TECHNICAL NOTE

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1 INTRODUCTION

Leosphere (“LS”) has developed the WINDCUBE LIDAR remote wind speed sensing device. GL Garrad Hassan (“GL GH”) has been requested to comment on the use of remote sensing wind measurements in the context of the development and financing of wind farm projects. This note presents GL GH’s position on the steps which GL GH considers necessary before a new remote sensing system may be considered to be a proven device in the context of the wind energy industry. The current status of the LS WINDCUBE LIDAR system within this process is discussed herein. Measurement of mean wind speed and direction are the focal points at this stage, though some insight on derived measurements such as Turbulence Intensity is also provided.

2 REMOTE SENSING DEVELOPMENT STAGES

Cup anemometers have been the industry standard for measuring wind speed at wind farm sites. Measurements from cup anemometers therefore must be considered the norm against which any alternative measurement device must be judged.

GL GH considers the process whereby a new remote sensing device may be considered to be a proven device to be as follows:

> ***Stage 1***
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> *During this stage a remote sensing device is commercially available and the device can routinely provide measurements of wind speed and direction with height. However, either limited measurements are available to validate the data produced against conventional measurements, or validation data indicate that error bars on remote sensing measurements are substantially higher than those which could be obtained from conventional measurements. During this stage, data from a remote sensing device can be useful in providing qualitative but not quantitative data. Remote sensing may assist with understanding the wind flow at a given site but the data may not be used quantitatively in a formal wind speed and energy production analysis for the purposes of project financing.*
>
> ***Milestone 1***
>
> *GL GH considers that a milestone is reached when a remote sensing device has been successfully tested at suitable test locations against conventional wind speed measurements over a range of heights relevant to wind energy applications (typically in the 50 m to 120 m range) and at least up to typical wind turbine hub heights. The tests will have demonstrated that the accuracy achieved through remote sensing is similar to that which would have been achieved with conventional anemometry. The results of the test will have been published in a suitable technical paper.*
>
> ***Stage 2***
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> *A device gains increasingly wide use on a range of sites with different meteorological characteristics. A device gains more operational experience and more is learned about the set-up, robustness and consistency of the measurement equipment. Confidence is gained that the device provides robust, continuous and accurate data over the full spectrum of operational conditions. Alternatively, specific conditions where the device does not provide robust data become well understood and can be excluded from analyses. Data from the remote sensing device may be used quantitatively within a formal wind speed and energy assessment provided that, where appropriate, site-specific validations against conventional anemometry data are undertaken.*
>
> ***Milestone 2***
>
> *A device has been used extensively over a range of sites in differing environmental and topographic regions with high data capture levels and numerous validations which demonstrate close agreement with data derived from conventional measurements and allow an objective quantification of measurement precision and accuracy of the device as a function of relevant external parameters.*
>
> ***Stage 3***
>
> *A device is considered proven for use in the assessment of wind farm sites. The data may be used quantitatively within formal wind speed and energy assessments with only limited or no site-specific validation against conventional anemometry.*

GL GH considers that many remote sensing devices currently have not achieved “Milestone 1” and therefore may only be considered to be at “Stage 1” as defined above.

3 LEOSPHERE WINDCUBE LIDARS

Commentary on the steps required to adopt remote sensing devices into the measurement of the wind regime at potential wind farm sites and an appraisal of the status of the Leosphere WINDCUBE device within this context.

3.1 GL GH Position Statement, November 2012

GL GH first saw validation data from a WINDCUBE Lidar in 2007 and 2008 [1][2][3][4]. Since that time, GL GH has had access to an increasing body of validation data from WINDCUBE devices including GL GH [5] [6] and 3rd party reports [7][8][9][12][13].

GL GH has gained increasing experience in the operation of WINDCUBE Lidar devices from deployments in the field. The largest body of data available is from sites located in simple terrain in Northern European locations which are typically characterised by a predominance of neutral stability atmospheric conditions. GL GH's experiences are that the data recorded by the WINDCUBE and WINDCUBE v2 in such conditions consistently lie within the error bar associated with industry best practice use of cup anemometers (within the 2 to 2.5% range for wind speeds between 4 m/s and 16 m/s). GL GH therefore considers for such conditions – referred to herein as "benign" conditions – the WINDCUBE and WINDCUBE v2 devices may be considered to be in Stage 3, i.e. proven for use in the assessment of wind farm sites for the purpose of wind farm development. Provided that the unit is tested and validated in such a way that its performance can be traced back to a reliable reference, it is expected that its measurement error bars would be similar to those assigned to high-quality calibrated mechanical anemometers.

Although these devices may be considered to be in Stage 3 operation for certain deployment scenarios, there are other deployment scenarios, referred to herein as "non-benign" scenarios, where greater care must be exercised in interpreting data from the Leosphere device; GL GH considers the WINDCUBE is in Stage 2 maturity for such conditions. These conditions are described below.

3.2 Non-Benign Scenarios

3.2.1 Complex Terrain

Experience from data recorded at sites located in more complex terrain (orography or roughness) has demonstrated that WINDCUBE measurements can deviate by much more than 2.5% from cup anemometers for certain terrain or flow conditions [14][15][17][18]. These differences are caused, in part, by differences associated with a cup anemometer being a close approximation to a point wind speed measurement while the WINDCUBE measurement is recorded over a substantial volume. Leosphere and others have put forward a method to estimate the volume-to-point correction using a Computational Fluid Dynamics (CFD) approach [18][19]. Results from this method are encouraging; however, GL GH considers that for complex terrain application, the issues which give rise to differences between volume and point measurements are complex. Experience has yet to be obtained to have full confidence in the efficacy of the correction.

It is therefore considered that application of WINDCUBE technology at complex terrain sites may only be considered to be in Stage 2 maturity. Further, GL GH has concerns on relying solely on WINDCUBE data when analysing a complex terrain wind farm. It is considered that for most applications, CFD adjustment of the raw WINDCUBE data will provide an improved result when compared with the unadjusted measurement. Within the context of this note, it is not practical to provide detailed guidance of what constitutes complex terrain; rather, it is necessary to apply site-specific meteorological and engineering judgement to such situations. However, it is considered an additional benefit of undertaking linear or non-linear CFD calculations to evaluate any necessary CFD correction; the magnitude of any correction can then be used to assess whether or not the site terrain is complex in the context of the use of data from a WINDCUBE device. A pragmatic way to differentiate between benign and non-benign deployments of a WINDCUBE is where the CFD correction in each directional sector of a 12-sector wind rose is less than a threshold of 2% in terms of required correction – unless it can be shown that non-benign sectors have negligible wind frequency and/or energy content.

More recently, Leosphere has introduced a Flow Complexity Recognition (FCR™) add-on to WINDCUBE v2 which makes use of its 5th vertical beam and real-time calculations to reduce the so-called complex terrain bias. The results of the first validation test reported by a 3rd party [20] and reviewed by GL GH seem promising. GL GH considers that this is a significant step towards understanding and tackling the complex terrain bias, which needs further validations under a number of different site and flow conditions. It is considered that for most applications the FCR add-on will provide an improved result when compared with devices not fitted with the FCR. Within the context of this note, it is not practical to provide detailed guidance of what constitutes complex terrain; rather, it is necessary to apply site-specific meteorological and engineering judgement to such situations. However, it is considered an additional benefit of undertaking a comparison between FCR-corrected data with uncorrected data to assess whether or not the site terrain is considered complex in the context of the use of data from a WINDCUBE device. A pragmatic way to differentiate between benign and non-benign deployments of a WINDCUBE is where the FCR correction in each directional sector of a 12-sector wind rose is less than a threshold of 2% in terms of required correction – unless it can be shown that non-benign sectors have negligible wind frequency and/or energy content.

3.2.2 Complex or Extreme Shear Environments

For sites where non-standard shear profiles, highly non-linear shear variations or extreme shear values can be observed, the volume averaging centred at the measurement height and weighted by the intensity of backscattered signal from the measurement probing depth may result in difficulties similar to complex terrain issues discussed above. It may be expected that there can be significant differences between point and volume measurements during such conditions, and GL GH is concerned that methods to convert volume-to-point or point-to-volume measurements are not yet well developed and validated for such non-benign-shear sites. An example of an area where high shear is an issue is in the Midwest of the US. Examples of other non-benign-shear situations are measurements at relatively low heights above ground level – typically around 40 m agl – or in forested or complex orography and roughness areas. GL GH considers it prudent to assume operation of WINDCUBE in such conditions to be in Stage 2 of maturity. A threshold which could be pragmatically used to identify non-benign high shear sites would be that 25% of measurement hours exhibit shear over the rotor disk with a power law exponent of 0.4 or more. For other non-benign shear situations, site-specific analyses of the shear values and profiles as measured by the device will be required.

3.3 Derived Quantities

3.3.1 Turbulence

Reviewing data from the WINDCUBE, it is clear that differences in point-to-volume measurements mean that turbulence data recorded by a WINDCUBE are different from those recorded by a cup anemometer [21][22][25]. It is important for lidars to provide such measurements, as the wind industry generally assumes turbulence measurements are made with cup anemometers, be it for wind resource assessment, wake calculation, power curve measurement [1], or wind turbine design [28].[1] Leosphere has recently presented a series of results where the WINDCUBE v2 5th beam is used to

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[1] While IEC 61400-1 does not specifically cite cup anemometry, industry practice is to use cup measurements.

provide turbulence intensity measurements which more closely match those measured by cup anemometers [20][26][27]. GL GH considers that this approach presents a significant step in understanding and using turbulence intensity as measured by the WINDCUBE v2. GL GH understands that external parameters such as atmospheric stability and measurement height are important drivers affecting the results. GL GH considers that the turbulence measurements currently available from WINDCUBE v2 will be most relevant for conditions of simple terrain, neutral stability, and low shear; however, they are height-dependent, and will increase in uncertainty and bias as shear and terrain complexity increases. The approach which GL GH would use to pragmatically identify sites which should be classified as non-benign would be the same as described in the above paragraphs when considering turbulence intensity measurements.

3.3.2 Flow Angle

GL GH notes that while the IEC standard [1] provides a precise methodology to estimate flow angles at sites, there is an increasing interest in measuring flow angles using remote sensing devices. Flow angle could indeed be estimated from horizontal and vertical wind speed components. However, the relatively small value of the vertical component with respect to the horizontal wind speed generally results in a significant level of uncertainty with respect to the derived flow angle. Combined with potential difficulties in non-benign sites as discussed previously, estimation of flow angle from remote sensing devices for the purposes of site condition analyses requires caution. GL GH recommends applying a pragmatic approach by using several methodologies in addition to remote sensing measurements.

3.4 Offshore Applications

For offshore applications, it is anticipated that similar uncertainty results would be obtained from an energy prediction based on data from a proven, validated remote sensing device mounted on a stationary platform as those uncertainty results from an energy prediction based on data from a conventional mast.

In addition to a body of onshore validation data, it is also important that a remote sensing device have some track record of offshore operation to demonstrate that the measurement equipment can operate effectively in an offshore environment.

Consideration has been given as to what further comments should be made to outline best practice and nuance the above statements. Offshore wind farms have high capital costs and therefore when employing relatively new technology for a purpose as vital as predicting the future energy output of a large wind farm, particular care should be exercised in the design of the measurement campaign.

Given the importance of measurement, it is considered appropriate to validate the specific device used at an appropriate onshore flat terrain test site before and – should inconsistent behaviour be observed during the measurement campaign – after the offshore measurement campaign. Comparison with a met mast provides traceability back to classical anemometry; therefore, the validation of the remote sensing device should be made against a tall conventional meteorological mast (although other measurement configurations may prove to be sufficient).

The length of the data set and data coverage rates achieved are key considerations in measurement campaigns and remote sensing campaigns should span a similar period as those undertaken with conventional masts. Also, it is important to deploy a device with a sufficient power supply and an appropriate O&M program such that it can be expected that data coverage rates up to hub height will be close to 100 %. It is also important that the equipment and power supply be such that the remote sensing device may operate for extended periods without interruption in highly challenging environments. Given the substantial cost of offshore platform installation, consideration should be made as to how data redundancy might be achieved through the installation of a shorter conventional tower, or a second remote sensing device, or other appropriate measures.

3.4.1 Stationary Platform Offshore Operation

GL GH generally considers stationary-platform offshore operation as a benign scenario for the WINDCUBE lidar provided that enough evidence is provided to ensure no significant flow distortion from the platform or its components might affect the measurements.

3.4.2 Non-Stationary Offshore Operation

For offshore applications where a WINDCUBE is used on a floating, unstable or non-stationary base rather than a stable stationary platform, there is increased uncertainty in the measurement obtained. GL GH has not yet seen sufficient validation data from floating application of a WINDCUBE to use such data with confidence for the purpose of formal wind energy wind resource assessment. Floating deployments would need to be considered on a case-by-case basis.

3.5 Practical Issues

As with any scientific measurement campaign, accurate data and very high data coverage rates are only achieved through compliance with manufacturer’s best practice guidance and attention to detail in the installation and operation of the WINDCUBE. GL GH notes that significant improvements have been brought to the WINDCUBE, notably with respect to eliminating the rotating mirror in WINDCUBE v2 and hence reducing the risk of mechanical failure. Additional focus areas to ensure accurate measurements and high data coverage include the provision of a robust power supply and the implementation of an appropriate maintenance and on-site monitoring including such items as wiper blades, fluids, and ancillary equipment. Where best practices are followed, GL GH would expect data coverage rates to be obtainable at turbine hub height which would be similar to those expected from high-quality, well maintained meteorological masts (e.g. better than 95%) for most proposed wind turbine sites. Care may be needed in more extreme environmental conditions such as cold climates, sites with extreme clear sky conditions, or deserts.

A concern with the installation of any measurement equipment is to ensure that the equipment is working correctly when it is deployed. As transportation distances to wind farm sites may be substantial, measures to increase confidence that the equipment is working correctly before and after the required deployment may be considered to be good practice.

For an operation in non-benign deployment scenarios as described above, or in cases where the possibility of correcting turbulence data to be representative of measurements made with a cup anemometer is particularly important, then an appropriate on-site calibration campaign against an alternative measurement system will be necessary to allow the proper interpretation of the data from the WINDCUBE at such sites when it comes to analysing the data.

4 SUMMARY

In summary GL GH considers that for benign sites, the WINDCUBE may be considered to be in Stage 3 operation. This means that where manufacturer’s recommendations and good measurement practice are followed, and where high data coverage rates are achieved up to heights of relevance for modern wind turbines, mean wind speeds will be within the error bars which would have been achieved with cup anemometry.

Sites which are not benign in this context are those in complex terrain and those where substantial periods of high or non-standard shear occur. The main text gives further details of how non-benign sites may be identified. For such sites WINDCUBE may be considered to be in Stage 2 maturity.

Summary Table

Model	**Benign Conditions**	**Non-Benign Conditions**
WINDCUBE v1	Stage 3	Stage 2
WINDCUBE v2	Stage 3	Stage 2
WINDCUBE v2 with FCR	Stage 3	Stage 2

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