Planetary boundary layer height detection from LIDAR measurements

C. TALIANU*, D. NICOLAE, J. CIUCIU, M. CIOBANU, V. BABIN
National Institute for Optoelectronics, Bucharest-Magurele, P. O. Box MG. 5, Romania

Lidar systems are powerful laser equipments which are able to estimate the Planetary Boundary Layer parameters from remote sensing measurements. Using lidar technique, the interface between PBL and free troposphere can be evidenced by the change in backscattered radiation level between the two layers. New scientific approach for the automatic detection of targets of this type from lidar signals uses wavelet covariant transform based on various functions. There are presented the results obtained in Romania by direct LIDAR measurements in the area of Bucharest and the original software developed by the Environmental group in INOE for lidar data processing and PBL height identification.

(Received October 14, 2005; accepted January 26, 2006)

Keywords: Planetary Boundary Layer, LIDAR, Wavelet covariant transform

1. Introduction

Remote sensing techniques such as lidar and sodar are invaluable for the measurement of Planetary Boundary Layer (PBL) properties that are difficult, or impossible, to measure directly at sufficient spatial or temporal resolution, over long periods, or with large area coverage for example boundary layer depth and entrainment zone structure. Lidar systems, in particular, have been widely used to examine the structure and variability of the BL top and to derive the entrainment zone depth [1-3]. The volume of data generated by Lidar systems with substantial and automated processing is essential if full use is to be made of all the information available. Developing robust algorithms for extracting the information of interest - typically the altitude of the BL top - can be challenging.

The lidar system used for measurements, is an elastic backscattering lidar based on a Nd:YAG laser, working at two wavelengths (1064 and 532 nm). It can detect in real time aerosols density profiles up to 10 km high with a spatial resolution of 6 m. Along with its remote sensing capabilities, the most important characteristic of this system is the instantaneous response, in relation with the propagation speed of light. In order to realize an eloquent study hundred of measurement in one session are necessary, so that for a real time response, the processing algorithm must be adjusted to handle high speed acquisitions. Beyond specific algorithms used to retrieve the backscattering coefficient versus distance from lidar data, for PBL studies new algorithms are needed. This is due to the fact that lidar signals are strongly decreasing with distance, and the presence of a low density target (as PBL) is impossible to be evidenced without mathematical processing. For example, the scattering of light by various shape particles must be known. We developed an analytical averaging method in scattering of light by non-spherical aerosols [4].

Several recent studies have utilized a wavelet method to provide automated detection of the boundary layer top from Lidar backscatter profiles by locating the maximum in the covariance profiles [2,5,6]. We developed an algorithm that utilizes information from the wavelet covariance transform at multiple dilations in order to identify the upper and lower limits of the transition zone. The method has been tested using real lidar data collected by LiSA system.

2. Experimental

2.1. Theory

The wavelet covariance transform was defined by [7] as a means of detecting step changes in a signal. It is based upon a compound step function.

The algorithm consist in the wavelet covariance transform between lidar signal profile and Haar function (step function) defined as:

$$h\left(\frac{x-b}{a}\right)=\begin{cases}+1 \rightarrow b-a/2 \le x \le b \\ -1 \rightarrow b \le x \le b+a/2 \\ 0 \rightarrow elsewhere\end{cases} \qquad (1)$$

where *h* is the Haar function, *a* is the spatial extent, or *dilation*, of the function, *b* is the location at which the Haar function is centered—the *translation* of the function.

The covariance transform of the Haar function, *W*,[5] is defined as:

$$W(a,b) = \frac{1}{a}\int_{x_0}^{x_{\max}} P(x)\cdot h\left(\frac{x-b}{a}\right)dx \qquad (2)$$

where P (x) is the lidar signal, x_0 and x_{max} are the lower and upper limits of the profile.

A local maximum in W (a, b) identifies a step in P (x) with a coherent scale of a, located at $x = b$. The problem to identifying features of interest is the selection of an appropriate dilation a. [8]

For the simple case where the mean backscatter is near constant both within and above the PBL, the choice of a is not crucial if it is large enough to distinguish the transition zone from small-scale variability in the signal. Under less ideal conditions the choice of dilation becomes important. A mean gradient in backscatter encompassing the entire wavelet results in a constant, nonzero value for W (a, b); if the gradient is localized and coincides with only part of the wavelet, then it will contribute to W (a, b) in proportion to the extent of the overlap. We consider the effects of vertical gradients, it is worth nothing some fundamental constraints on the useful values of the dilation and translation. Any real lidar profile is finite in length, useful values of a and b are thus limited to combinations for which the entire nonzero portion of the Haar function lies within the altitude range of the backscatter profile, outside of these limits part of the integral is undefined. The closest b may approach to the ends of the profile is thus a/2. The absolute maximum value of a is equal to the length of the measured profile. However, this extreme is of no practical use since b is then constrained to a single value of a/2. In practice the upper limit to the useful range of dilations is about twice the distance from the transition zone to the nearest end of the measured profile, at greater dilations the wavelet cannot be translated to a position at which its midpoint, b, coincides with the top of the PBL.

The regions of the vertical gradients in the lidar backscattering are: PBL, over PBL, and the inversion across [9]. Let's consider for the theoretical study an idealized backscatter profile with the transition zone base at $H1$ and its top at $H2$, and the location of the maximum in W (a, b) as a increases. For $a < (H_2 - H_1)$ there are multiple values of b for which $W(a, b)$ has the same (maximum) value; this is the region where the wavelet is entirely encompassed by the transition zone. As a approaches (H_2 - H_1), the range of values narrows, converging on the midpoint of the transition zone, which remains a unique solution for all larger values of a up to ($H_2 + H_1$). At this point the translation of the Haar function is limited by the bottom of the profile. If a is further increased, the maximum in W (a, b) occurs when b is as low as possible, and $b(W_{max})=a/2$. For this case - an idealization of a well mixed BL with constant backscatter above the transition zone - the choice of dilation is not critical provided it lies within the limits $(H_2 - H_1) \le a \le (H_2 + H_1)$. Let's now consider the more general case when there are gradients in backscatter above and below the transition zone. An analytical solution can be derived easily for idealized profile, since the product of the backscatter profile and the Haar function amounts to the summation of the areas between the profile and an arbitrary zero line, here set at the base of the profile for convenience. The translation that gives a maximum in W (a, b) for any given dilation can then be found by differentiating the expression for W (a, b) with respect to b and solving for zero (for our idealized profile there is no minimum in the W (a, b) profile, only a single maximum) [9].

2.2. Program development

A dedicated LabVIEW program for PBL top detection was developed in INOE, based on the algorithm early described. In order to obtain the convolution altitude profile, the algorithm must be executed for all values of b in x_o-x_{max} interval. If the identification of a specific target is wanted (at specific height, of specific density), the algorithm must be applied for a proper interval, or the input parameter a must be selected so that targets with other characteristics can be unlooked. For example, in order to evidence clouds height it is necessary to run the algorithm up to an altitude of 2000 m, because this the maximum altitude possible for a cloud presence. On the other hand, PBL top cannot exceed 1000 m, abut its density is much lower then a cloud's, so is better to run the algorithm up to 1000 m and to select an higher value for a. For each data profile, the program returns the altitude corresponding to the maximum of convolution.

We tested the program on real lidar data collected by LiSA system.

3. Results

LiSA system is placed in a dedicated laboratory, at a certain height, in order to permit horizontal sounding, towards the boundary of Bucharest city. Measurements were done in various meteorological conditions at different times of the day, in order to reveal system's limitation and to establish the capabilities of the processing program to extract the presence and location of the targets (in our case PBL) from lidar data [10, 11]. In Fig. 1 and 2 some results of our experiments are presented.

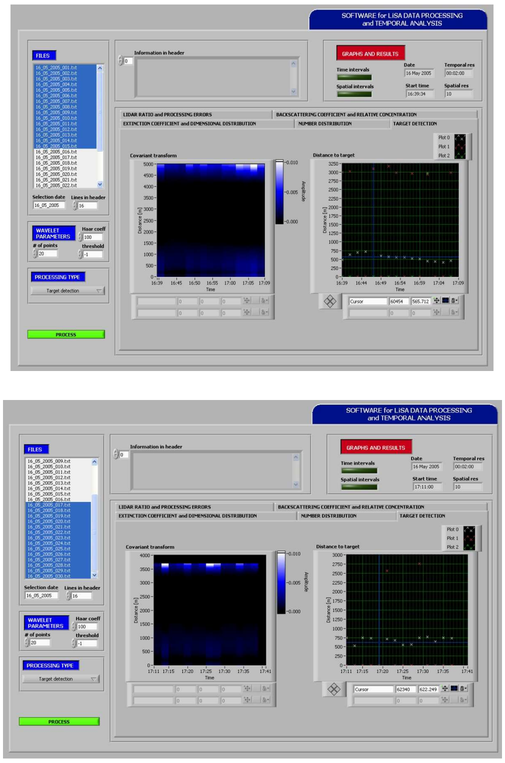

Fig. 1. The map of wavelet covariance transform and PBL for cloudy (left) and clear sky (right) (15.05.2005, Magurele, LiSA).

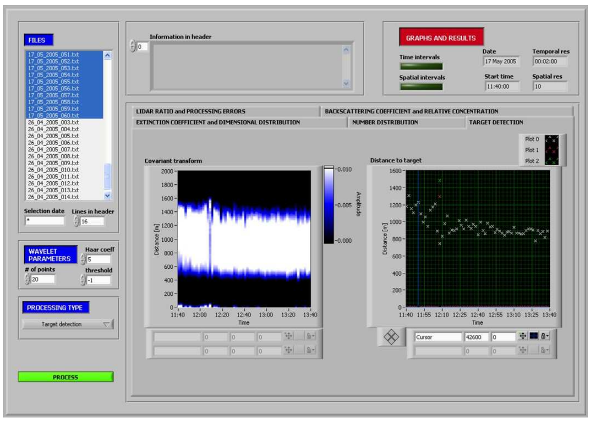

Fig. 2. The map of wavelet covariance transform and PBL for poor visibility (15.05.2005, Magurele, LiSA).

4. Discussion

From these images one can conclude that, with a proper choice of *a* and selection interval, the program can derive clouds altitude and PBL height. These are visible on the graphs by the 2 dot-lines in different colors in the left image. In this case, some low density clouds are present in the sky, making possible the detection of PBL top even if the entire altitude interval was used as input. In the covariant transform graph, only one maximum can be seen because the other one (corresponding to PBL top) is much smaller then the first one (corresponding to the cloud). Even so, the program returns both targets altitudes. In the second example (right image), the sky was really clean, so no cloud was detected, but the PBL top.

As one can see in Fig. 2, in case of poor visibility (middle of a summer day), due to high aerosols loading and intense light background, it was impossible to get useful signal beyond 2 km height. As consequence, the program was able to detect only the PBL top and no high altitude clouds were evidenced.

5. Conclusions

In good visibility conditions, the program can identify distant targets, like high altitude clouds. This is possible during night time, when traffic and industrial contribution on aerosols atmospheric loading is small, or after rain, when the atmosphere is clean, due to wet deposition of aerosols.

In poor visibility conditions, during day time or before rain, when the relative humidity is increased, the signal is noisy, reducing the detection distance. In this case the program can only provide PBL's height and eventually low altitude clouds.

The program processes lidar data which will be used to determine PBL top and pollutants loadings but also to study their temporal evolution. The user has the possibility to simultaneously process more data sets, when the comparative study is wanted. Also, by varying the Haar coefficient a, one can evidence targets of different densities.

The possibility to select only specific altitude intervals as input for the wavelet algorithm increases the processing speed and the detection accuracy for a certain target type. In thi sense, processing the entire data set can "hide" low density targets if a high density target is also present. Even so, the covariant transform graph shows 2 maximums, one less pronounced then the other, which permits to the user to distinct between the 2 targets. It must not be neglected the importance of the graphical interface of the program, which consult the user in following the right steps to obtain a good result, but leaves the liberty to vary the input parameters, scales and graphs colors.

References

[1] I. M. Brooks, D. P. Rogers, Bound.-Layer Meteor. **95,** 189 (2000).

[2] S. A. Cohn, W. M. Angevine, J. Appl. Meteor. **39,** 1233 (2000).

[3] P. P. Sullivan, J. Atmos. Oceanic Technol. **17,** 1455 (2000).

[4] D. N. Nicolae, C. Talianu, M. Cobanu, C. Radu, V. Babin, C. P. Cristescu, J. Optoelectron. Adv. Mater. **6**(3), 831 (2004).

[5] K. J. Davis, D. H. Lenschow, S. P. Oncley, C. Kiemle, G. Ehret, A. Giez, J. Geophys. Res. **102,**

29 219 (1997).
[6] E. Dupont, J. Pelon, C. Flamant, Bound-Layer Meteor. **69,** 1 (1994).
[7] C. Flamant, J. Pelon, P. H. Flamant, P. Durand, Bound-Layer Meteor. **83,** 247 (1997).
[8] S. Soderberg, M. Tjernstrom, J. Geophys. Res. **106** (D16), 17 811 (2001).
[9] Ian M. Brooks, Journal of Atmospheric and Oceanic Technology **20**, 1092 (2003).
[10] J. R. Garratt, 1992: The Atmospheric Boundary Layer. Cambridge University Press, 316 pp.
[11] Doina Nicolae, Program for Lidar data processing, 2nd National Conference on Virtual Instrumentation, June 25, 2005, "Politehnica" University, Bucharest.
[12] Camelia Talianu, Doina Nicoleta Nicolae, Mircea Ciobanu, Vasile Babin, Constantin P. Cristescu, Automatic Target Detection Using Statistical Validation For Long-Term Surveillance Lidar, Esa Special Publication Sp-561, 2004, p. 255-258.

* Corresponding author: camelia@inoe.inoe.ro