Analytical Feasibility Study of Wind Lidar with Long-Duration Frequency-Modulated Pulse

Eiichi Yoshikawa(a), Tomoo Ushio(b), Hiroshi Yamasuge(b)

(a) Japan Aerospace Exploration Agency
6-13-1 Osawa, Mitaka, Tokyo, 181-0015, Japan
(b) Tokyo Metropolitan University
6-6 Asahigaoka, Hino, Tokyo, 191-0065, Japan

yoshikawa.eiichi@jaxa.jp

Abstract: A wind lidar using pulses with frequency modulation and long duration is proposed. The proposed wind lidar emits pulses with frequency modulation and long duration, receives its returned signals, and consequently records the returned signals which is converted to a microwave frequency. The proposed lidar a-priori generates multiple reference signals which are replicas of the transmitting signal with being shifted by presupposed Doppler frequencies, and parallelly implements convolutions between a returned signal and each of the reference signals. The convolution results correspond to range profiles at each of the presupposed Doppler shifts. That is, the multiple convolutions derive a range-velocity profile of received signal. While range and velocity resolution are in a trade-off relation in a traditional wind lidar, in the proposed wind lidar, they can be designated independently on each other.

Keywords: Coherent Laser Radar, Doppler, Frequency Modulation.

1. Introduction

Wind lidars have recently become utilized in various practical purposes since they have been reasonable to be purchased. The author has worked for aviation weather safety using a wind lidar, such as wake vortex detection [1][2], low-level turbulence advisory [3], and development of airborne wind lidar [4]. Through these researches, the author has heard many users making complaints against wind lidars about their slow scanning speed, short observation distance, poor accuracy of measurements, and coarse range resolution. Although traditional wind lidar needs to shorten its transmitting pulse in order to improve range resolution, shortening pulse duration enlarges Doppler velocity resolution. Since range resolution and velocity resolution are thus in a trade-off relation, lidar system design is non-flexible and it is only way for improving signal-to-noise ratio (SNR) to enhance peak power of laser pulses.

The authors proposed a wind lidar using pulses with frequency modulation and long duration, that can designate range resolution and velocity resolution independently [5]. Simply speaking, the pulse compression technique, that is frequently utilized in the radar engineering field for both point-targets’ and distributed-targets’ detections [6], [7], is applied with a modification as below. In principle, the radar’s pulse compression technique does not work in a case with a large Doppler frequency shift, and does not work on lidar. A returned signal with a large Doppler frequency shift does not have a correlation with a reference signal that is normally a replica of a transmitting signal. The proposed lidar generates multiple reference signals which are with presupposed Doppler frequency shifts, and convolutes a returned signal with each of the reference signals. The convolution results correspond to range profiles at each of the presupposed Doppler shifts. That is, the multiple convolutions derive a range-velocity profile of received signal. This paper describes an analytical feasibility study of the proposed wind lidar.

2. Hardware

Figure 1 shows an example of the proposed wind lidar. A laser light of continuous wave is mixed with microwave pulses with frequency modulation and long duration by an acousto-optic modulator, then modulated laser pulses are emitted to the air. After a returned light is down-converted to microwave by a heterodyne detector, the microwave signal is recorded by a analog-to-digital converter.
3. Software

Figure 2 shows a calculation flow of the proposed wind lidar. Multiple reference signals are generated in advance of observation by applying presupposed Doppler frequency shifts to a digital waveform of transmitting signal. Multiple convolutions of a received signal with each of the multiple reference signals are parallelly performed, and calculation results are rearranged to form a range-velocity profile.

4. Analytical Performance

See [5] about detailed derivation for the analytical performance. Because of the software of the proposed lidar, ambiguity function for ranging is equivalent to an autocorrelation function of the transmitting signal. For example, when the transmitting signal is with a linear frequency chirp, its autocorrelation can be approximated to a sinc function. Range resolution accomplished by a modulated signal is expressed as

\[ \Delta r \approx \frac{c}{2B}. \]  

(1)

where \( \Delta r \), \( c \), and \( B \) are range resolution, speed of light, and bandwidth of modulation, respectively. Meanwhile, ambiguity function for velocimetry is represented by cross-correlations of a single frequency wave (at a Doppler frequency shift due to target) to ones at presupposed frequency shifts. As a result, it is also a sinc function whose velocity resolution is as
\[ \Delta v \approx \frac{c}{2fT}. \]  

(2)

where \( \Delta v \), \( T \), and \( f \) are velocity resolution, pulse duration, and frequency of a carrier light, respectively. As obviously shown in Eqs. (1) and (2), range resolution is independent on velocity resolution in the proposed wind lidar. Since a wind lidar receives returned signals from aerosol particles, a signal intensity at a desired range-velocity is resulted from a summation of signals returned from aerosol particles existing in a range-velocity lattice which is defined by range and velocity resolution. A signal-to-noise ratio can be estimated as a ratio of the received signal intensity and noise (a convolution result of background noise and a reference signal),

\[ SNR \approx \frac{c^2}{8a_r^2} \frac{n|x|^2}{a_n^2B_T}. \]  

(2)

where \( a_r \) and \( a_n \) are amplitude of transmitting signal and receiving noise, respectively. \( |x| \) is mean of absolute square of aerosol particles’ scattering amplitude. Note that \( |x|^2 \) additionally contains a gain of telescope, attenuations due to roundtrip propagations, and so on. \( n \) is the number of aerosol particles in the range-velocity lattice defined by a range-velocity resolution.

5. Conclusion

This paper proposes a new wind lidar which emits a laser pulse with frequency modulation and long duration. In the proposed wind lidar, multiple reference signals supposing possible Doppler frequency shifts is generated a-priori, and multiple convolutions between a returned signal and each of the reference signals are simultaneously implemented. Since a convolution result corresponds to a range profile at a Doppler velocity, the set of convolution results is equivalent to a range-velocity profile of aerosol particles. Two-dimensional range-velocity ambiguity function of the proposed wind lidar is approximately represented by a (two-dimensional) sinc function whose range and velocity resolution are defined independently, while they are dependent in a traditional wind lidar.

In order to accomplish range resolution of 30 m, for example, the proposed wind lidar uses a long duration pulse with a bandwidth of 5 MHz. While a traditional wind lidar needs to equip a laser source with a narrow linewidth of a few hundreds of kHz and with pulse duration of 0.2 micro seconds, the proposed wind lidar alleviate those constraints to a linewidth of several MHz and pulse duration of several tens of micro seconds. That is, the proposed wind lidar can be designed simply with a semiconductor laser, and, if a high-power semiconductor laser is developed, it will solve the traditional wind lidars’ problem due to low power.


