End-to-end simulation of a coherent Lidar in a turbulent wind field

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Abstract: For operational applications such as wind resource assessment or turbine control, to warrant the performances in velocity accuracy and data availability is required. A Lidar simulator (Simulid™) has been developed for assessing the velocity accuracy and the data availability of pulsed coherent wind Doppler Lidar system worldwide. This simulator takes into account both the Lidar parameters (instrument hardware, signal processing, beam propagation...) and the aerosol properties. Recently, Simulid™ has been coupled with a 3D wind model (Turbsim) to perform simulated wind measurements in any representative wind field, including turbulence. We present the methodology and the validation process. Velocity accuracy is compared with experimental tests performed in a frozen propagation medium and the representativeness of the simulated wind measurements is discussed.

Keywords: Coherent Laser Radar, Lidar Instrumental Simulator.

1. Introduction

Accuracy and availability of atmospheric sensors are of critical importance, especially when their measurements are the inputs of numerical models or decision-making processes. For example the idea of Lidar-assisted wind turbine control is spreading out within the wind industry as it opens the door to new possibilities in improving wind turbine design and efficiency and reducing costs. In order to develop appropriate Lidar-assisted control strategies as well as to evaluate their benefits and mitigate their limitations, the support of realistic simulation tools is needed. In this paper the methodology developed to simulate realistic Lidar wind measurement is presented.

2. Ideal Lidar measurement

It is well known that coherent Doppler Lidars cannot measure wind locally but perform instead a spatial averaging of the wind speed within the volume of atmosphere that is spanned by the pulse during acquisition [1]. More precisely, given a point of measurement \( \vec{x} = [x, y, z] \), the radial wind speed seen by the Lidar can be approximated by the following convolution:

\[
v_t(\vec{x}) = \int_{-\infty}^{\infty} \varphi(r) \times v_t(r, \vec{x}) \, dr \quad (1)
\]

where \( \varphi(r) \) is the range weighting function of the Lidar derived from its pulse shape and apodization window and \( v_t(r, \vec{x}) \) is the local radial wind speed given by the projection of the wind field at a given timestamp \( t \) onto the unit vector of the Lidar line of sight (LOS) \( \vec{n} \), i.e.

\[
v_t(r, \vec{x}) = <\vec{n}, \vec{v}_t(r\vec{n} + \vec{x})> \quad (2)
\]

where \( <·,·> \) stands for the standard dot product (see Figure 1).

Several existing aero-elastic simulation tools use this approximation to simulate Lidar measurements. However, this approximation corresponds to an ideal Lidar measurement as it is not sensitive to the effects of atmospheric conditions, hardware and software real capabilities (e.g., detector noise, spectral resolution ...). Both of these aspects are taken into account in the methodology developed in LEOSPHERE, firstly, by modeling the influence of the atmosphere/Lidar configuration on the
backscattered power and, second, by reproducing the embedded signal processing on realistic Doppler spectra.

Figure 1: Four-beam Lidar in a wind-field

3. Methodology for realistic Lidar measurement simulation

3.1. Carrier-to-noise ratio simulation via Simulid™

Pulsed Doppler Lidars as any other atmospheric sensors have measurement performances that depend on local weather conditions and Lidar configurations. Both influence the so-called Carrier-to-noise ratio (CNR) which directly reflects the amplitude of the signal backscattered to the Lidar. Leosphere has developed a CNR simulation tool, Simulid™ [2], which takes into account both the instrumental and the atmospheric contributions with two distinct models (steps 1-2 of Figure 2):

- The instrumental model simulates the beam propagation based on a Gaussian model. It accounts for the instrument hardware (optics/detector efficiency, lens aperture, pulse energy and duration, noise power) and signal processing specificities (accumulation time, FFT size)
- The atmospheric model derives aerosol extinction $\alpha$ and backscatter $\beta$ coefficients from a given atmospheric condition (either user-defined or taken from the Monitoring Atmospheric Composition & Climate (MACC) model)

These two contributions are then combined to compute a CNR profile as follows

$$
CNR(r) = F(r) \times \int_0^r \alpha(r') dr' \tag{3}
$$

where $r$ denotes the distance between the Lidar and the point of measurement. Simulid™ also provides a CNR threshold to filter data and hence assess the availability of the measurement [2].

3.2. Doppler spectra simulation

In real Lidar systems, measured radial wind speeds are the outputs of a signal processing chain which consists in translating the received signal into a Doppler spectrum through a Fourier transform and then applying a Doppler frequency estimator. These two steps are reproduced within our simulation tool. Realistic Doppler spectra are obtained by using a generative model, called Feuilleté model [3-4]. This model takes as inputs the CNR and the radial wind speed profiles within the neighborhood of the measurement point to derive the statistics of the resulting Doppler spectrum (step 3 of Figure 2). The Doppler frequency estimator used in LEOSPHERE Lidars, based on a maximum likelihood estimator [3-4], is then applied on the simulated spectrum (step 4 of Figure 2). The overall simulation scheme is described in Figure 2.
3.3. Temporal acquisition

The scheme described above deals with the simulation of a single Lidar measurement at a given timestamp. Time series of Lidar measurement are obtained by propagating the wind field throughout time. In this study, since 2D temporal wind fields generated by TurbSim [5] are used, wind propagation is performed via the frozen turbulence Taylor hypothesis which states that the wind field is uniformly propagated, i.e.

$$\vec{V}_{t+dt}(x, y, z) = \vec{V}_t(x - \bar{U}dt, y, z)$$  \hspace{0.5cm} (4)$$

where \(\bar{U}\) is the mean horizontal wind speed (step 5). However, it is straightforward to adapt our methodology to 3D temporal wind fields. Finally, note that the methodology developed in this study easily deals with the case of multi-beam Lidars (as in Figure 1) by taking into account several additional parameters such as the number of LOS, the LOS order sequence, switching time …

4. Results and validation

4.1. Example of simulated time series

The figure below compares for three different levels of CNR (from high to low, close to the CNR threshold) the simulated Lidar radial wind speed (green) with the true local radial wind speed (blue) and the weighted approximation (red) given in (2).

![Figure 3: Example of simulated time series of radial wind speed (WS) for different levels of CNR](image-url)
This figure illustrates the benefits of our methodology over (2): while the weighted approximation is simply a smoothed version of the true local radial wind which is blind to the level of CNR, our approach yields wind speed measurements that are sensitive to the level of CNR as it is observed in practice. Moreover, for a low level of CNR, the developed methodology occasionally produces data with a CNR below the CNR threshold. Such data is an outlier that will be considered as not valid by our data filtering procedure.

4.2. Precision validation

An experimental setup has been developed to perform measurements in a frozen propagation medium, i.e. with scattering motionless particles, under a controlled level of CNR. Figure 4 plots for two different pulse durations the simulated and the experimental velocity precision (defined as the standard-deviation of the measured wind speed over a collection of samples) as a function of CNR. The excellent agreement between the simulation and the real experiment shows that our simulation tool is able to generate wind speed measurements with a realistic level of precision.

5. Conclusion

The Lidar simulator developed by LEOSPHERE to simulate the response of a Lidar to a dynamic wind-field that models the entire measurement chain and includes all sources of noise. It provides wind speed measurements that have been shown to be highly representative of real measurements both in terms of availability and precision.

6. References