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Windcube FCR measurements

Principles, performance and recommendations for use of the Flow Complexity Recognition (FCR) algorithm for the Windcube ground-based Lidar

Summary:

As with any remote sensor, standard Windcube wind reconstruction assumes flow homogeneity across the volume of measurement. In complex terrain or conditions, this assumption is no longer valid and measurements become inaccurate. Leosphere has developed a method to capture flow inhomogeneity and obtain accurate wind measurements in complex flow conditions. This has been available since 2012 under the name "Flow Complexity Recognition".

The present document aims at providing details on the method, its expected performance and limitations, as well as recommendations of use.

Summary

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1. Glossary

FCR: flow complexity recognition

LOS: Line of sight

U: wind speed along the South to North axis

V: wind speed along the West to East axis

Vr: radial wind speed

W: wind speed along the vertical axis

2. Standard wind reconstruction

2.1. Windcube geometry

The Windcube uses five laser beams, also called lines of sight (LOS), to reconstruct wind speed and direction at several heights above ground: one vertical and four inclined 28° from the vertical and orientated towards the cardinal points. During installation, the reference LOS 0 has to be placed to the North or its deviation to the North should be indicated in the software.

2.2. High frequency measurements (1 Hz)

At high frequency (1 Hertz), a LOS measurement at a given height is a radial wind speed measurement (Vr). Vr is the component of the wind velocity at the location of measurement along the axis of the LOS. It is not possible to retrieve the wind velocity from a single Vr since it measures only one component of the wind velocity. Therefore, at a given height, all Vr from different LOS must be combined to produce the wind velocity.

The easiest way of combining several Vr is to assume wind flow homogeneity at a given height: each of the horizontal wind speeds, the wind direction and the vertical wind speed are constant across the measurement volume. In such conditions, any Vr is measuring the exact same wind velocity across the measurement volume and, especially, above the Windcube. Then, the Vr measurements are converted into the wind component along North axis (U) and the wind component along East axis (V) using basic geometry transformation. The wind speed and wind direction can then be directly computed from the U and V values.

The principles and equation of horizontal wind reconstruction are drawn in figure 1 below. The four cardinal LOS are indicated with their heading values: 0° for North, 90° for East, 180° for South and 270° for West. The vertical LOS is not represented as it is not used for horizontal wind speed reconstruction.

This reconstruction is performed independently at each height for each new radial wind speed measurement using the previous values in the equation.

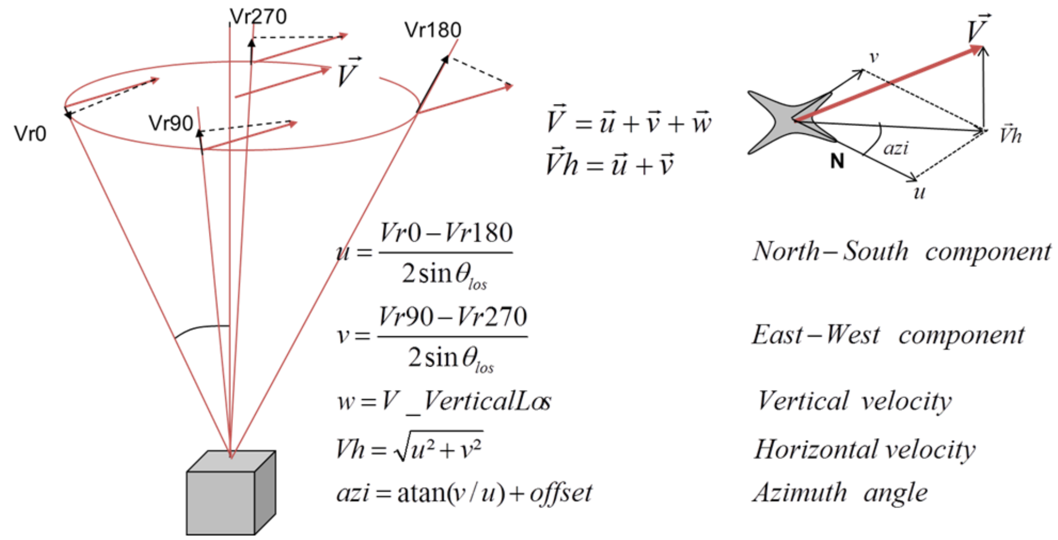


Figure 1 - Windcube standard wind reconstruction at high frequency

2.3. Average measurements (10 minutes)

The 10 minute average wind speed and direction are obtained from the averaging of the high frequency wind speed and wind direction. Each high frequency measurement is associated with a validity status (1 or 0) resulting from specific Lidar signal processing. Only valid measurements are taken into account for the averaging.

2.4. Limitations in complex flow

The wind homogeneity assumption is no longer valid in complex flow since the wind velocity is different from one LOS to another. For example, a significant hill induces non negligible inflow angle and thus generates vertical wind speed as shown in figure 2. For this hill, the vertical wind speed is different between the South LOS and the North LOS indicating that the wind flow is not homogeneous.

The solution is to account for wind velocity differences between the points of measurement when combining radial wind speeds.

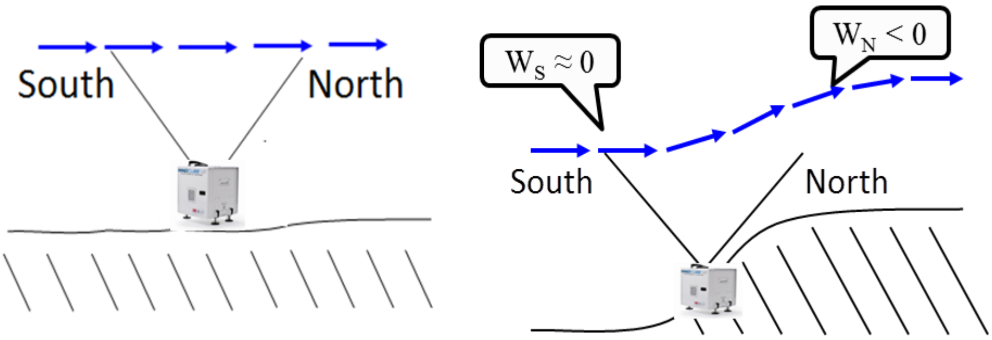


Figure 2 – Example of homogeneous flow (left) and heterogeneous flow (right)

3. FCR wind reconstruction

The FCR is an algorithm which associates the 10 minute average measurement of the Windcube with fluid mechanics equations in order to determine the wind velocity (ie wind speed and wind direction) for a given terrain topography. It embeds a 3D wind field model for complex terrain called SWIFT. This model has been configured to produce a mass-consistent wind field using data from the Windcube.

3.1. Input

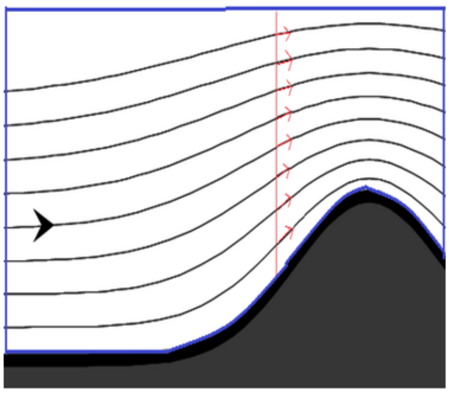
It requires two types of input data to be retrieved automatically:

- **Site topography**: the FCR uses corresponding topographic tiles from the embedded SRTM or ASTER public database based on the configured GPS input. The database contains the terrain elevation at a 100 meter resolution for a 1 km*1 km square, downscaled at a 10 meter resolution.
- **Wind measurements:** wind speed and wind direction at several heights at a single location as measured by the Windcube standard wind reconstruction.

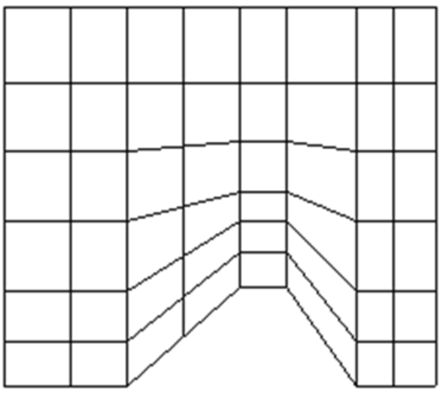
3.2. Method

SWIFT is designed to rapidly compute wind fields from on-site observations. These comply with the first Navier-Stokes equation, mass conservation, to account for terrain effects on the flow structure. The influence of atmospheric stability on wind flow over terrain is modeled using a weighting factor α (ratio of the horizontal wind component to the vertical wind component).

Calculation is made on a 1 km² grid which is regularly spaced along the horizontal plane and vertical axis. The mesh resolution is 10 meters for the horizontal plane and 5 meters for the vertical axis. The bottom of the grid is adapted to the terrain topography. Figure 3 shows an example of grid associated to a terrain.



Example of terrain topography



Example of associated grid

Figure 3 - Example of grid associated to a hill

The computation involves two steps detailed below:

1. **Wind field initialization** over the entire map. This step is important for subsequent computations as it fixes the boundary conditions of the flow, particularly at the lateral boundary and domain top (H). These conditions can be modified only slightly in the following adjustment step.
2. **Adjustment to terrain topography**. This step ensures mass conservation of the wind field by forcing realistic boundary conditions (zero flux at ground and domain top levels) and adjusting both horizontal and vertical velocity components.

3.2.1. Wind field initialization

Prior to the CFD calculation, the wind field should be initiated at the grid points. Each grid point is given a null vertical wind speed value (W). The U and V components are initiated from the Windcube measurement as defined below.

Vertical interpolation

First, U and V values are computed for each grid point on the vertical axis above the Windcube, providing a wind profile at a single location. The two nearest measurements of each grid point height are identified and **interpolated** to the grid point. Below the first measurement point, U and V are extrapolated according to a log-law profile for which the parameters are the first range gate U and V value and a fixed roughness length. Above the highest measurement point the profile is set to a U and V value corresponding to the U and V value of this highest point. This process is carried out independently for U and V components. The diagram below (figure 4) shows the principle of the interpolation of two Windcube measurements (blue points) to the grid point, at a given height.

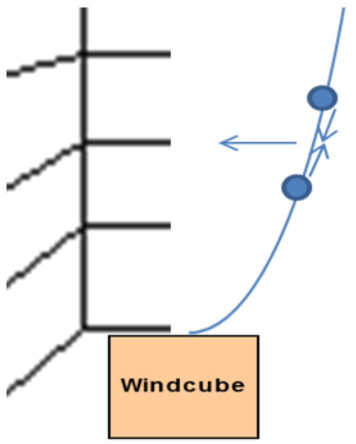


Figure 4 - Windcube wind speed interpolation: two measurement points (blue) are interpolated to the grid point

Horizontal extrapolation

This wind profile is then extended across the terrain: U and V values at a given height are used for all grid points at the same height with respect to the terrain. Figure 5 below shows an example of the interpolation method for a hill.

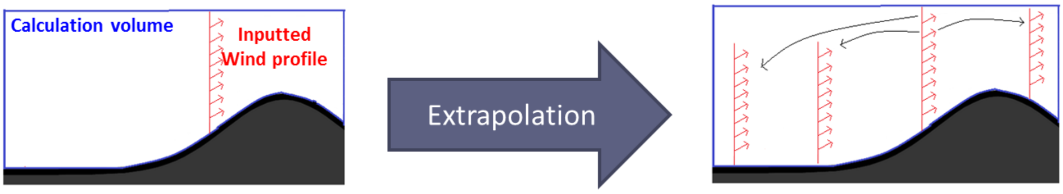


Figure 5 - Interpolation method for initial wind field

At the end of this process, for a given height above the ground level, the initial wind speed is the same over the terrain and corresponds to the interpolated wind speed of Windcube standard wind reconstruction.

3.2.2. Adjustment to terrain topography

The basic notations are:

- $\vec{V}_0 = \begin{pmatrix} u_o \\ v_o \\ w_o \end{pmatrix}$ represents the field interpolated from original measurements
- $\vec{V} = \begin{pmatrix} u \\ v \\ w \end{pmatrix}$ represents the final field with zero (adjusted) divergence

The following two equations must be solved:

1. mass conservation for an incompressible fluid (ρ = constant), let div $\vec{V} = 0$,
2. constraint to be the closest possible to the initial interpolated wind field $\vec{V}_0$

A function is then defined in which the incompressibility constraint is introduced through a Lagrangian multiplier λ. The function is expressed as:

$$\mathrm{J}(\vec{V},\lambda) = \int_{\Omega} (u-u_o)^2 + (v-v_o)^2 + \frac{1}{\alpha}(w-w_o)^2 \, d\Omega + \int_{\Omega} \lambda \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right) d\Omega \quad [\text{eq.}1]$$

Where Ω is the internal volume of the computation domain.

The α value is a weighting factor on the vertical wind speed measurement which refers to thermal stability. α values close to 0 model stable thermal condition and α values close to 1 model neutral and near-unstable thermal conditions. The α value is set to the constant value of 1 in FCR allowing for efficient correction with strong wind, which is generally associated with neutral or near-unstable conditions. This setting of the thermal stability induces the value of W calculated from the above equation 1 is strongly driven by the mass conservation term.

Mathematical resolution

The function is minimized when the values of its derivatives according to $\vec{V}$ and λ are simultaneously zero. The result is the following equation using an adapted grid for the calculation:

$$\begin{cases} div\vec{V} = 0 \\ [\mathrm{A}](\vec{V} - \vec{V}_o) = \vec{\nabla}\lambda \end{cases} \text{ where [A] is the matrix } \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1/\alpha \end{pmatrix}$$

The problem calls for the resolution of an A X = B matrix system. The algorithm used for the resolution is the Gauss-Siedel successive over relaxation (SOR) procedure, which involves a convergence criterion over the λ value.

Once the λ converges below a fixed threshold value, the wind velocity is obtained. The resulting wind field at the location of the Windcube is consistent with the initial Windcube measurements but also takes into account the surrounding topography and especially the wind flow curves within the measurement volume.

3.3. Output

The output is a corrected 10 minute average file (*.sta*), with corrected wind speed and wind direction values, that comes in addition to the original dataset (renamed *.stastd*). Both datasets are stored in the system, whereas only corrected data are sent to Windweb.

4. Performance of FCR

4.1. Campaign results

The FCR has been tested and validated by independent industry experts in various locations around the globe. Several results are publicly available and can be shared upon request.

In this chapter we present three campaigns where independent parties were involved and detailed results are available. All happened in complex terrain, here defined as a site for which:

- slopes are lower than 30°
- standard deviation of elevation around the Windcube is less than 30 meters
- terrain ruggedness index is below 1.5

The terrain is considered highly complex terrain if one of these requirements is not fulfilled.

CRES (Greece)	*moderately complex site*	**2010**
Acciona Energia / Barlovento (Spain)	*moderately complex site*	2011
DTU/COWI (Denmark)	*moderately complex site*	2012

Table 1 - Selection of FCR campaigns

4.1.1. CRES, Greece, 2010

The campaign lasted for 2.5 months and compared results from a Windcube v1, Windcube v2 and a 100 meter high mast equipped with 3 Measnet calibrated cup anemometers at 54m, 78m, and 100m. The below pictures shows the installation set up: the terrain is hilly with very low vegetation and the systems are placed by the mast location.

Figure 6 – Site overview (left) and equipment installation (right)

The comparison with cup anemometers was done using the standard Windcube v1 and v2 data (assuming homogeneity) and FCR Windcube v2 data. It was observed that gain of the linear regression of FCR is less than 1% for the side-mounted anemometers (54 meters and 78 meters) and less than 2% for the top mounted anemometer (100 meters). The offsets and correlations for the two wind reconstructions lie in the same range.

Height	Gain (standard)	Gain (FCR)	Offset (standard)	Offset (FCR)	R2 (standard)	R2 (FCR)
54 meters	0.934	1.006	0.092	0.076	99.84%	99.81%
78 meters	0.939	1.009	-0.029	-0.017	99.83%	99.82%
100 meters	0.960	1.020	0.108	0.101	99.82%	99.85%

Table 2 - Comparison results between standard WIndcube v2 and FCR measurements

The wind speed deviation for the FCR lies between the uncertainty (k=2) of the calculated cup wind speed. The figure below shows the comparison of cup uncertainty to wind speed bias per wind speed class for the height of 100 meters. It is observed that the FCR is equivalent to the cup uncertainty.

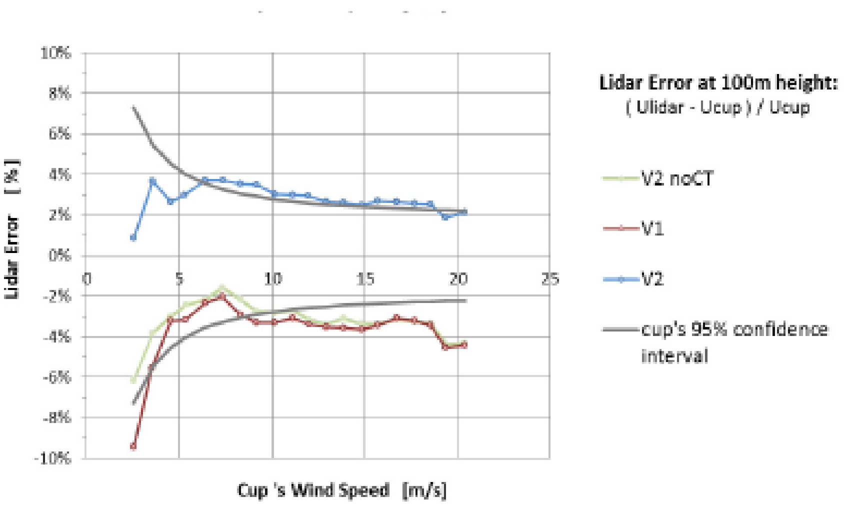


Figure 7 - Uncertainty of cup compared to FCR measurements (*v2 noCT*), and standard Windcube measurements (*v1*, *v2*) bias at 100m

4.1.2. Acciona Energia and Barlovento, Spain, 2011

The campaign lasted for 7 weeks. The Windcube was compared to a 80 meter mast equipped with Vector A100L anemometers at 40, 60, 73 and 80 meters. The terrain is forested and moderately complex as shown in below figure.

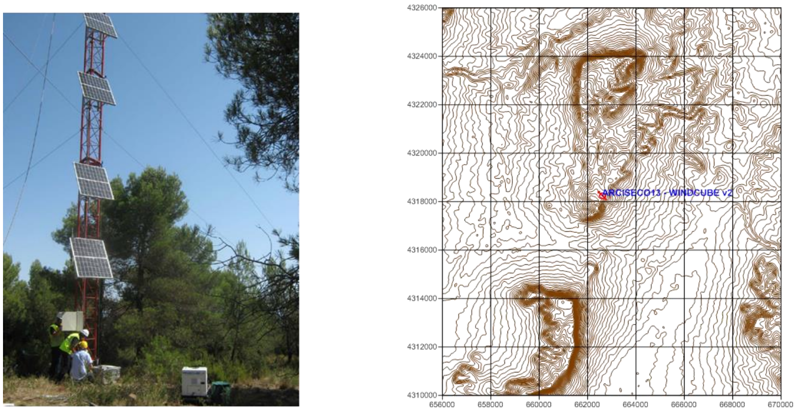


Figure 8 - Picture of the site (left) and topographical map (right)

The comparison was done using a linear regression between the cup data and the FCR data. A gain very close to 1 and a static offset around 0.23 m/s was observed. Correlation was 99%. The results showed good fit between the FCR and the cup anemometers. The bias could be due to the high forest around the Lidar. Specific recommendations are given below for siting of Windcube near forests.

Height	Gain	Offset	R2
80 meters	1.000	0.233	99.19%
73 meters	0.990	0.239	99.18%
60 meters	0.999	0.246	99.87%

40 meters	0.994	0.204	98.74%

Table 3 - Results of FCR

4.1.3. COWI and DTU, Denmark, 2012

The campaign lasted for 3.5 months. The Windcube was installed close to a 75 meter high mast equipped with Thies First Class wind sensors at 30m, 55m, 75m, 77.5m. The terrain features a very steep slope at South and very low vegetation.

Figure 9 - Topographical map (left) and Windcube v2

The comparison with the cup anemometers was done using the standard Windcube data (assuming homogeneity) and FCR data. It was observed that gains of the linear regression for FCR are less than 1.2% for all heights and that the offsets are lower than 0.15 m/s. Correlation values for both reconstructions are equivalent and around 99.5%.

Height	Gain (standard)	Gain (FCR)	Offset (standard)	Offset (FCR)	R2 (standard)	R2 (FCR)
55 meters	0.949	1.012	0.197	0.146	99.46%	99.56%
75 meters	0.946	1.008	0.189	0.142	99.47%	99.57%
77.5 meters	0.943	1.004	0.162	0.116	99.46%	99.59%

Table 4 - Comparison results

From the datasets, the sensitivity to various environmental parameters could be screened. The first parameter is the wind direction. Looking at the topographical map on figure 9, one can expect high deviation of standard wind reconstruction in the South wind sector due to the steep slopes. The below figure 10 shows the deviations between cups and Windcube at 77.5 meters with regards to the wind direction given by the wind vane at 53 meters. The left graph is the standard reconstruction and the right graph is the FCR reconstruction. For the standard wind reconstruction, higher deviation is observed in the South wind sectors than for the other wind sectors. The FCR shows no specific dependency with the wind direction showing the different type of wind flow are correctly identified and corrected.

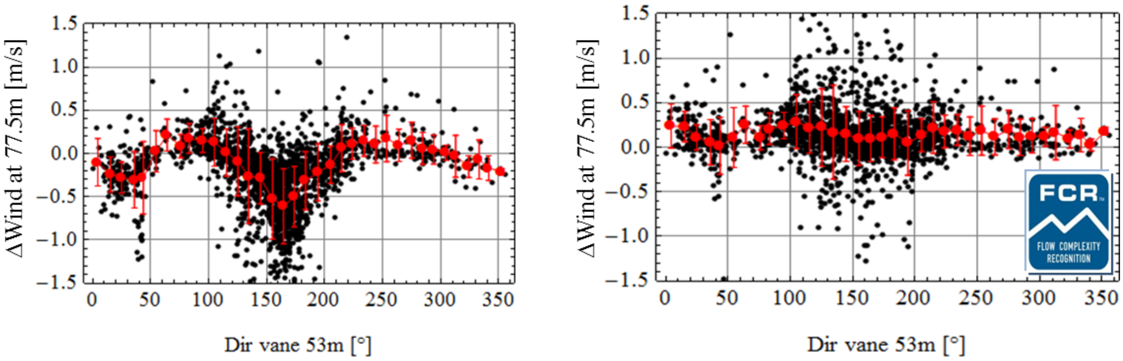


Figure 10 - Wind sectors wise deviations

Similar results are observed for the thermal stability, for which the proxy used here is the shear (figure 11) and wind speed (figure 12). The FCR doesn't show sensitivity to these parameters unlike the standard wind reconstruction. It shows that the FCR algorithm correctly identifies and accounts for the different types of wind flow.

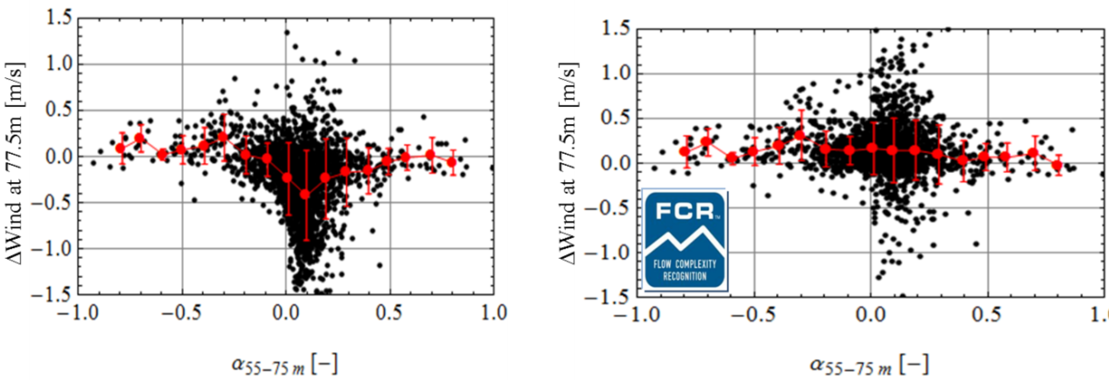


Figure 11 - Deviations sensitivity to shear (right is standard wind reconstruction and left is FCR)

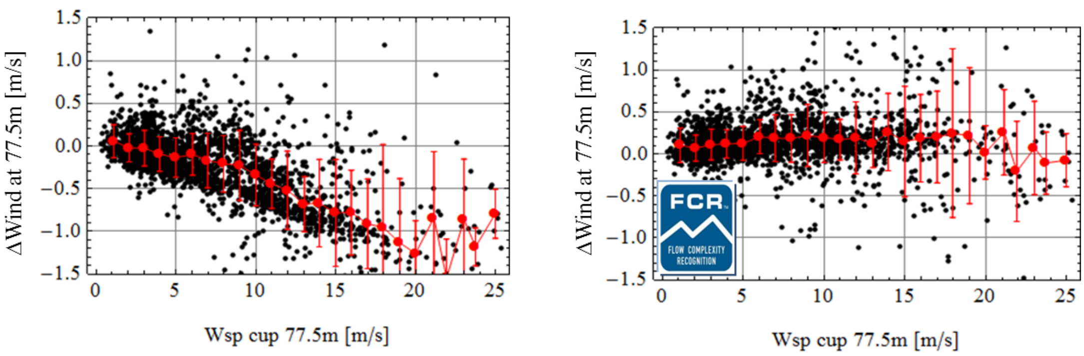


Figure 12 - Deviations sensitivity to wind speed (right is standard wind reconstruction and left is FCR)

4.2. Limitations

Although performance of the FCR has been demonstrated in several conditions, it doesn't solve all problems arising in complex flow, a particularly challenging topic within the industry. This chapter intends to present the main known limitations.

Don't hesitate to contact us if you have doubts about the suitability or interest of the FCR on a particular project. We will help you in making the best decision based on our experience and your objectives.

4.2.1. Very complex flow

Accuracy and precision of FCR measurements in very complex flow are deteriorated: very complex terrain or areas with high and inhomogeneous roughness (urban).

Although limited feedback is available, deviations of around 6% have been observed. This is expected as the FCR is using the mass conservation equation but does not force the flow to match the others equations of Navier-Stokers, namely the momentum conservation and the energy conservation. Very local phenomena such as flow recirculation cannot be captured.

To illustrate this, figure 13 shows a wind flow simulation using FCR equations and another one also accounting for the momentum equation. The terrain used for the simulation is a hill with steep slopes. It can be seen that the difference between the two wind flows is quite large in the recirculation, explaining why the FCR would mistakenly reconstruct the wind speed for these types of phenomenon. It is thus recommended to use the FCR only in terrains which are not likely to generate flow recirculation as found with very complex terrain.

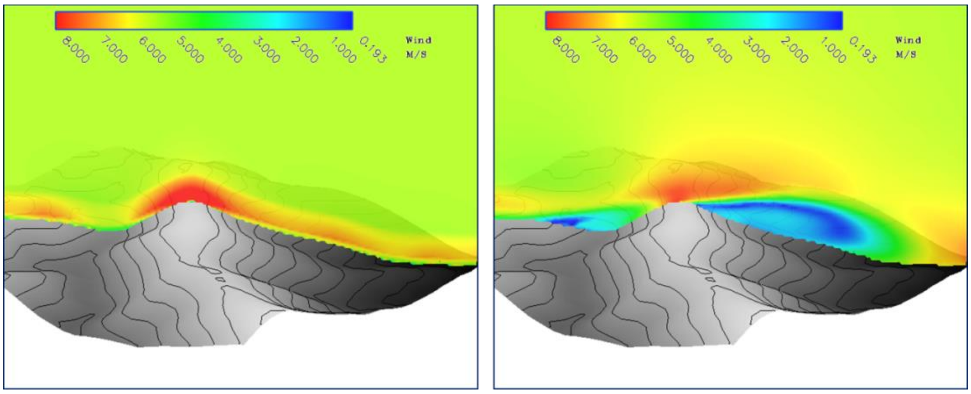


Figure 13 - FCR wind flow simulation (left) compare to advanced CFD

4.2.2. Roughness length

Roughness length is fixed at a low value in the FCR equation. In high roughness, such as forest or urban areas, this assumption is broken leading to a bias of measurement due to wrong wind profile modeling.

4.3. Data availability

The only existing data filtering in the standard reconstruction is based on the strength of returned signal. Only valid radial wind measurements are used in the 10 minute average. Since the FCR algorithm doesn't have additional filtering, it has no impact on data availability.

5. Recommendations for use

5.1. Distance to obstacles

In order to avoid limitations due to high flow complexity or roughness length, the minimum distance to obstacles should be at least three times the height of the obstacles. General recommendations regarding Windcube siting should also be followed.

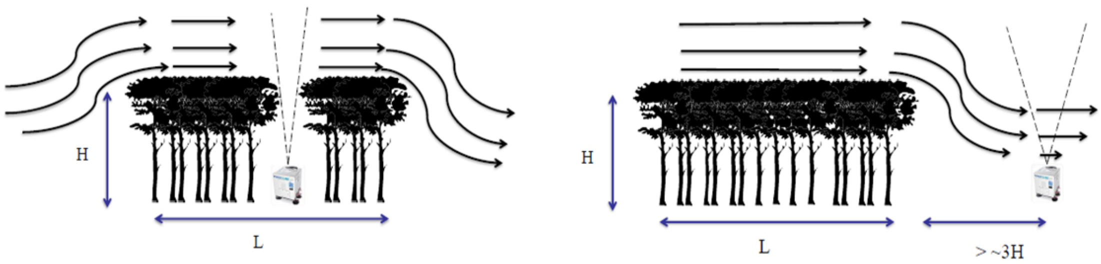


Figure 14 - Siting of the Windcube to obstacle

5.2. North heading

The FCR algorithm uses absolute wind direction information to match measurements with terrain topography. The Lidar doesn't directly measure this information but a relative direction compared to its axis. To retrieve the absolute wind direction in the file, we simply need to know the alignment of this axis with the geographical North.

In practice, the software will consider the LOS 0 as being orientated to the North. During installation, is it then required to physically orient the Lidar so that LOS 0 is indeed aligned with the North, or indicate in the software the offset value to the geographical North.

A compass can be used to perform this operation, as described in the Windcube user manual. To calculate magnetic declination based on location, online sources can be used such as: https://www.ngdc.noaa.gov/geomag-web/.

5.3. GPS coordinates

The GPS coordinate accuracy is critical for the good use of FCR since it defines the topography which is used as input for the flow modeling. The GPS coordinates should be accurate to a maximum of 10 meters. We recommend adding known GPS coordinates manually in the software for maximum confidence.