PO.027

ZephyCube - LIDAR data CFD correction in complex terrain

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Introduction

The Windcube uses the Doppler effect, that is the measurement of the frequency shift of a laser beam backscattered by aerosols in the atmosphere, to calculate the wind speed at its vertical. The frequency shift of the laser beam is proportional to the projection of the wind speed vector at the measurement point along the direction of the beam.

Since the wind speed is described by a three-dimensional vectors, it is needed to measure such a shift along at least 3 non-collinear directions (no need for these three directions to constitute an orthogonal basis). The unavoidable consequence of this is that the different measurements cannot be made exactly at the vertical of the Windcube. Rather, the lidar will measure different wind speed components at different points in space, using five different laser beams, also called lines of sight (LOS).

Under the assumption of flow homogeneity in the volume of measurement, the orthogonal components of the wind speed can be deducted from these values via simple trigonometrical formulas. In simple terrains, these measurements shifted from the vertical of the Windcube don't impact much the result as the flow homogeneity hypothesis is valid on the volume of interest. Yet the latter doesn't hold anymore in complex terrain, and this is why one need to use a high fidelity model to extrapolate the measurements made along the bended beams to the vertical of the Windcube. In order to correct the error in complex terrain, we take benefit from CFD result where we can have some knowledge about how the wind behaves inside the measurement volume.

ZephyCube will allow its user to automatically extract the CFD results needed for lidar data correction. Additionally it will provide 2 basic algorithms for the data reconstruction, one using the standard .sta files output of the Windcube lidar, and the other using directly the beam measurements for more accuracy.
This document describes the working principles behind ZephyCube.

1 Scope of the correction

The Windcube V2 measures the vertical wind speed using a vertical laser beam. This component therefore doesn't need to be corrected as the measurement is made directly at the targeted point. Thus, the CFD correction will only be computed on the horizontal wind speed.

The Windcube V1 however doesn't include this vertical beam so the full wind speed vector needs to be corrected. But this is component can be directly calculated from the 4 beams measurements.

The present document deals only with the Windcube V2 measurement correction.

2 CFD Calculation

ZephyCube will either use **existing CFD models from ZephyCFD** will lidar entities or it will create an **automatic CFD project from scratch** for each considered lidar. This automatic project would have fixed discretization parameters, namely:

- **A High-Resolution Mesh (30m horizontal resolution)** used to evaluate the wind characteristics for the prevailing directions according to the measured wind roses. Simulations shall be run **every 5 degrees** for 16 prevailing directions.
- **A Low-Resolution Mesh (100m horizontal resolution)** used to evaluate the wind characteristics for the non-prevailing directions according to the measured wind roses. Simulations shall be run **every 15 degrees** for 16 non-prevailing directions.

ZephyCube will need to know the measurement heights of the Windcube, as well as its scan angle and direction offset. These parameters can be input manually or detected automatically from a .sta file.
Using the CFD project, ZephyCube automatically extracts results at the 5 beam points (center, north, south, west, east) of each measurement height. These results are normalized with reference to the beam point in the center, giving speedup ratios and direction deviations.

As these normalized results are coming from a given number of calculated wind sectors, they are then interpolated with a 1° step to complete a 360° rose of normalized results. At that point these results are made available for the user to perform their own lidar data correction.

3 Embedded reconstruction methods

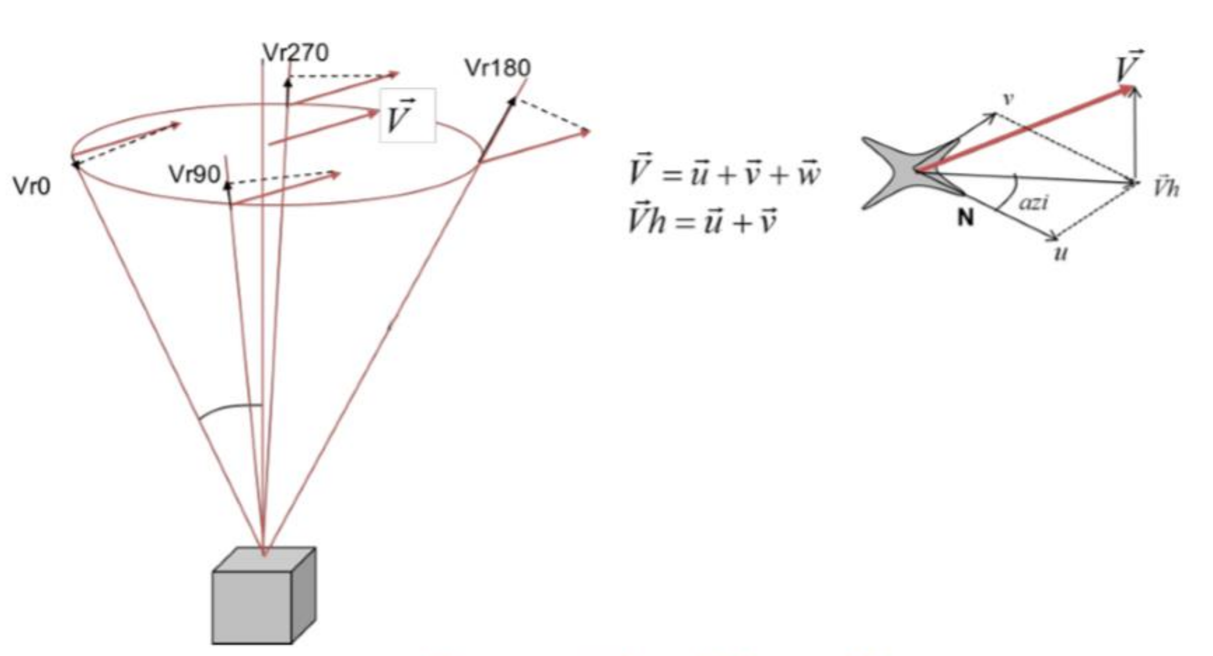

Figure 1: Representation of the problem

In Figure 1, we notice the wind vector is reconstructed from 5 beams into 3 components, $\vec{u}$ component from north beam and south beam, $\vec{v}$ component from west beam and east beam, $\vec{w}$ from the vertical beam.

We now take a specific look at how the north beam and south beam construct the $\vec{u}$ component, With figure 2. The $\vec{v}$ component would follow the same rule.

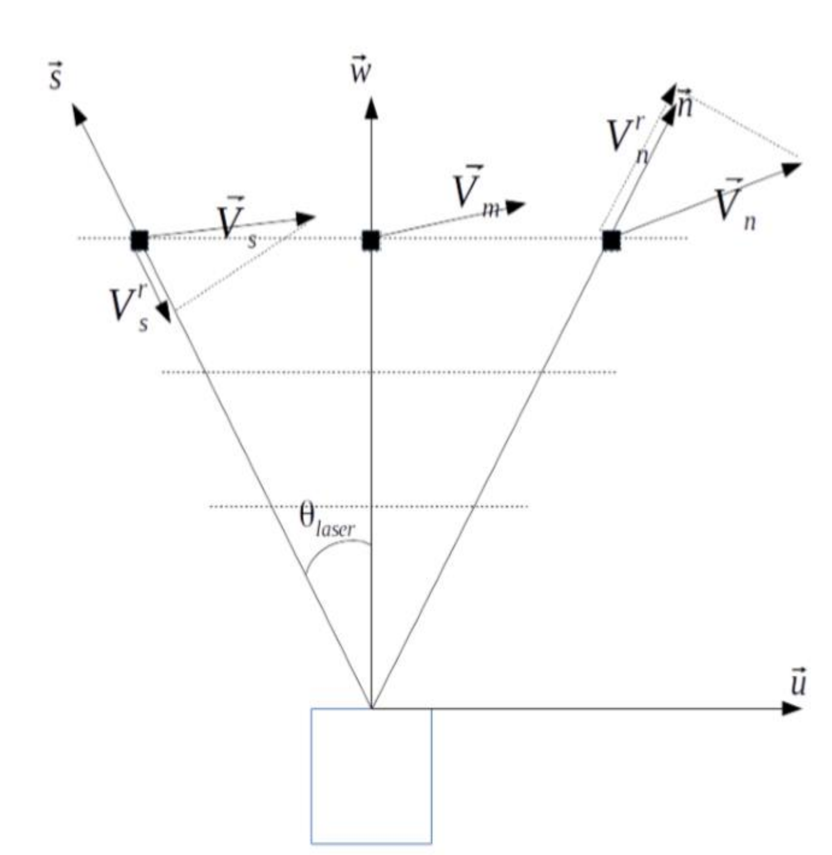

Figure 2: representation of the north/south part of the problem in a 2D plane

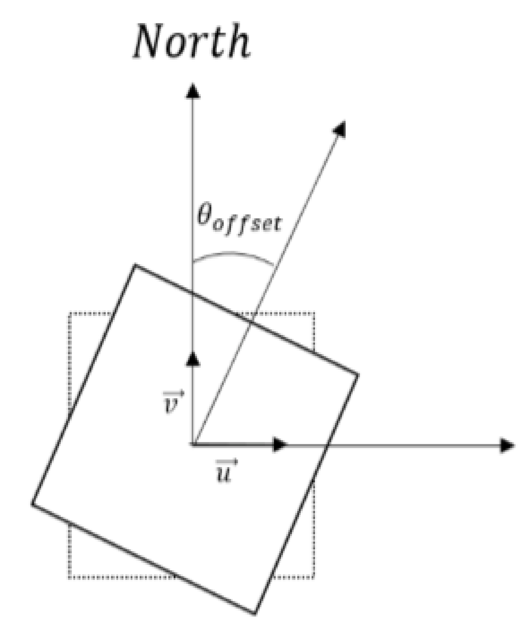

Figure 3: Top view of the Windcube showing the offset as θ_{offset}

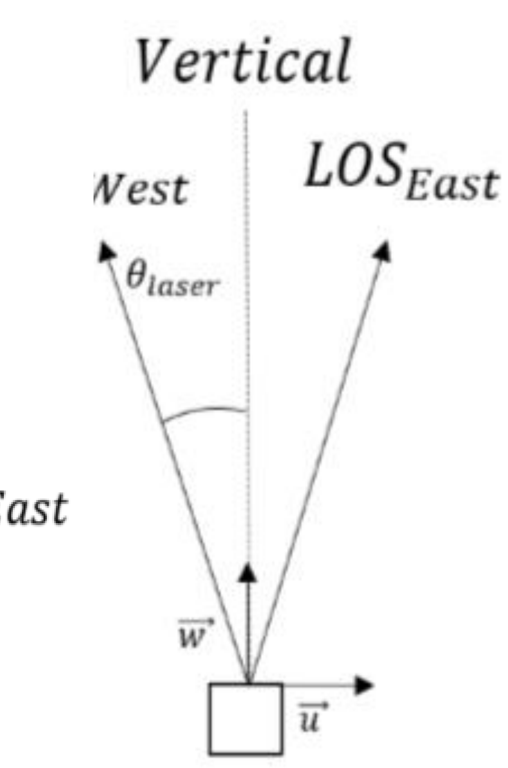

Figure 4: Vertical section of the Windcube showing the scan angle as θ_{laser}

V_n^r and V_s^r are the projections of wind on the north beam and the south beam, respectively:

$$V_n^r = \vec{V}_n \cdot \vec{n}$$
$$V_s^r = \vec{V}_s \cdot \vec{s}$$

With

$$\vec{V}_n = u_n \cdot \vec{u} + w_n \cdot \vec{w}$$
$$\vec{V}_s = u_s \cdot \vec{u} + w_s \cdot \vec{w}$$

The angle between the beams and the vertical direction is θ_{laser}. With it the unit vectors of the north and south beams are expressed as:

$$\vec{n} = \sin(\theta_{laser})\vec{u} + \cos(\theta_{laser})\vec{w}$$
$$\vec{s} = -\sin(\theta_{laser})\vec{u} + \cos(\theta_{laser})\vec{w}$$

And the components V_n^r and V_s^r are finally expressed as:

$$V_n^r = u_n \sin(\theta_{laser}) + w_n \cos(\theta_{laser}) \quad (1)$$
$$V_s^r = -u_s \sin(\theta_{laser}) + w_s \cos(\theta_{laser}) \quad (2)$$

The following parts describe the different approaches to this equation system, to express u_m the horizontal component of $\vec{V}_m$ the wind speed at the vertical of the Windcube.

3.1 No correction: Homogeneous flow

This is the initial data, for which it is supposed that the wind is homogeneous regardless of the LOS:

$$u_n = u_s = u_m$$
$$w_n = w_s = w_m$$

(1) - (2) then gives:

$$V_n^r - V_s^r = 2u_m \sin(\theta_{laser})$$

Thus the relation:

$$u_m = \frac{V_n^r - V_s^r}{2\sin(\theta_{laser})} \quad (3)$$

This is the value which is stored in the standard .sta files outputed by a Windcube, as north component of the horizontal speed. It is noted u_{sta} in the rest of the text.

3.2 CFD correction

Choice of the CFD scenario

The correction process uses speed-up coefficient computed in the CFD model which are defined relatively to a boundary direction of the wind. For each wind data to be corrected, one need to choose the more representative CFD scenario and this is achieved using the measured wind direction at the vertical of the Windcube.
However one will here face a problem: the direction recorded by the Windcube is calculated using the flow homogeneity hypothesis, which doesn't hold in complex terrains and consequently might be biased. One would need to know as an input the corrected wind direction to choose the CFD scenario and proceed to the correction.

Our ability to solve this kind of inverse problem is highly dependent on the speed-up coefficient values and is therefore site specific. In order to avoid this issue in the general case, we will assume that the sensibility of the speed-up coefficient is not strongly dependent on the synoptic direction, which will allow us to use the non-corrected wind direction.
The accuracy of this assumption might be verified by computing the dérivée of each speed-up coefficient (along each direction) relatively to the synoptic direction and checking that their values are small enough.

3.2.1 Scalar correction

The CFD model used in ZephyTOOLS assumes that normalized results will remain constant, meaning that wind speedup ratios only depend on directions and not on wind speeds. This assumption is correct for the range of wind speeds studied with high Reynolds numbers and can easily be verified in ZephyTOOLS by varying the reference velocity at the inlet.

As a result, the speed-ups and the inflow angle are not affected by the wind speeds at the inlet and so the ratios $a_n = u_n/u_m$, $a_s = u_s/u_m$, $b_n = w_n/w_m$ and $b_s = w_s/w_m$ can be considered as constant for different wind speeds which allows taking directly the ratio calculated from CFD.

Using the speedups, we express the relation between u_m and the LOS components as:

$$u_m = u_s/a_s = u_n/a_n$$
$$w_m = w_s/b_s = w_n/b_n$$

(1) - (2) then gives:

$$V_n^r - V_s^r = (a_n + a_s)u_m \sin(\theta_{laser}) + (b_n - b_s)w_m \cos(\theta_{laser})$$

$$\Leftrightarrow u_m = \frac{2\frac{V_n^r - V_s^r}{2\sin(\theta_{laser})} - (b_n - b_s)w_m \cot(\theta_{laser})}{a_n + a_s}$$

Where we recognize (3) the expression of u_{sta}. Thus the relation:

$$u_m = \frac{2u_{sta} - (b_n - b_s)w_m \cot(\theta_{laser})}{a_n + a_s} \quad (4)$$

With u_{sta} and w_m being known already.

In practice, there are some exaggerate positive and negative values when using this expression, which should not be the case. Therefore, some filtering is made with additional assumptions:

Homogeneous horizontal speed for horizontal speeds under 1m/s

For this hypothesis, we suppose that for horizontal speeds below 1m/s, the horizontal component of the wind speed field is homogeneous, that is to say:

$$u_m = u_s = u_n$$
$$w_m = w_s/b_s = w_n/b_n$$

(1) - (2) then gives:

$$V_n^r - V_s^r = 2u_m \sin(\theta_{laser}) + (b_n - b_s)w_m \cos(\theta_{laser})$$

$$\Leftrightarrow u_m = \frac{2\frac{V_n^r - V_s^r}{2\sin(\theta_{laser})} - (b_n - b_s)w_m \cot(\theta_{laser})}{2}$$

Where we recognize (3) the expression of u_{sta}. Thus the relation:

$$u_m = u_{sta} - \frac{(b_n - b_s)w_m \cot(\theta_{laser})}{2} \quad (5)$$

3.2.2 Vector correction

When the raw measurements from the 4 beams are available, a CFD-based reconstruction from scratch should improve the correction accuracy as it avoids the errors inherent to the reconstruction method behind .sta files.

Projection on the beams

In all the problem, we work with an orthogonal basis of the 3-dimensional space whose first vector points east direction ($\vec{u}$), second north ($\vec{v}$) and third the vertical ($\vec{w}$). In this basis, the coordinates of the 4 normalized beam vectors (called Line Of Sight) are:

$$\overrightarrow{LOS_{North}} = \sin(\theta_{offset})\sin(\theta_{laser})\ \vec{u} + \cos(\theta_{offset})\sin(\theta_{laser})\ \vec{v} + \cos(\theta_{laser})\ \vec{w}$$
$$\overrightarrow{LOS_{South}} = -\sin(\theta_{offset})\sin(\theta_{laser})\ \vec{u} - \cos(\theta_{offset})\sin(\theta_{laser})\ \vec{v} + \cos(\theta_{laser})\ \vec{w}$$
$$\overrightarrow{LOS_{East}} = \cos(\theta_{offset})\sin(\theta_{laser})\ \vec{u} - \sin(\theta_{offset})\sin(\theta_{laser})\ \vec{v} + \cos(\theta_{laser})\ \vec{w}$$
$$\overrightarrow{LOS_{West}} = -\cos(\theta_{offset})\sin(\theta_{laser})\ \vec{u} + \sin(\theta_{offset})\sin(\theta_{laser})\ \vec{v} + \cos(\theta_{laser})\ \vec{w}$$

With θ_{offset} the offset angle of orientation of the Windcube towards north (see Figure 3) and θ_{laser} the angle of inclination of the beams from the vertical (see Figure 4).

The wind speed vector at the vertical of the Windcube can be expressed as follow:

$$\overrightarrow{V_{wind}^{raw}} = V_h\sin(\alpha)\ \vec{u} + V_h\cos(\alpha)\ \vec{v} + V_v\ \vec{w}$$

With V_h the horizontal wind speed, α the wind direction and V_v the vertical wind speed.

The projections of the wind vector along each beam direction are then given by the scalar product (see Figure 5): $P_{beam}^{raw} = \overrightarrow{LOS_{beam}}.\overrightarrow{V_{wind}^{raw}}$

These projections are the raw values measured by each beam using the Doppler effect, which are needed for this reconstruction method.

Calculation of the speed-up coefficients

The extrapolation coefficient along the beam direction from the LOS (denoted M_{beam}) to the vertical of the Windcube (denoted M_{vert}) calculated from the CFD is therefore:

$$SU_{beam}^{M_{beam}\rightarrow M_{vert}}(\alpha) = \frac{\overrightarrow{V_{wind}^{CFD}}(M_{vert},\alpha).\overrightarrow{LOS_{beam}}}{\overrightarrow{V_{wind}^{CFD}}(M_{beam},\alpha).\overrightarrow{LOS_{beam}}}$$

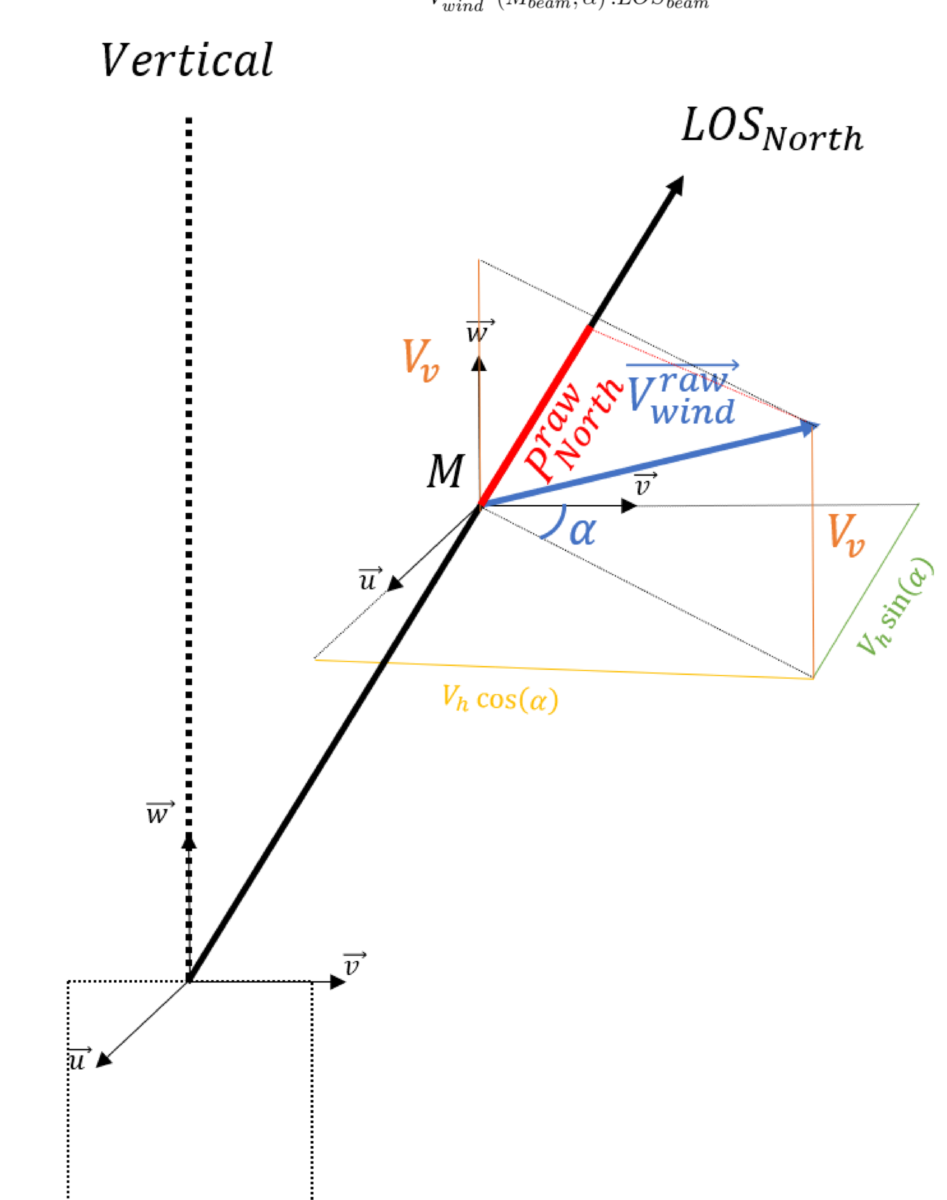

Figure 5: Projection P_{North}^{raw} (red) of the raw wind vector along the North beam direction

Extrapolation of the projections

For each of the four beam direction and given the input wind direction α, the extrapolation of the projection goes as follow:

$$P_{beam}^{corr} = P_{beam}^{raw}.\ SU_{beam}^{M_{beam}\rightarrow M_{vert}}(\alpha)$$

Calculation of the corrected horizontal wind speed

The following trigonometrical formulas enable to calculate the wind vector from these corrected components:

$$\overrightarrow{V_{wind}^{corr}}.\vec{u} = \frac{P_{East}^{corr} - P_{West}^{corr}}{2\ \sin(\theta_{laser})}\cos(\theta_{offset}) + \frac{P_{North}^{corr} - P_{South}^{corr}}{2\ \sin(\theta_{laser})}\sin(\theta_{offset})$$

$$\overrightarrow{V_{wind}^{corr}}.\vec{v} = -\frac{P_{East}^{corr} - P_{West}^{corr}}{2\ \sin(\theta_{laser})}\sin(\theta_{offset}) + \frac{P_{North}^{corr} - P_{South}^{corr}}{2\ \sin(\theta_{laser})}\cos(\theta_{offset})$$

If needed (Windcube v1) the third component, along the $\vec{w}$ axis can be calculated using following formula:

$$\overrightarrow{V_{wind}^{corr}}.\vec{w} = -\frac{P_{East}^{corr} + P_{West}^{corr} + P_{North}^{corr} + P_{South}^{corr}}{4\ \sin(\theta_{laser})}$$

Beam measurement recovery rates

When dealing with raw beam measurements, it may happen that the recovery rates at a given heights are not good enough, especially since all 4 beams are needed for the above method to be applicable. It may be necessary to design a CFD-based methodology which uses not only the beam measurements of a same height, but actually every beam from every height to reconstruct the measurement at a given height.