues

There are important differences between pulsed and continuous-wave (CW) coherent Doppler lidars, and between coherent and direct-detection lidars. The differences between WindCube and HALO (both pulsed coherent lidars operating at 1.5 μm) are much less important, at least for purposes of assessing backscatter.

ZephIR (our example here of a continuous-wave unmodulated coherent Doppler lidar) emits ~1 Watt of eyesafe infrared radiation and detects the small fraction of this light that is backscattered from aerosol particles in the atmosphere. We assume these particles have the same speed and direction as the wind; their motion shifts the light's frequency via the Doppler shift. Wind speeds are derived from measurements of this frequency shift, and we measure at a particular point in space by focusing the lidar beam at that point [3]. Hence, in order to achieve a successful measurement:

- In the detector output – an electrical current or voltage – there must be sufficient signal to exceed the background noise floor. The current is usually well described as a random Gaussian variable composed of many small contributions, each associated with the light backscattered from an aerosol particle
- This signal must be due to scattering from within the focal region of the lidar beam (other contributions are at best unwanted, and may be harmful)
- The scatterers must be moving at the same speed as the wind.

Below we consider these separately. First, extremely clean air may have *insufficient scatterers* to provide a reliable signal-to-noise for the lidar. We estimate the likely occurrence based on a theoretical analysis of lidar performance and available experimental data. Next, low cloud can lead to a breakdown of the second criterion in that the received signal can be contaminated or even dominated by *scattering from the cloudbase* rather than from the focal region. Finally, during *precipitation*, the droplets of rain falling under gravity that provide the lidar signal do not precisely follow the local wind. We briefly discuss rainfall statistics and the implications for ZephIR.

Note that ZephIR and other lidars will perform a number of quality checks in order to identify and exclude any incorrect data. A thresholding procedure excludes spurious signals generated by random system noise. Scattering from solid targets (e.g. birds, aircraft) that move at speeds quite different from the wind speed can be identified and eliminated by an outlier rejection algorithm. Data acquired during heavy rain can be identified from its extreme downward motion (see below). ZephIR is insensitive to very low wind speed (< 0.15 ms^{-1}), but such calm conditions are not usually relevant to turbine operation.

Direct-detection wind lidars operate principally with Rayleigh (molecular) scattering, not Mie (aerosol) scattering. Molecular Doppler shifts show a large spread, typically some hundreds of MHz, around the mean Doppler shift: there are contributions from molecular thermal motion, from wind fluctuations, and from density fluctuations that move with the speed of sound. These lidars can work well in conditions where coherent aerosol lidars fail; airborne versions have been used to measure winds at high altitudes (50,000 feet and more) where the air is very clear and thin. But currently they remain more expensive and optically more intricate, for example because of large critically-aligned free-space interferometers.

Backscatter and detection bandwidth

The sensitivity of the correctly-functioning ZephIR lidar is well understood [3]:

$$SNR = \frac{\pi\eta P_T \beta(\pi)\lambda}{Bh\nu}$$

where SNR is the signal-to-noise ratio in terms of power spectral density, η is the detection system efficiency, $\beta(\pi)$ is the atmospheric backscatter coefficient, λ the laser wavelength, B the bandwidth occupied by the signal, and $h\nu$ the photon energy. The risk of window contamination (which can lead to reduced transmission and loss of signal) is largely eliminated by the wash/wipe system and can be ignored. We will now use the above expression to derive a minimum value for the backscatter coefficient that will allow correct lidar operation.

Note that we have lumped any along-axis spatial weighting into the single term $\eta\ \beta(\pi)$. This weighting is usually close to Lorentzian for ZephIR. For pulsed lidars it includes both the same Lorentzian focused-beam term and some further (and usually dominant) weighting from the pulse shape and the post-detection processing [3].

For ZephIR the parameters take the following values:

$\eta \sim 0.3$
$P_T = 1$ Watt
$\lambda = 1.58$ µm
$h\nu = 1.25 \times 10^{-19}$ Joule

The system performs many averages of spectral data, so that a successful measurement is possible even when SNR < 1. The threshold of sensitivity for ZephIR is approached with an SNR value of 0.1, giving the requirement:

$\beta(\pi)/B > 8 \times 10^{-15}$ m^{-1} sr^{-1} Hz^{-1}

The bandwidth B needs some discussion. In ZephIR its lower limit is typically set by speckle fluctuation of the lidar returns: the scan rate of the beam through the aerosol particles gives rise to a minimum B of ~200 kHz. Turbulence and shear result in an additional broadening because of the range of velocities now present within the lidar probe volume. Close to topographic features, this additional contribution to the bandwidth can be considerable and dominant, of order 1-2 MHz.

A reasonable value for typical minimum detectable backscatter is:

$\beta(\pi)_{min} = 6 \times 10^{-9}$ m^{-1} sr^{-1}

The standard WindCube models use a stop/stare scan, where the beam direction is briefly fixed for the duration of a Doppler measurement; then before the next measurement the direction is changed by typically 90 degrees. Thus there is no beam scanning during a measurement, and no associated contribution to the broadening. But there are other broadening mechanisms in WindCube and similar pulsed lidars, so that the ~200 kHz mentioned above becomes unimportant in any comparison.

The turbulence and shear contributions increase with the length and width of the probe volume. For ZephIR (a CW lidar) the length varies with sensing range, from under 10 cm at range 10 m to about 35 m at range 200 m. For pulsed lidars (e.g. WindCube, Galion, WindTracer) the relevant length varies only slightly with range, being set essentially by the pulse duration and shape and the choice of processing. These are fixed for a given WindCube model and the lengths are of order 25 to 70 m, i.e. somewhat longer than for ZephIR over most relevant ranges. ZephIR cannot bring the lidar beam to a distinct focus at ranges much above 300 m: the beam is nearly collimated and "range resolution" is lost. In the presence of a strong backscattering layer (e.g. cloud), ZephIR makes excellent Doppler measurements even at ranges of many hundreds of metres, but on its own it does not range-resolve them, as we now discuss.

Cloud reflections

The issue here is the presence of a low cloudbase that can scatter the lidar beam and give rise to spurious signals. Under severe conditions the contribution to the Doppler signal from the cloud can contaminate, or even dominate, that from the aerosols at the desired height [4]. If left uncorrected in normal wind profile conditions, this will lead to an overestimate of wind speed. The severity depends on a number of factors; the risk of problems increases for:

- low cloud height
- high lidar range setting
- low aerosol scattering at beam focus.

Cloud returns are not a problem in the same sense for pulsed lidars, because they are separated in time from the desired aerosol returns and can be processed within separate "range gates".

Note that this is the only contribution to loss in availability that depends strongly on height. Modelling of the scattering and practical experience with ZephIR suggest that for measurement of windspeed at heights of up to 60 m there is no serious problem. At higher altitudes, the cloudbase returns commonly manifest themselves as a narrow higher-speed Doppler component that is distinct from the true aerosol return. Algorithms have been developed that identify and eliminate these cloud returns so that only the aerosol returns from the correct chosen height are analysed; see the UpWind deliverable [4] for the current ZephIR algorithm.

We therefore need to estimate the fraction of the time for which cloudbase problems are present, and then estimate the fraction of this period during which the algorithm is unable to cope successfully with the elimination of cloud returns. The algorithm relies on an additional measurement with the lidar focused at high altitude (> 400 m). In this setting, any cloud return becomes the dominant component in the spectrum and is easily identified. The resulting spurious component is then eliminated from the individual spectra obtained at lower altitudes. The algorithm copes well with conditions of uniform cloudbase. Broken cloud is likely to present more difficulty, particularly when combined with high wind speed as this leads to rapid evolution of the cloudbase returns over the measurement timescale.

The likelihood of such conditions (low, broken cloud with high wind speed) is hard to estimate from available information, and particularly for maritime environments. The ceilometer data from Chilbolton [5] can give only a crude indication of the variations in cloud height, but it does indicate that the cloudbase is usually > 1000 m which will give little problem for the lidar. Our rough estimate of the probability of problem conditions, based on practical trials experience and limited analysis of lidar data, gives a loss of availability of ~1 % for measurement at a height of 100 m and ~3 % at height 150 m.

In a similar manner, low-level mist layers could lead to an underestimate of wind speed. Thick fog can lead to loss of availability for any lidar, and will cause problems for ZephIR at its greatest heights (because of reduced beam penetration) if visibility < 100 m. CENER and CRES experience is that fog and rain (rather than low density of aerosols) are the major determinants for lidar availability; in the Spanish mountains, fog may be significant up to ~ 35 % of the time.

Rain

During rain, the drops themselves provide strong backscatter signals, and hence the lidar may measure raindrop speed rather than aerosol speed. There are three separate issues to consider from the point of view of lidar wind data:

- Downward motion causes the vertical wind component to be in error
- Rain has a range of droplet size; the velocities are similarly varied leading to spectral broadening. This can lead to errors in the least-squares fitting routine
- The horizontal wind component can be in error if the drops have fallen through a strong shear layer, since the drops take time to reach their terminal velocity.

For the first of these issues, a rain sensor can identify the presence of rainfall and for these periods the vertical windspeed data will be eliminated from the database. Rain in which droplet radii are less than ~0.1 mm presents little problem for the other two issues: the terminal downward velocity is of order 1 ms^{-1} or less (leading to only minor spectral broadening), and the drops approach their horizontal terminal velocity over a characteristic vertical distance of only 15 cm or less. For larger drops the situation worsens; problems will only occur during heavy rain, with large droplet size. It should be noted that even in heavy rain, reliable data for horizontal wind speed will be acquired when the wind speed is high (to reduce the relative effect of spectral broadening and downward motion on the analysis) and shear is low.

In order to assess the worst-case impact of rain on availability, we therefore make a rough estimate of the fraction of time during which rain is falling with droplet radii exceeding 0.1 mm. The classic Marshall-Palmer model of raindrop size distribution [6], [7] says that a rainfall rate of 1 mm / hour gives a mean drop radius close to 0.1 mm. Then for an estimate of the occurrence of this rainfall rate we can use a value of mean annual rainfall, combined with data on the typical statistical distribution of rainfall rates.

Rain rate and rain attenuation are crucial, throughout the world, in assessments of the reliability of communications including satellite links [8]. The American Meteorological Society classes rainfall up to 2.5 mm / hour as light, with higher rates classed as moderate / heavy / violent. The probability of a given rain rate X generally decreases with X, and various distributions of rain rate (exponential, gamma, log-normal) have been proposed. The problem splits in two:

- The rain occurrence P_R, i.e. the probability that rain is falling at any given time

- The fraction of time during which the rain rate exceeds our chosen threshold X_T (given that it is raining).

For an exponential distribution with mean rate m, this fraction is $\exp(-X_T/m)$. The mean annual rain rate is mP_R, and the product $P_R \exp(-X_T/m)$ is maximum (i.e. we have our worst possible loss of availability) when $m = X_T$.

For coastal sites in Eastern England, mean average rainfall over the last 20 years [9] is close to 600 mm, giving a mean annual rate of 600 / 8760 ~ 0.0685 mm / hour. So for a threshold of 1 mm / hour, the worst case would be $P_R \sim 0.0685$ (it rains about 7 % of the time), and the total time per year during which the rainfall rate exceeds 1 mm / hour is about 200 hours (2.5 %).

3. Field experience

Field experience with ZephIR

There is an increasing amount of experience and data from ZephIR measurements. An early and independent assessment of availability in the field was made by Risø's wind energy team, a world-leading group in the field of wind measurement. They deployed a prototype ZephIR system at their test site for large wind turbines at Høvsøre, NW Jutland in April 2004. The system functioned autonomously and reliably over a period of 13 weeks, and was operated remotely from Roskilde (350 km distant) with results typically downloaded daily via a datalink. The Høvsøre site is within 2 km of the sea, giving confidence that the data are broadly representative of a maritime environment. Risø reported availability of order 95 % during the total test period [10].

Risø ran a ZephIR essentially uninterrupted at Horns Rev offshore for 6 months from May 1 through October in 2006. Excluding downtime caused by a power supply failure, M Courtney estimated the availability as 88 % [11].

This was one of the first batch of production ZephIRs, without some later improvements to algorithms and hardware. Since 2004, the sensitivity has improved by at least a factor 4 via a combination of:

- Reduced noise floor due to improved laser performance
- Faster processing and increased duty cycle
- Improved photodetector performance.

Many successful ZephIR trials have been carried out by QinetiQ and UpWind partners in various locations and at different times of the year. Several examples were reported recently by UpWind partners:

- A three-week campaign in complex terrain in Bosnia in 2007 [12]. Data availability decreased with altitude; at 100 m it was around 85 % for ZephIR and around 54 % for the simultaneously operated Aerovironment 4000 minisodar.
- "Excellent reliability and data availability" during the trials with a hub-mounted ZephIR at Tjaereborg on a 2.3 MW NM80 turbine [13]. This is a novel and potentially stressful installation, so its high reliability is encouraging.
- CENER's ZephIR was upgraded in early 2009 and performed without serious fault during 7 months of tests on complex terrain. Availability was approximately 94 % (lidar correctly working with sufficient CNR), or approximately 86 % (after removal of data where cloud and fog interference is suspected). Data filtering and statistics are summarised in [14], and this quantitative "ten-minute-average" availability is closer to the definition we use above.

The list of available reports is regularly updated at:
http://www.naturalpower.com/zephir-laser-anemometer/papers-evaluations-studies

The recently introduced ZephIR 300 model is described at:
http://www.naturalpower.com/zephir-300-wind-lidar

Field experience with WindCube

Risø ran two campaigns using two different WindCube wind lidars at Høvsøre, the first during 22nd of December 2007 to 22nd of February 2008, and the second during 6th of July 2008 to 26th of October 2008 [15].

Sauvage and Cariou [16] list ten validation campaigns for the WindCube 70 model, between May 2008 and December 2009.

The 2008 evaluation report by Deutsche WindGuard [17], concentrating on lidar/cup comparisons at a nominal height of 98.4 m, uses a total of 2956 ten-minute periods. Results are presented for three definitions of availability:

- The number of ten-minute periods in which the sensor declared at least one valid eight-second measurement, divided by 2956
- The number of valid eight-second periods, divided by the total number of eight-second periods
- The number of ten-minute periods in which there were no invalid eight-second measurements, divided by 2956.

The third definition ("all data available in 10-minute period") is the most demanding and is indeed unnecessarily strict for many purposes, since the ten-minute averages obtained after discarding any invalid eight-second periods are often still useful. The DWG report refers to wind vector measurements (horizontal and vertical components, and bearing), whereas the definition we chose for ZephIR refers to V_H only.

In the DWG report this worst-case availability varies from ~95% at 40 m height to ~50 % at 220 m. At 98.4 m height the figure is ~87 %. DWG also commented favourably on the accuracy of WindCube even when no data filtering was applied. As with ZephIR, improvements have been made since 2008 to the WindCube hardware and software. There was an error in "apodisation" or data windowing, which introduced anomalies at particular Doppler frequencies, and hence at particular wind speeds for a fixed choice of scan cone angle [2]; this was christened the "Courtney bump" and quickly cured by Léosphère.

Field experience with HALO Photonics

The HALO Photonics pulsed Doppler lidars have been deployed in trials to assess urban aerosols, boundary mixing layers, turbulence, and rainforest meteorology. Most of the data sets available are therefore for conditions of less relevance to UpWind: higher altitudes, very strong backscatter, cloud and ice properties etc. The most comprehensive database of 1.5 μm lidar measurements is still the Chilbolton one (see Section 4).

Pearson et al. [18] describe a 51-day deployment at the UK Met Office (Cardington), and present SNR histograms after filtering for cloud effects. "We have found experimentally that the threshold SNR for reliable data is on the order of –23 dB. This can be approximately interpreted as the experimentally determined SNR threshold above which the probability of a false Doppler estimate is less than 5 %. Predictions of this threshold have been published previously…and appear to be in reasonable agreement with this experimentally observed result".

They briefly review the physics of photocounts and speckle fading, and the large literature on lidar Doppler estimation. The SNR is defined in a “wideband” sense and measured from the pulsed lidar time series, and “the weak returns from many pulses are accumulated prior to estimating the Doppler information”. This micropulse mode is also used in WindCubes, and the analysis would be different for lidars using a few large pulses.

Bozier et al. [19] discuss the potentially useful correlation between lidar $\beta(\pi)$ and point measurements of the density of fine particulate matter (i.e. $PM_{2.5}$, the measure for particles of size up to 2.5 μm). They show good qualititative agreement between one-hour $PM_{2.5}$ measurements and ten-minute averages of calibrated $\beta(\pi)$. The background level appears of order 10^{-7} m^{-1} sr^{-1}, and the results do not necessarily mean that $PM_{2.5}$ is a reliable guide to drop-out statistics.

Davis et al. [20] describe a 2007 two-month trial, in the German Black Forest, of the Salford University lidar built by HALO Photonics: “left unattended and fully controlled over the internet…measurements were limited only by atmospheric moisture (rain/fog), a lightning strike and a mains power failure”.

4. Other databases of β(π) for the ABL

There are many networks and databases of atmospheric boundary layer (ABL) aerosol distributions, but their relevance to UpWind is often low – for three main reasons. First, they are dominated by wavelengths near 355 nm, 532 nm, 905 nm, 1.064 μm and 10.6 μm, rather than the 1550-1580 nm typical of coherent wind lidars. Second, their researchers and sponsors are usually interested in airborne pollutants, smoke plumes and chemicals, but not in the background statistics of clean unpolluted air; that is, they concentrate on periods and regions of strong scattering by unwanted or interesting aerosols, not on rare occurrences of very weak β(π). Third, when drop-out statistics and low backscatter *are* treated, this tends to be in the context of large-scale and/or high-altitude measurements (e.g global winds, spaceborne or airborne lidars, mesoscale weather models etc.).

The following is a short list of sources consulted recently for this report:

(1) **Chilbolton** data. For an initial assessment of the probability that backscatter falls below the required minimum value, resulting in loss of system availability, QinetiQ examined ceilometer data from the Chilbolton backscatter lidar. This is an upward-pointing pulsed system at 905 nm wavelength, operated by the University of Reading Meteorological Department; Chilbolton is located in southern England some 40 km from the coast. The backscattered radiation is detected and measured, and time-of-flight information is used to derive range-resolved β(π) values at up to 10 km altitude.

The minimum β(π) that can be measured by the Chilbolton lidar is ~10^{-7} m^{-1} sr^{-1}. This is roughly equivalent to ~6 x 10^{-8} m^{-1} sr^{-1} at 1.58 μm. β(π) is commonly assumed to be inversely proportional to λ, but with several caveats. Particle size distribution, and the effects of multiple scattering, must be considered, and there is no simple scaling that transforms results at around 1 μm or 2 μm to ZephIR's operating wavelength. We can say that, in the low scattering conditions of interest here, β(π) at 1.58 μm will be slightly lower than the Chilbolton values. ZephIR will therefore function correctly even when backscatter falls a factor 10 below the minimum Chilbolton β(π). Drop-outs appear comparatively rare at Chilbolton, of order a few percent of the total time, indicating that it will be very uncommon for the backscatter to drop below our $\beta(\pi)_{min}$, so we expect a loss of availability of order 1 % or less.

The Chilbolton facilities, including a HALO pulsed lidar and Léosphère 355 nm elastic backscatter lidar, were recently summarised by Brooks et al. [21].

(2) **EARLINET** (European Aerosol Research Lidar NETwork). Its website www.earlinet.org lists the following:

- Global Atmosphere Watch (GAW) Atmospheric Lidar Observation Network (GALION – note the possible confusion with the HALO/Sgurr product)
- Molecular Pathology Laboratory Network (MPLNET)
- Asian Lidar Network (ALN)
- Commonwealth of Independent States Lidar Network (CIS-LINET)
- Regional East Atmospheric Lidar Mesonet (REALM)
- Americas Lidar Network (ALINE).

(3) Léosphère have introduced the network **LEONET** (see http://leo-net.eu/about/) for collating and presenting data from their clients' installations.

(4) We have consulted the technical staff of **Lockheed Martin (**formerly Coherent Technologies) whose 2 μm WindTracer lidar is well known and who have recently introduced more compact systems at 1.6 μm. The difference between 1.6 μm and the ZephIR / WindCube operating wavelengths is insignificant for studies of aerosol distribution and backscatter. LM do not have separate databases releasable to UpWind, but some results of their work with the University of Alabama are published.

(5) Note that, apart from these published databases, estimates of relative $\beta(\pi)$ and – with more effort – absolute $\beta(\pi)$ can be obtained by any user of these commercial lidars. The HALO lidar (as used in Sgurr's Galion system) has been calibrated in three ways:

- directly, that is by estimating all other terms in the lidar CNR equation so that $\beta(\pi)$ is the only unknown
- by comparison against Chilbolton ceilometer measurements
- by the self-calibration method [22] where the total path integrated backscatter is measured in thick cloud and the absorption depth is related to $\beta(\pi)$.

With appropriate processing, ZephIR and WindCube production models can also provide $\beta(\pi)$ values. The ZephIR averaged spectra are stored for offline inspection, and the total spectral power (roughly, the sum of powers in all the spectral bins, after removal of the estimated noise floor and the cloud contribution) indicates the average backscatter for that measurement. This is not usually of direct interest to customers, but it is easily derived offline or with a small additional real-time algorithm. Hence the variations in backscatter over time and space can be tracked – although we need at least one additional reference measurement to derive *calibrated* values of β in m^{-1} sr^{-1}. Similarly, WindCube's maximum-likelihood algorithms estimate both spectral width and CNR, and the latter is a relative measure of backscatter (range-resolved).

Weather conditions routinely met in the tropics will present severe difficulties for CW lidars and even for pulsed lidars if the scattering physics is not well understood. The cloudbase can be at very low or zero altitude; scattering can be strong, and vary strongly with height (so that a non-range-resolving sensor is immediately in trouble). The Mie scattering strength depends sensitively on droplet geometry; and cross-calibration against ceilometers is complicated by multiple scattering and by the wavelength sensitivity of water absorption. Fortunately these tropical conditions are less relevant to most wind energy sites.

Similarly, the strong backscattering from ice crystals requires careful interpretation and study of the size distributions, the balance between specular and diffuse scattering, the degree of multiple scattering, and the changes in structure as the crystals fall through layers of air of different temperature and degree of saturation [23], [24]. Variations of the so-called "colour ratio" for two sensors with different wavelengths, for example the 1.5 μm lidar and the 905 nm ceilometer, can be inferred from careful inspection of the time records published on the Chilbolton website. If we are to extract calibrated values of clean-air low-altitude $\beta(\pi)$, therefore, the Chilbolton databases need considerable "filtering" and expert interpretation. Again, the difficulties of precisely estimating $\beta(\pi)$, and how it varies in space and time, are not of central interest in this report; what matters is whether $\beta(\pi)$ is too *low* for lidar operation.

5. Summary

(1) In the UpWind context, “availability” often means availability of ten-minute-averaged horizontal winds, and we have used this definition where possible

(2) We have assessed several causes of loss of system availability for the ZephIR lidar. Most are independent of the height at which the measurement is performed. A breakdown of the losses is as follows:

Insufficient backscatter: 1 %
Rain: < 2 %

Cloud and fog lead to a further loss in availability that is more severe at higher altitudes. The loss in availability is estimated to be < 0.5 % for heights up to 60 m, 1 % for 100 m and 3 % for 150 m.

An overall estimate of availability is obtained by combining all the losses listed above, and assuming they are independent so that their occurrence is uncorrelated. Hence we obtain:

Availability (below 60m): 95.5% - 99%
Availability (height 100m): 95% - 98%
Availability (height 150m): 93% - 96%

The largest uncertainty surrounds the effect of cloud. This has little impact on the availability below 60 m height, but may lead to modification of the values at greater heights.

The analysis in this report has largely tried to consider worst cases, and is based on incomplete information on atmospheric statistics. Thus the values of availability above may be pessimistic. The values are broadly in line with an expectation based on an independent assessment of availability by Risø National Laboratories, Denmark. In that study, a value of 95 % availability was obtained.

We are excluding tropical forest, where conditions are highly challenging: low mist and cloud, cloud formation immediately above the surface, high humidity and strong dependence on water droplet size, and unreliable read-across to non-tropical regions.

(3) Though concentrating on ZephIR, we have also discussed (and listed references for) pulsed lidar measurements and a large number of atmospheric databases. For example, by agreement with Risø, researchers may access the data products from the 12 MW and Horns Rev campaigns [11].

Almost everywhere on the Earth, the boundary-layer **backscatter $\beta(\pi)$** is sufficient for > 95 % availability from current commercial lidar wind profilers. Dust particles, aerosols and pollutants are maintained in the atmosphere by natural and artificial processes: volcanoes, vehicle and powerplant emissions, forest fires etc. The air must be extremely clear (polar regions, high altitudes) for ZephIR, WindCube or Galion to fail.

(4) Statistics for mechanical **reliability** (according to agreed definitions) are usually confidential and hard to obtain from manufacturers. Risø's opinion is that the mean time between failure (defined as the failure, for whatever mechanical or optical reason, to provide reliable ten-minute averages) has increased to several months. The literature suggests that little has changed in over 30 years of lidar experience: the main sources of failure in practice are power supplies and connectors, not lasers.

We **recommend** that any checking and thresholding should be explicitly acknowledged in data analysis and published results; and when we reach a threshold where the system is *not* deemed to be correct and reliable there should be a data flag which will allow those times to be discounted. A percentage figure for reliability or availability loses much of its meaning if these filters and thresholds are not discussed.

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6. References

[1] An uncompromising definition is used in the Public Performance Measure (PPM) for train networks in the UK: "*The actual number of trains that arrived at destination within ten minutes of their scheduled time, compared to the number of services in the timetable. No services are excluded from this, for any reason*".

"The PPM combines punctuality and reliability into a single performance measure. It measures the performance of individual trains against their planned timetable. Punctuality is expressed as the percentage of trains 'on time' compared to the total number of trains planned. For long distance operators, such as Virgin Trains, a train is defined as on time if it arrives within ten minutes (i.e. nine minutes 59 seconds or less). Reliability is a measure of the percentage of trains that are cancelled or do not complete their full planned journey".

www.virgintrains.co.uk/about/

[2] A Oldroyd, D Kindler and M Courtney, "Testing and calibration of various LiDAR remote sensing devices for a 2 year offshore wind measurement campaign", Proc. EWEC'09, Marseille (March 2009).

[3] C A Hill and M Harris, "QinetiQ lidar measurement report", UpWind report (2010).

[4] C A Hill and M Harris, "QinetiQ report on cloud removal algorithm", UpWind report (2010).

[5] www.met.reading.ac.uk/radar/quicklooks

[6] J S Marshall and W M Palmer, "The distribution of raindrops with size," Journal of Meteorology **5**, 165-166 (1948).

[7] Raindrop size distributions and radar reflectivity, R Uijlenhoet, Hydrology and Earth System Sciences **5**, 615-627 (2001). Various refinements and gamma distributions have been suggested. For "drizzle" (light precipitation rates), O'Connor et al. (submitted to J. Climate) have recently suggested that the 1948 Marshall-Palmer size distribution overestimates the drop size.

[8] J S Ojo, M O Ajewole and S K Sarkar, "Rain rate and rain attenuation prediction for satellite communication in Ku and Ka", Progress in Electromagnetics Research B **10** (2008).

[9] www.meto.gov.uk/climate/uk/averages

[10] D A Smith, M Harris, A S Coffey, T Mikkelsen, H E Jørgensen, J Mann & R Danielian, "Wind lidar evaluation at the Danish wind test site in Høvsøre EWEC submission, (2004).

[11] C Hasager et al., "12 MW: Horns Rev experiment",
http://130.226.56.153/rispubl/reports/ris-r-1506.pdf

[12] S Bourgeois, R Cattin, I Locker and H Winkelmeier, "Analysis of the vertical wind profile at a bura-dominated site in Bosnia based on sodar and ZephIR lidar measurements", EWEC 2008.

[13] T Mikkelsen, K Hansen, N Angelou, M Sjöholm, M Harris, P Hadley, R Scullion, G. Ellis and G Vives, "Lidar wind speed measurements from a rotating spinner", EWEC 2010.

[14] P Gomez, UpWind 6.2 report (2010), including statistics and reliability for February 2009 – August 2009.

[15] C Hasager et al., "12 MW: final report", June 2009
http://130.226.56.153/rispubl/reports/ris-r-1690.pdf

[16] L Sauvage and J-P Cariou, "New long range lidar for airport wind profiling", WakeNet3-Europe, Palaiseau (2010).

[17] A Albers and A W Janssen, "Evaluation of Windcube", report PP 08007, DWG Consulting (2008).

[18] G Pearson, F Davies and C Collier, "An analysis of the performance of the UFAM pulsed Doppler lidar for observing the boundary layer", J. Atmos. Oceanic Technology **26** 240-250 (2009).

[19] K E Bozier, G N Pearson and C G Collier, "Doppler lidar observations of Russian forest fire plumes over Helsinki", Weather **62**, 203–208 (2007).

[20] J C Davis, C G Collier , F Davies, G N Pearson, R Burton and A Russell, "Doppler lidar observations of sensible heat flux and intercomparisons with a ground-based energy balance station and WRF model output", Meteorologische Zeitschrift **18**, No. 2, 155-162 (April 2009).

[21] I M Brooks et al., "Boundary layer structure and aerosol properties: lidar retrievals and in-situ measurements", 18th Symposium on Boundary Layers and Turbulence, 9–13 June 2008, Stockholm.

[22] E J O'Connor, A J Illingworth and R J Hogan, "A technique for autocalibration of cloud lidar", J. Atmos. Oceanic Technology **21**, 777-786 (2004).

[23] C D Westbrook and A J Illingworth, "Testing the influence of small crystals on ice size spectra using Doppler lidar observations", Geophysical Research Letters **36** (2009).

[24] C D Westbrook, A J Illingworth, E J O'Connor and R J Hogan, "Doppler lidar measurements of oriented planar ice crystals falling from supercooled and glaciated cloud layers", Q. J. R. Meteorol. Soc. **136**, 260–276 (2010).

Additional references

E J O'Connor, R J Hogan, A J Illingworth and C Westbrook "How well do operational models represent drizzle and light rain when compared with radar and lidar observations?", submitted to J. Climate.

U Wandinger et al., "Long-term aerosol and cloud database from correlative CALIPSO and EARLINET observations" CALIPSO/CloudSat Science Workshop, Madison, 28-31 July 2009 .

G Pappalardo et al, "EARLINET for long term aerosol observations", Proceedings of the 8th International Symposium on Tropospheric Profiling, ISBN 978-90-6960-233-2, Delft, The Netherlands, October 2009.

J D Spinhirne, S. Chudamani, J F Cavanaugh and J L Bufton, "Aerosol and cloud backscatter at 1.06, 1.54, and 0.53 μm by airborne hard-target-calibrated Nd:YAG /methane Raman lidar," Applied Optics **36**, 3475-3490 (1997).

C Werner, F Köpp and R L Schwiesow, "Influence of clouds and fog on LDA wind measurements", Applied Optics **23**, 2482-2484 (1984).

J M Vaughan, N J Geddes, P H Flamant and C Flesia, "Establishment of a backscatter coefficient and atmospheric database", ESA contract 12510/97/NL/RE (1998).

S D Mayor, "High pulse-energy atmospheric aerosol lidar at 1.5-microns wavelength: opportunities for innovation from a meteorologist's perspective", CLEO/QELS 2010.

S Guibert, V Matthias, M Schulz, J Bösenberg, R Eixmann, I Mattis, G Pappalardo, M R Perrone, N Spinelli and G Vaughan, "The vertical distribution of aerosol over Europe - Synthesis of one year of EARLINET aerosol lidar measurements and aerosol transport modeling with LMDzT-INCA." *Atmospheric Environment* **39** (16), 2933-2943 (2005).

B N Holben et al., "AERONET—A federated instrument network and data archive for aerosol characterization", Remote. Sens. Environ. **66**, 1-16 (1998).

http://www.nsstc.uah.edu/~sundar/?p=research&area=air-quality&field=us-air-quality#/?p=research

V Srivastava, J Rothermel, A D Clarke, J D Spinhirne, R T Menzies, D R Cutten, M A Jarzembski, D A Bowdle, and E W McCaul, "Wavelength dependence of backscatter by use of aerosol microphysics and lidar data sets: application to 2.1- μm wavelength for space-based and airborne lidars," Appl. Opt. **40**, 4759-4769 (2001)