Critical Evaluation of the Cross-Correlation Algorithm Using Synthetic Backscatter Images and Synthetic Wind Velocity Fields

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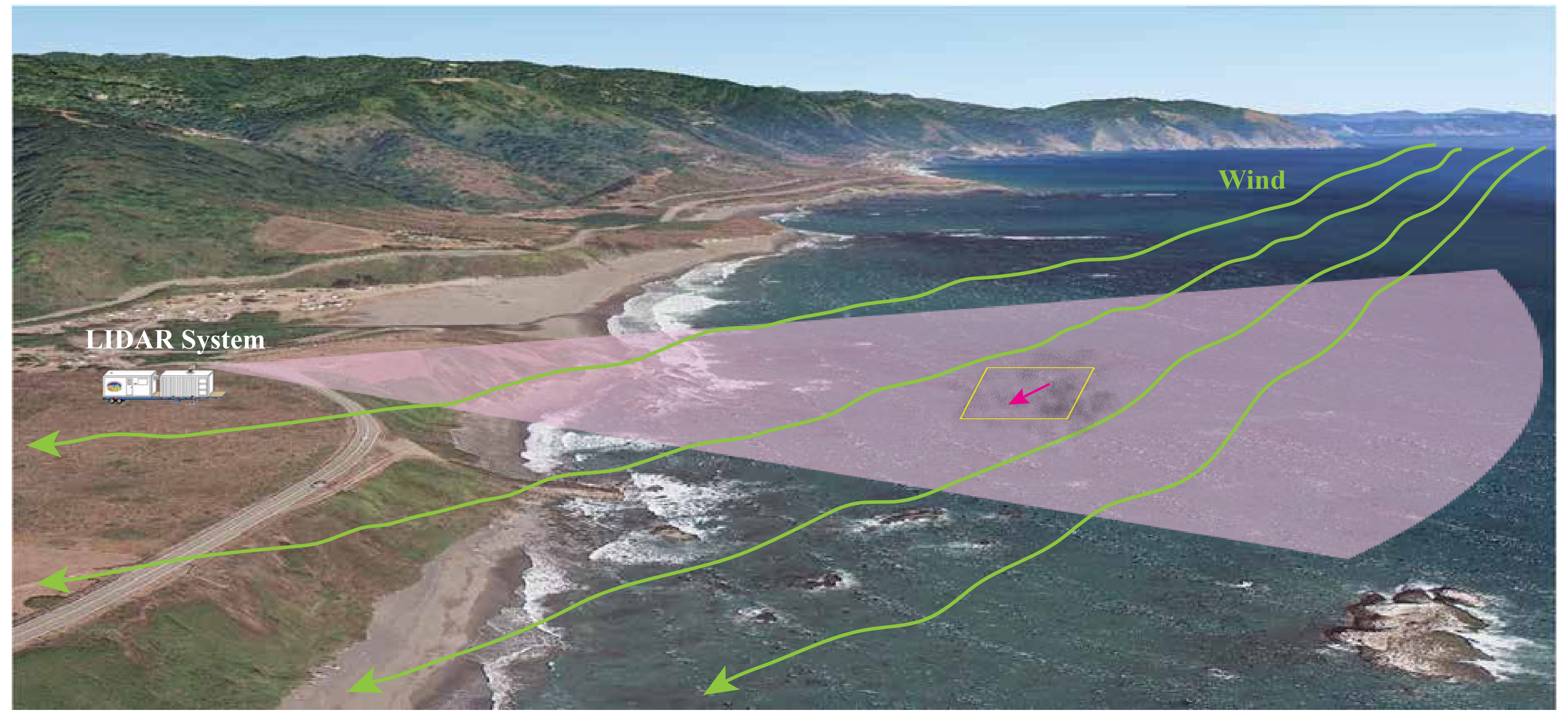
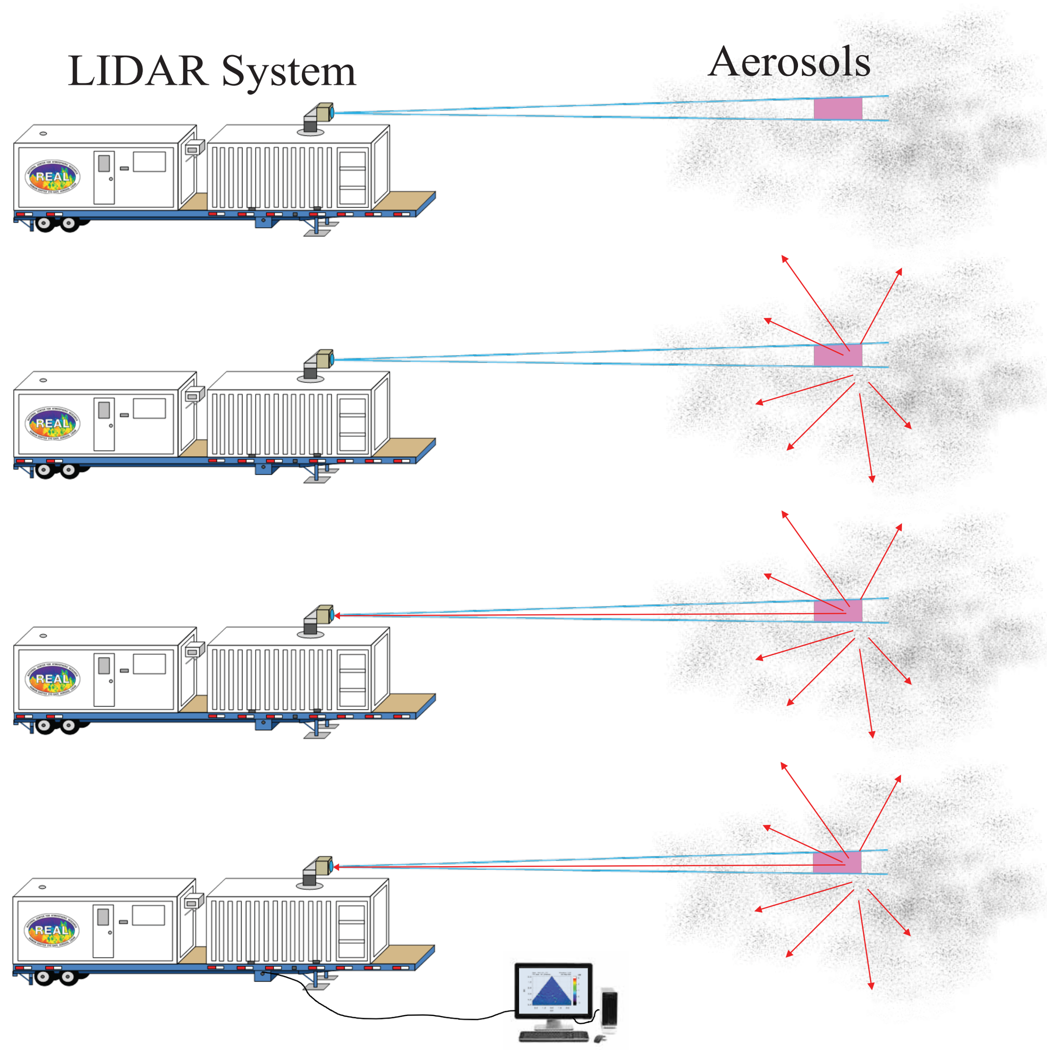
How to Measure the Wind?

Wind is a renewable energy resource, and the accurate measurement of the wind velocity is crucial to assess wind energy potential [1]. Wind speed can be measured by anemometers, but this measurement requires a stationary platform such as a tower. High wind velocity potentials exist offshore, but it is very difficult to errect towers from a floating platform. In this case, **LIDAR** (LIght Detection And Ranging), is attractive, since it may be able to measure offshore wind velocity remotely from the coast. This could be done by scanning the laser beam horizontally over the ocean (2-dimensional scan), and applying motion estimation algorithms (numerical procedures in the form of computer programs) to estimate the wind velocity field from displacement of aerosol features [2].



How LIDAR Works



(1) LIDAR system emits pulses of Infrared Radiation into the atmosphere.

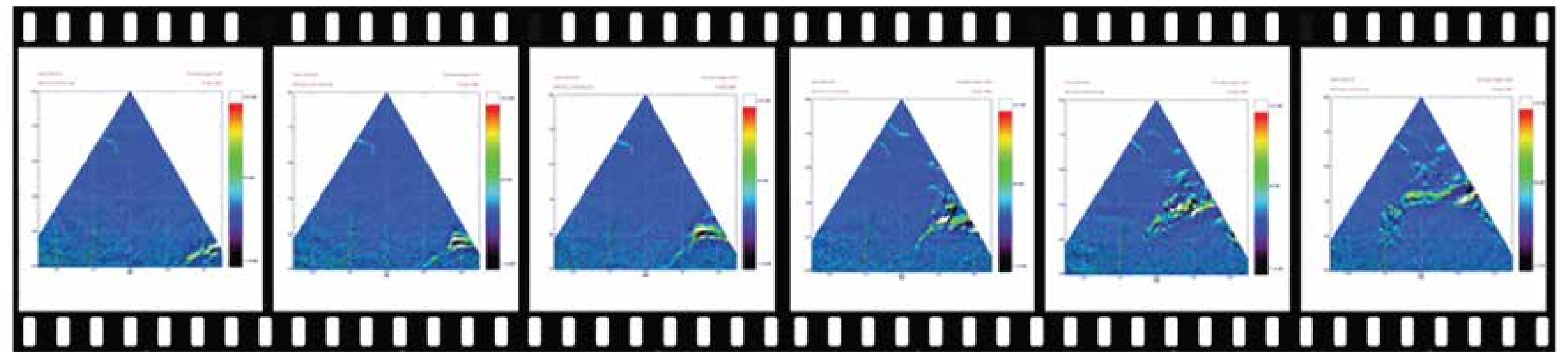
(2) Radiation is scattered in all directions by aerosols.

(3) Some of the radiation is backscattered into a detector. Data is collected as scans.

(4) Image of backscattered radiation is created. We typically scan the atmosphere every 10~20 seconds.

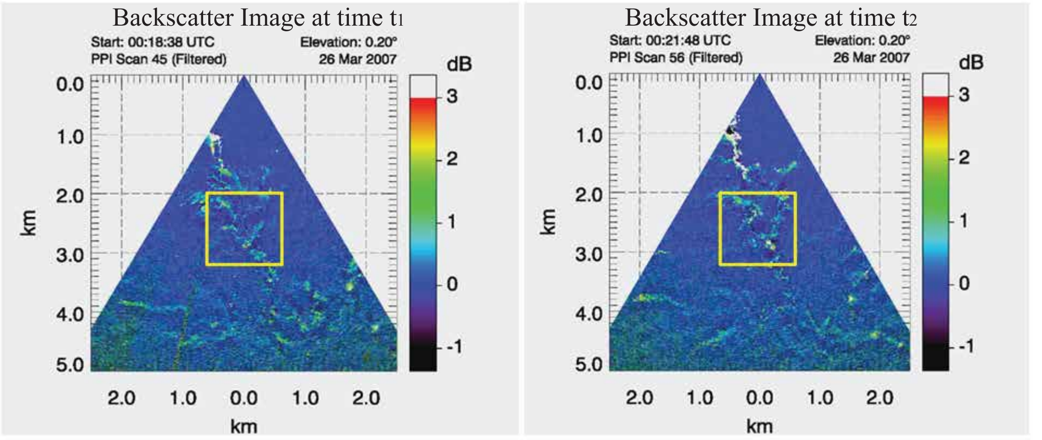
Wind Velocity Estimation

LIDAR can not see individual aerosol particles, but it is able to see aerosol features that is composed of large number of aerosol particles. LIDAR scans atmosphere horizontally every Δt = 10 ~ 20 s, and we have a sequence of images.



To estimate the wind velocity, we assume that aerosol features move with the wind. Then,

Velocity of Aerosol Features = Wind Velocity



If the displacement vector of aerosol featues (Δx, Δy), for two consecutive images, is obtained, we can find the wind velocity v.

$$\textbf{Velocity: } V = \left(\frac{\Delta x}{\Delta t}, \frac{\Delta y}{\Delta t}\right)$$

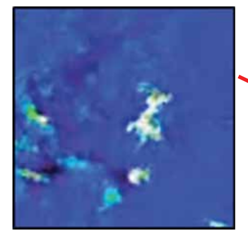
where $\Delta t = t_2 - t_1$ is the time interval between the consecutive scans.

However, when aerosol features move, shapes of features are changed. Then, we need algorithms (numerical procedures in the form of computer program) to estimate the displacement. One of the algorithms is the **cross-correlation algorithm**.

Cross-Correlation Algorithm

The cross-correlation is the measure of similarity of two waveforms. The displacement vector (Δx, Δy) is estimated by similarity of two images. Let $I_1(x, y)$ for the 2-dimensional backscatter intensity at time t_1, and $I_2(x, y)$ for that of time t_2. Then, the 2-dimensional cross-correlation function r_{xy} can be calculated as shown in Figure below. The displacement vector in the time interval $\Delta t = t_2 - t_1$ is estimated by the location of the peak of the cross-correlation function. Finally, from the displacement vector and known time interval, the wind velocity vector v is calculated by the equation v = ($\Delta x/\Delta t$,$\Delta y/\Delta t$).

$I_1(x, y)$ Backscatter Image at time t_1



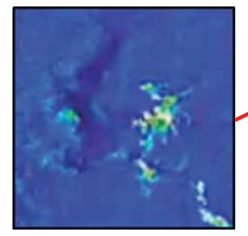
Fast Fourier Transform
$I_1(k_x, k_y)$

Cross-Correlation Function (CCF), $\mathbf{r_{xy}}$

$$r_{xy} = \frac{1}{S_1 S_2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I_1(k_x, k_y)\, I_2^*(k_x, k_y)\, e^{i 2\pi (x k_x + y k_y)}\, dk_x dk_y$$

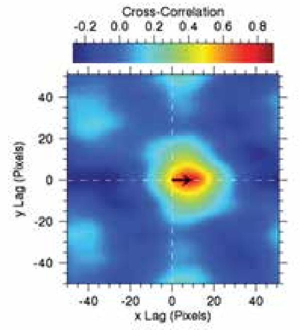
(Notes) S_1 and S_2 are the standard deviations of $I_1(x, y)$ and $I_2(x, y)$ respectively, and exponential term represents the inverse Fourier Transform.

$I_2(x, y)$ Backscatter Image at time t_2



Fast Fourier Transform
(Complex Conjugate)
$I_2^*(k_x, k_y)$

Plot the Cross-Correlation Function (CCF) as a function of lags
x_{lag} = -x, and y_{lag} = -y



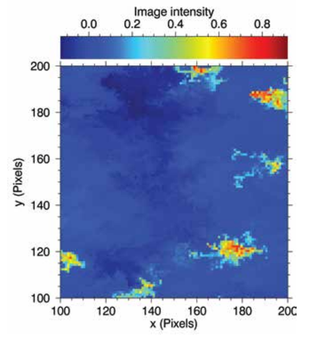
Location of the peak of CCF represents the displacement of aerosol features in the time interval $\Delta t = t_2 - t_1$

Statements of Problem

The cross-correlation algorithm has been applied to real aerosol LIDAR data for wind measurement previously [3], [4]. However, comprehensive evaluations of the cross-correlation algorithm under controlled conditions are lacking. Thus, we need to test the performance of the cross-correlation algorithm by generating and using synthetic aerosol backscatter images and velocity fields.

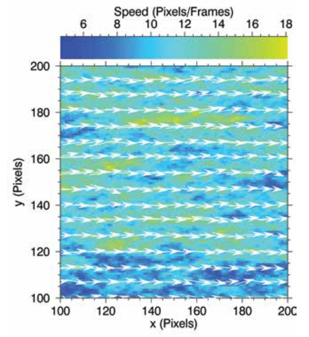
Methodology

(1)



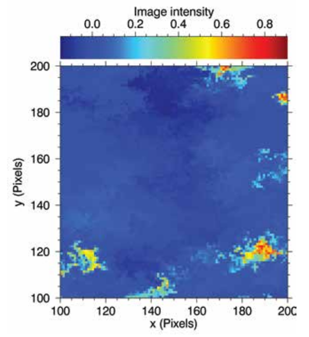
Create a synthetic backscatter image (at t_1).

(2)



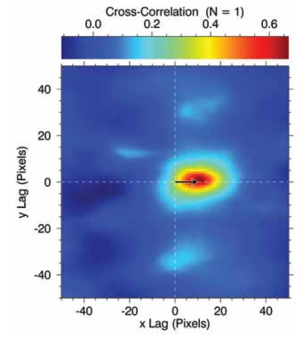
Create a synthetic wind velocity field.

(3)



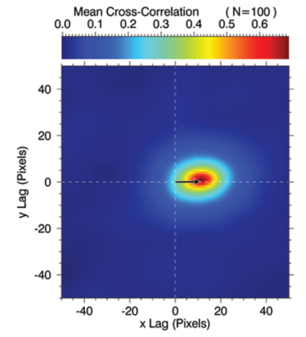
Apply the velocity field to get new image (at t_2).

(4)



Apply the cross-correlation algorithm to get the displacement vector.

(5)



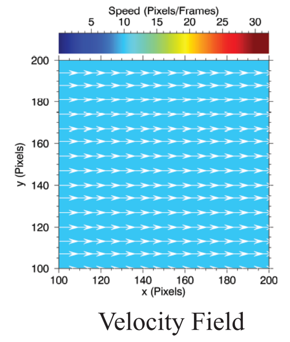
Test is repeated (N = 100) using different synthetic backscatter images.

The wind velocity fields are created by the sum of analytical function and turbulent fluctuation fields described by Mann [5], [6]. To make a better estimation of the displacement vector, we apply the multi-pass approach (displaced the second box).

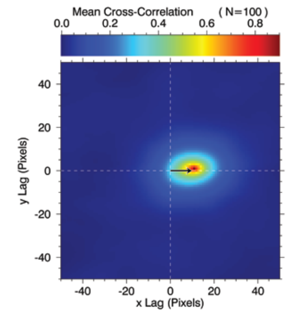
Finally, compare the prescribed velocity field (2) and the cross-correlation algorithm results (5).

Results

Uniform Flow

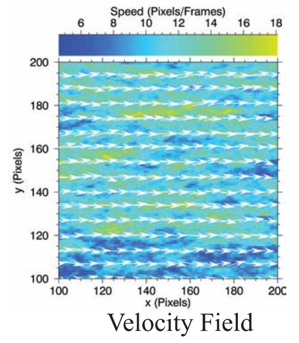


Velocity Field
Mean (10.00, 0.000) Pixels/Frames
SD (0.000, 0.000) Pixels/Frames

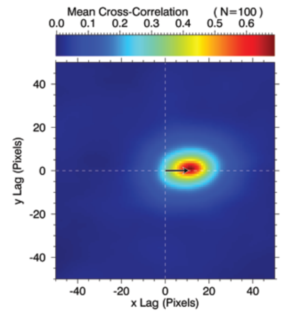


CCF Resultant Displacement
Mean (9.984, 0.00005) Pixels
SD (0.0035, 0.00044) Pixels

Uniform Flow with Turbulent Fluctuations

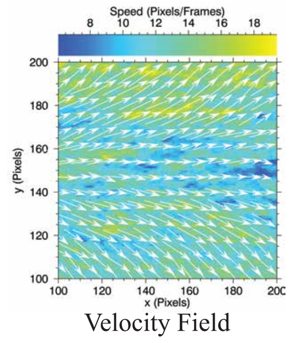


Velocity Field
Mean (11.08, 0.104) Pixels/Frames
SD (1.971, 1.232) Pixels/Frames

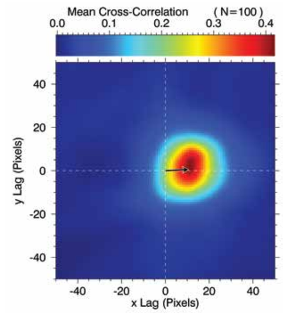


CCF Resultant Displacement
Mean (10.75, 0.07016) Pixels
SD (0.7781, 0.2885 Pixels

Divergent Flow with Turbulent Fluctuations

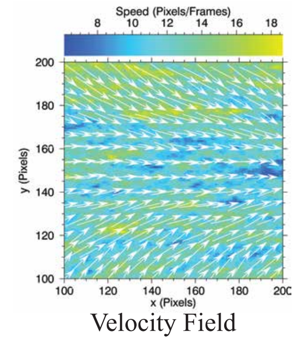


Velocity Field
Mean (11.08, 0.103) Pixels/Frames
SD (1.971, 6.183) Pixels/Frames

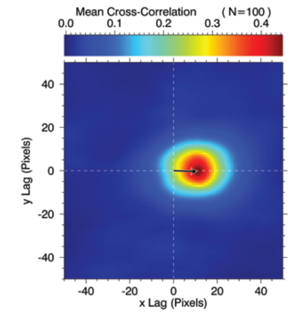


CCF Resultant Displacement
Mean (10.56, 0.5530) Pixels
SD (1.722, 5.349) Pixels

Convergent Flow with Turbulent Fluctuations

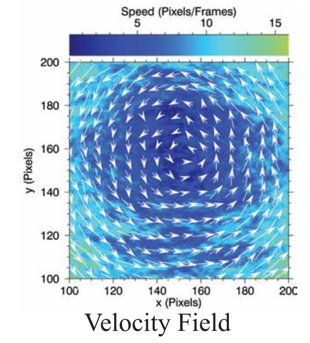


Velocity Field
Mean (11.08, 0.103) Pixels/Frames
SD (1.971, 5.728) Pixels/Frames

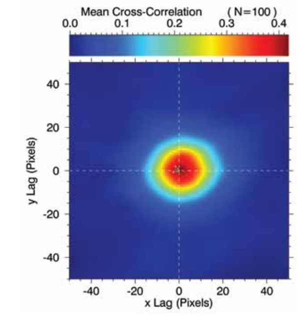


CCF Resultant Displacement
Mean (10.71, -0.3952) Pixels
SD (1.545, 3.539) Pixels

Circular Flow with Turbulent Fluctuations

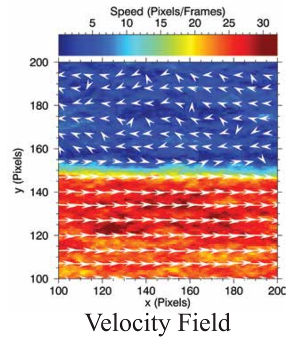


Velocity Field
Mean (1.083, 0.104) Pixels/Frames
SD (5.462, 5.922) Pixels/Frames

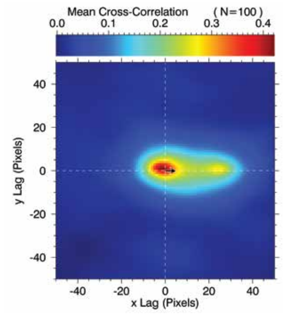


CCF Resultant Displacement
Mean (0.3451, -0.1178) Pixels
SD (3.379, 4.338) Pixels

Shear Flow with Turbulent Fluctuations



Velocity Field
Mean (11.23, 0.104) Pixels/Frames
SD (13.87, 1.232) Pixels/Frames



CCF Resultant Displacement
Mean (4.945, -0.1145) Pixels
SD (14.16, 0.978) Pixels

Conclusion

The results show that the cross-correlation algorithm provides reliable displacement vectors if the flow is uniform. However, because the cross-correlation algorithm only results in one displacement vector for the entire block, the performance of the cross-correlation algorithm decreases as non-uniformity of the wind velocity fields increases.

References

[1] Brower, M. C., (2012), *Wind Resource Assessment: A Practical Guide to Developing a Wind Project,* John Wiley & Sons Ltd.
[2] Eloranta, E. W., J. M. King and J. A. Weinman, 1975: The determination of wind speeds in the boundary layer monostatic lidar. J.Appl. *Meteor.,* **14**, 1485-1489.
[3] Schols, J. L. and E. W. Eloranta, 1992: The calculation of area-averaged vertical profiles of the horizontal wind velocity from volume-imaging lidar data. J. Geophys. Res., **97**, 18 395–18 407.
[4] Mayor, S. D., J. P. Lowe, and C. F. Mauzey, 2012: Two-component horizontal aerosol motion vectors in the atmospheric surface layer from a cross-correlation algorithm applied to elastic backscatter lidar data, *J. Atmos. Ocean. Technol.,* **29**, 1585-1602.
[5] Mann Jacob, 1994: The spatial structure of neutral atmospheric surface-layer turbulence, *J. Fluid Mech.,* **273**, 141-168.
[6] Mann Jacob, 1998: Wind field simulation, *Prob.Engng. Mech.,* **13**, No. 4, 269-282.

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