Project funded by the European Commission under the 6th (EC) RTD Framework Programme (2002- 2006) within the framework of the specific research and technological development programme “Integrating and strengthening the European Research Area”

Project UpWind

Contract No.:
019945 (SES6)

“Integrated Wind Turbine Design”

Remote Sensing (UpWind WP6)
QinetiQ Report on Cloud Removal Algorithm

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Document Information

DOCUMENT TYPE	Technical report (deliverable 6.3.1)
DOCUMENT NAME:	Cloud removal algorithm QINETIQ/TS/FPPS/TR0902404
REVISION DATE:	15 September 2010
CLASSIFICATION:	R1: Restricted to project members
STATUS:	Released

Contents

Abstract This report describes an important step in the signal processing for the ZephIR^{TM} coherent Doppler lidar. The effects of cloud returns are removed at an early stage, so that they do not disturb the estimation of lower-altitude wind profiles.

STATUS, CONFIDENTIALITY AND ACCESSIBILITY										
Status				**Confidentiality**				**Accessibility**	
S0	Approved/Released	x		**R0**	General public			Private web site	x
S1	Reviewed			**R1**	Restricted to project members	x		Public web site	
S2	Pending for review			**R2**	Restricted to European. Commission			Paper copy	
S3	Draft for comments			**R3**	Restricted to WP members + PL				
S4	Under preparation			**R4**	Restricted to Task members +WPL+PL				

PL: *Project leader* **WPL:** *Work package leader* **TL:** *Task leader*

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, and then formal certification of lidar methods and their introduction into existing standards. QinetiQ, as the manufacturer of the ZephIR lidar used extensively by the partners in this Work Package, provides the required expertise on lidar principles and technology.

QinetiQ’s written contributions include an updated report on the lidar measurement process [1] and another on lidar calibration techniques [2]. The present report provides more detail about an important step in the lidar signal processing. The effects of cloud returns are removed at an early stage, so that they do not disturb the estimation of lower-altitude wind profiles.

The ZephIR^{TM} lidar anemometer is a continuous-wave instrument which simultaneously receives light scattered from all ranges along its laser beam. It achieves “range resolution” by bringing the beam to an external focus, at a particular range anywhere up to about 200 m; the heterodyne detector output signal is then dominated by contributions from a narrow region centred on the focus (beam waist), with a sensitivity profile of roughly Lorentzian shape [1].

At long range this sensitivity falls as the inverse square of the range, but we cannot rule out the possibility of contamination by strong scatterers, and it has long been recognised that cloud contributions can be appreciable if a highly-scattering cloud sheet lies within the Lorentzian wings. Figure 1 shows the typical effect on lidar signals. For simplicity the backscatter is assumed roughly uniform below cloud level, and the possibility of angular shear has been ignored. The red contributions to the spectra represent the signals of interest, derived from scattering by aerosols at the desired measurement height. Their strength (integrated spectral power) is roughly independent of height for the lower heights, but for the cloud measurement (where the beam is nearly collimated) the aerosol return is more spread in frequency and its integrated power is diminished. The purple contributions are the cloud returns and show dramatically different behaviour: they line up with the same spectral width and shift at all measurement heights, and their strength rapidly drops as the measurement height reduces. It is this clearly-defined behaviour that permits their identification and elimination.

The behaviour indicated in Figure 1 is well established and consistent with ZephIR observations in a variety of locations and conditions. The cloud signal is usually unchanging over the timescale of several seconds required for measurement at different heights.

The first version of the ZephIR cloud removal algorithm successfully treats the basic case where the *aerosol spectrum* (at the measurement height) and the *cloud spectrum* do not overlap. The cloud spectrum is measured by setting a long focal range of 300 m. Experience, especially the detailed analysis by Risø of measurements performed at Høvsøre, indicated bias problems for two broad types of conditions:

1. Clear skies (no cloud) – the measured cloud spectrum is simply the aerosol spectrum, but the probe volume is likely to cover a variety of wind speeds and to produce a wide weak spectrum
2. Significant spectral overlap between aerosol and cloud signals (low shear, or angular shear).

In these conditions a simple spectral subtraction, as in the first version, may be unsatisfactory. We need to subtract a correctly *power-scaled* cloud contribution.

The improved algorithm obtains the cloud spectrum with a nominal focus range of 800 m (essentially a collimated beam) so the aerosol contribution is much reduced. A separate 38 m measurement gives a reference of the aerosol return with minimal cloud contribution. The dependence of spectral power with height is then used to identify the presence or absence of cloud. If it is absent (case 1 above), no subtraction takes place so there is no bias from this source. For case 2 we derive a nonzero scaling by comparing the cloud signal strength at different measurement heights.

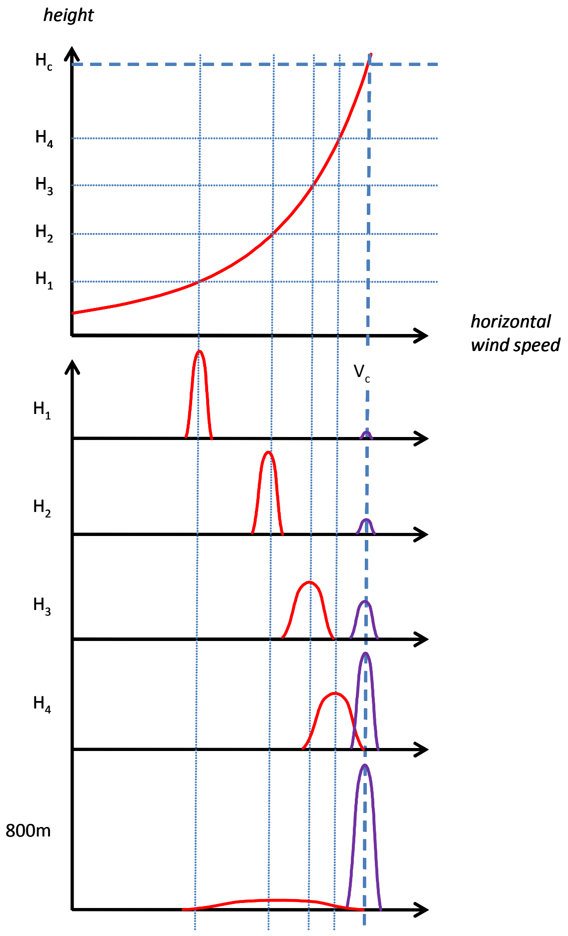

Figure 1: The origin and nature of cloud signals. The upper plot shows a typical wind profile, containing a cloud layer at height H_c. The lower plot illustrates the Doppler spectra measured by a ZephIR system probing the wind profile at several heights H_1 to H_4, as well as a cloud spectrum when the focus is at very long range (800 m). The horizontal scales in the upper and lower plots are adjusted (wind speed is proportional to Doppler shift) to line up the traces. Aerosol returns = red, cloud return = purple.

2. The revised algorithm

The basic steps are:

1. Acquire data for 1 second focused at 38 m. This measurement is representative of the aerosol.
2. Acquire data for 1 second focused at 800 m. The nearly collimated beam gives a long probe length and a sensitivity that varies slowly with height. Hence the return is dominated by any strongly scattering cloud layer.
3. Run through measurement heights as normal, starting with the highest (up to 150 m) immediately after the 800 m measurement to ensure minimal evolution of the cloud signal.
4. Apply the threshold to each spectrum in the usual way (at 800 m, 38 m and measurement heights). In the presence of a low cloud sheet, the 800 m spectral power will be dominated by the cloud return.
5. For each spectrum at each measurement height, compare with the corresponding 800 m spectrum obtained at the closest value of azimuth angle and identify those bins that could in principle be contaminated (i.e. the Doppler frequencies where, in the 800 m spectrum, there is non-zero return power). Calculate the power measured, summed over those bins only, for each angle θ at each height h; call this PM(h, θ). This step isolates any cloud return contribution in the wind speed measurement.
6. The ZephIR "scaling factor" S_h, at a given height h, for a given angle, is 255 divided by the peak value in the spectrum. Average these factors over all the (N) angles for which the spectra at that height are non-zero:

   $$S_h = \frac{1}{N}\sum_{n=1}^{N}\frac{255}{peak_n}$$

   where $peak_n \neq 0$. Produce values for S_{800} and S_{38}. Note there is one angle-averaged value of S_h per three-second period, but there are up to 50 values of PM per one-second period at a given height.
7. Use S_{800} and S_{38} to determine the presence or absence of a low cloud layer. In the absence of cloud, no further correction is required. If cloud is identified:
8. From each spectrum at the measurement heights, subtract the scaled cloud contribution: that is, the cloud spectrum from the 800 m measurements, multiplied by a cloud multiplication factor (CMF).
9. Calculate the centroid and continue to calculate wind speeds as before.

One other change is that, in the presence of cloud but at very low wind speeds, the system returns no wind speed rather than (as previously) a speed that is likely to be incorrect.

Steps 8 (cloud identification) and 9 (CMF) are crucial. We need threshold tests for S_{800} and S_{38} (to decide whether correction is needed) and also a choice of overall strength of correction. We need a balance between the risks of overcorrection (CMF too high) and of incomplete elimination of the cloud signal (CMF too low). CMF should not be allowed to exceed 1. Currently we take a simple approach:

- If S_{800} is below a first threshold, or S_{800} / S_{38} is above a second threshold, then a cloud layer requires correction. If neither condition is met, then no correction is applied. These two thresholds are based on experience at QinetiQ / Natural Power / Risø.

- $CMF(h, \theta) = F*PM(h, \theta)/PM(800, \theta)$ where F is a constant of order unity.

Other approaches are possible (for example a CMF_h whose factor F varies with height), but we expect that this revised algorithm will cope well with almost all conditions and reduce any overall bias to insignificant levels. In the current ZephIR firmware, Natural Power has also implemented an algorithm to detect fog contamination and filter (i.e. discard) the affected data.

3. Future work

Considerable testing at Høvsøre, including correlation with ceilometer data, has already taken place. Sincere thanks are due to the Wind Energy Department at Risø DTU for their detailed studies and analysis that have led to identification and improved understanding of problems associated with cloud returns. Future activities may include:

- Further verification of cloud identification routine, preferably with reference to ceilometer data.
- Verification of algorithm on selected representative test cases, e.g. low or incomplete cloud base, thick fog to ground level, mist layers, and low shear.
- Continuing verification of algorithm on a large data set, preferably with reference data from cups.
- Long term test of any remaining bias in overall cloud removal algorithm.

4. References

[1] C A Hill and M Harris, “QinetiQ lidar measurement report”, UpWind report (2010).

[2] C A Hill and M Harris, “QinetiQ report on lidar calibration”, UpWind report (2010).