Lidar measurements and wavelet covariance transform method to estimate the atmospheric boundary layer heights in Medellín, Colombia

Medidas lidar y método de transformada covariante de ondas para estimar las alturas de la capa límite atmosférica en Medellín, Colombia

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ABSTRACT:

The Atmospheric Boundary Layer (ABL) includes the portion of the atmosphere which is directly influenced by the presence of the Earth's surface, and usually has much higher aerosol concentration than free troposphere above. Lidar system measures the intensity of backscattered light mainly from aerosol particles as a function of distance. Thus, the significant change in the backscatter across the top of the BL provides a means of determining ABL heights. Whereas an urban area situated in a complex mountain valley of Colombian tropical Andean region, we present the first results of estimating the height of the daytime ABL for Medellín city (Lat: 6°15' 38.37", Long: -75° 34' 40.46", Alt: 1483 m a.s.l.), using the wavelet covariant transform method in processing the elastic backscatter signal collected by a lidar built in Medellín city.

Key words: Backscatter Lidar Signal, Atmospheric Boundary Layer Height, Wavelet Covariant Transform Method.

RESUMEN:

La capa límite atmosférica (CLA) comprende la porción de atmósfera que es influenciada directamente por la presencia de la superficie terrestre, y usualmente contiene una mayor concentración de partículas de aerosol que la troposfera libre. Un sistema lidar mide la intensidad de luz retrodispersada principalmente por partículas de aerosol como una función de la distancia. Así, el cambio significativo de la concentración de aerosol en la parte superior de la CL proporciona un medio para determinar las alturas de la CLA. Considerando un área urbana situada en un complejo valle de montaña de la zona andina tropical colombiana, presentamos los primeros resultados del estimativo de la altura de la CLA diurna para la ciudad de Medellín (Lat: 6°15' 38.37", Long: -75° 34' 40.46", Alt: 1483 m sobre el nivel del mar), usando el método de transformada covariante de ondas en el procesamiento de las señales de retrodispersión elástica colectadas por un lidar construido en la ciudad de Medellín.

Palabras clave: Señal de Retrodispersión Lidar, Altura de la Capa Límite Atmosférica, Método de la Transformada Covariante de Ondas.

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1. Introduction

The atmospheric boundary layer (ABL) is directly influenced by the Earth's surface and responds to surface forcing with timescale of an hour or less [1]. We will consider the ABL as the stratum of air in which the atmospheric turbulence caused by thermal or mechanical forcing produces an intensification of the chaotic movements of the air, encouraging the phenomenon of diffusion and transport of energy and matter typically up to a level defined by the presence of thermal discontinuity, from which the behavior of the atmosphere is not subject to such turbulent fluxes [2].

Thermal surface forcing phenomena produces convective motions in the ABL and therefore should be classified as stable, unstable and neutral layer. A stable boundary layer occurs typically at night time when no energy incoming from the sun causes the temperature inversions in the vicinity of the surface. An unstable boundary layer begins with the sunrise; the ABL has an intense agitation or vertical mixing resulting in an increase of the thickness of the air volume affected by surface warming reaching its maximum value after midday. Neutral conditions in the atmosphere are less frequent, they are usually associated with high wind and

cloudy situations where the effect of wind transport and poor surface warming result in atmospheres of low vertical mixing. With sunset, the termination of energy contribution from the sun causes the collapse of the mixing layer with a rapid decrease in its thickness, giving rise to a stratification at or close to neutrality, forming a residual boundary layer in which has remain a turbulent residual activity of the mixed layer [2].

Our case study is Medellín city (Lat: 6°15' 38.37", Long: -75° 34' 40.46", Alt: 1483 m a.s.l.). Which is situated in a complex mountain valley of Colombian tropical Andean region, surrounded by mountains (rise up to 3000 m a.s.l.) and lush vegetation, see Fig.1, with about 3.5 million inhabitants, typical temperature of 20 °C, relative humidity of 70%, and rainfall events in almost all the year [3,4]. At daytime the thermal forcing above Medellín is influenced mainly by the exchange of sensible heat and water vapor between the surface and the ABL.

ABL top height is a crucial parameter in air pollution models because it determines the vertical space and consequently the volume for pollutants mixing, which is a key parameter for assessment of concentrations. Commonly used methods for estimate the ABL height include the Richardson number method and parcel method

based on wind and temperature profile data [5,6]. Lidar (light detection and ranging) systems provide continuous measurement of numerous atmospheric quantities, including the vertical profile of atmospheric aerosol from which the ABL height can be derived. However, in our study region are scarce measuring instruments and atmospheric models. In this regard, a Lidar station built in the urban area of Medellín is being used to study the internal structure and behavior of the ABL height.

Lidar systems measure the intensity of backscattered light as a function of distance from the instrument. The primary contribution to the backscatter signal is from aerosol particles suspended in the atmosphere. The ABL usually has a much higher aerosol concentration than the free troposphere above and thus provides a stronger backscatter across the top of the boundary layer favors a convenient means of determining the local boundary layer height. Several recent studies [5-8] utilized a wavelet transform technique to provide a scale-dependent approach to determine the ABL height and also retaining the original lidar backscatter information. We report here the first results of estimating the height of the daytime ABL for Medellín city. Wavelet technique is applied and

included in an automatic algorithm to analyze the backscatter data obtained from 532 nm wavelength (2^{nd} harmonic Nd:YAG) elastic lidar measurements. The key of the wavelet analysis was the selection of an appropriate dilation parameter (vertical scale).

2. Lidar system

In this work the backscatter measurements from lidar system built at Medellín city are used. Our lidar is based in a pulsed Nd:YAG laser operating simultaneously at three wavelengths: 1064 nm, 532 nm and 355 nm (results at 532 nm will be reported only). Both transmitter and receiver systems use optical elements with a high spectral efficiency in a monostatic coaxial configuration. The Newtonian telescope has 0.2 m of diameter and 1.2 m of effective focal length. Photo detectors with high quantum efficiency, gain and both spectral and temporal response turn the backscatter light into an electrical signal recorded in analog mode, with a vertical resolution of 3.75 m [9]. A system's sketch is showed in Fig. 2. The system general characteristics are referred in Table I.

Fig. 1. Medellín location in an urban zone on the Colombian Andean region.

Fig. 2. Lidar system's sketch.

 TABLE 1
 General characteristics of lidar system.

Laser		Receiver		Specifications	
Active medium	Nd:YAG	Telescope	Newtonian	Configuration	Coaxial vertical
Energy	0.4 J/1064 nm 0.2 J/532 nm 0.1 J/355 nm	Focal length	1.2 m	Min. power detected	< 5 nW
Divergency	0.5 mrad	Diameter	0.2 m	Acquisition	20 MS/s @ 16 bit
Pulse length	6 ns	Detectors	PMT	Spatial resolution	3.75 m
Pulse repetition frequency	10 Hz	Response	$6 \times 10^1 - 3 \times 10^6$ V/W		

3. Method and algorithm

In a tropospheric elastic lidar the intensity of backscatter light abruptly decrease at top of ABL. It is based on the assumption that aerosol is much more abundant within the ABL than in the free troposphere. So the change in the gradient of the signal lidar recorded is used as indicator of the ABL height.

For an elastic lidar system operating at a single wavelength, the raw backscatter signal equation can be expressed as:

$$P(R) = C \frac{\xi(R)}{R^2} \beta(R) e^{-2 \int_0^R \kappa(R) dR} + P_{BG}, \quad (1)$$

where C is a characteristic constant of the system; $\xi(R)$ is the geometrical form factor interpreted as a probability (based on geometrical considerations) that radiation from a target plane at range R reaches the detector sensitive area; $\beta(R)$ represents the volumetric backscatter coefficient at wavelength λ and range R ; $\kappa(R)$ is the volumetric extinction coefficient in an inhomogeneous atmosphere and P_{BG} is the background signal from the sunlight and others sources like electronics parts of lidar system [10,11].

In order to determine the ABL height, it is necessary to process the raw lidar data, from Eq. (1) into background noise correction, range

correction, and energy normalization, which is known as normalized range-corrected lidar signal:

$$X(R) = \frac{[P(R) - P_{BG}]R^2}{E}, \quad (2)$$

where E is the output laser energy. To improve the signal-to-noise ratio, the $X(R)$ is averaged into signals with intervals of 50 seconds. In Fig. 3 is shown the normalized $X(R)$ obtained from our lidar system.

The abruptly decrease in $X(R)$ function (shown in Fig. 3) could be associated to ABL height [6,7], and can be automatically obtained by applying the wavelet covariance transform (WCT) to lidar data. This method makes a convolution between $X(R)$ function and an h function in an interval of interest [6-8]. The WCT is expressed as:

$$WCT(a, b) = A \int_{R_i}^{R_f} X(R) h\left(\frac{R-b}{a}\right) dR, \quad (3)$$

where R_i and R_f are lowest and highest range limits of the backscatter lidar signal; A is a normalization constant; a is the dilation parameter related to the spatial extent of h and b is the translation or location at which the h function is centered.

The $WCT(a, b)$ expressed in Eq. (3) is a measure of the similarity of the normalized range-corrected lidar backscatter signal $X(R)$, and the h function, which is commonly taken as a Haar or derivative Gaussian function, like the next Eqs. (4) and (5) express respectively:

Fig. 3. Normalized range-corrected lidar signal.

$$h\left(\frac{R-b}{a}\right) = \begin{cases} +1 & b - \frac{a}{2} \leq R \leq b, \\ -1 & b \leq R \leq b + \frac{a}{2}, \\ 0 & \text{otherwise,} \end{cases} \quad (4)$$

$$h\left(\frac{R-b}{a}\right) = -\frac{c}{a^2} (R-b) c e^{-\frac{(R-b)^2}{2a^2}}. \quad (5)$$

In Eq. (5) c is a normalization constant. Figure 4 shows the h functions as describe both Eq. (4) and Eq. (5).

The covariance transform $WCT(a, b)$, in the case of a clear lidar profile as in Fig. 3 with high backscatter values in the ABL and significantly lower backscatter values in the free troposphere, takes a clear local maximum at the height (b value) of the ABL top [6], see Fig. 5.

The selection of an appropriate value of the dilation a is the main challenge for a successful retrieval of the ABL height with the wavelet covariance transform method. For rather small values of a , signal noise dominates the vertical

Fig. 4. (a) Haar function profile. (b) Derivative Gaussian function profile.

Fig. 5. (a) Normalized range-corrected lidar signal; (b) Haar wavelet (solid line), Gaussian wavelet (dash line); (c) WCT profile obtained from Haar (solid line) and Gaussian wavelet (dash line).

profile of WCT, see Fig. 6. On the other hand, a too large dilation may not permit us to resolve the ABL top when further aerosol layers are present in the lower free troposphere. The optimum value for a is equal to the width of the abruptly decrease of intensity in $X(R)$, which is usually not known [7]. The dilation a is expressed as:

$$a = n\Delta R, \quad n = 2, 4, 6, 8, \dots \quad (6)$$

where ΔR corresponds to the lidar system vertical resolution. The position of the translation b has to be chosen in between two discrete data points to assure the symmetry in Eq. (3).

In this way our algorithm includes seven successive steps carried out on individual lidar profiles:

- Noise detection, to identify where the lidar

signal becomes too weak (signal-to-noise ratio).

- Obtain $X(R)$ lidar profiles from raw lidar data set.
- Take the first order derivative of each $X(R)$ profile, to determine the interval $[R_i, R_f]$ and identify an R value within of the $[R_i, R_f]$ interval.
- Evaluate the φ_m function:

$$\varphi_m = |X(R + m\Delta R) - X(R - m\Delta R)|, \quad (7)$$

where ΔR is lidar vertical system resolution and $m = 1, 2, 3, \dots$

So, the dilation parameter a in each $X(R)$ profile will be obtained for the m value from which both φ_m and φ_{m+1} values do not significantly differ to each other. Then:

$$a = (R + m\Delta R) - (R - m\Delta R) = 2m\Delta R. \quad (8)$$

- Evaluate the $WCT(a, b)$ functions for each $X(R)$ profile.
- Identify automatically the height corresponding to each local peaks of the $WCT(a, b)$ functions.
- Generate an ABL behavior plot with all this heights.

4. Results

Backscatter lidar measurements were based on the protocol showed in Table II.

We report the first results of the ABL height over Medellín. Figures 7 (left) and 8 (left) show a normalized range corrected lidar profile from observations made with our lidar at 532 nm in the morning on 26 March and 13 June, 2013,

Fig. 6. (a) Normalized range-corrected lidar signal; (b) WCT profile obtained for two different dilations values: $a=22.5$ m (solid line) curve; and $a=75$ m (dash line).

TABLE 2
Lidar measurements protocol

Wavelength λ [nm]	Mode	Prom/ Profiles	Spatial Resolution [m]	Temporal Resolution [s]	PMT Gain	Sample rate
532	Analog	500	3.75	50	10^6	40 MHz

Fig. 7. Lidar measurement at 532 nm on March 26, 2013. Left: Normalized range-corrected backscattered signal; Center: $WCT(a,b)$ profile with $a=60$ m; Right: Contour plot, red dots indicate the estimated ABL heights and its time evolution over Medellín.

Fig. 8. Lidar measurement at 532 nm on June 13, 2013. Left: Normalized range-corrected backscattered signal; Center: $WCT(a,b)$ profile with $a=60$ m; Right: Contour plot, red dots indicate the estimated ABL heights and its time evolution over Medellín.

with clear sky conditions. The profiles clearly show the transition from the ABL top toward free atmosphere. Figures 7 (center) and 8 (center) show the corresponding $WCT(a,b)$ profile, obtained with a dilation parameter optimized to a value of 60 m in the lidar data analysis algorithm for all profiles measured on this dates. The position of maximum peaks within 300 m and 700 m (values of b parameter) correspond to ABL height on each lidar profile. A summary of the results is show in the contour

plots in Fig. 7 (right) and Fig. 8 (right) where the red dots curve represent the ABL time evolution over Medellín.

5. Conclusions

Lidar station built in the urban area of Medellín, despite being located in a complex mountain valley, has become a useful and reliable tool for the study of the daytime development of the ABL

height. We have shown here the first results of the ABL height, involving the WCT method to analyze the backscatter data obtained from our lidar system.

The backscatter vertical profiles obtained from our lidar system show the significant change in the backscatter across the top of the boundary layer providing a convenient means of determining the local ABL height.

WCT method provides a scale-dependent approach to estimate the ABL height and also retained the original lidar backscatter information. Wavelet technique has been included by Lasers and Spectroscopy Group, Universidad Nacional de Colombia Sede Medellín, in an automated algorithm to analyze the backscatter signal data from 532 nm lidar backscatter measurements, to estimate the ABL height in the urban zone of Medellín city. The results shown here reveal that the key of the

wavelet analysis was the selection of an appropriate height-dependent dilation parameter.

6. Expectations

Perform continuous lidar observations of the top height of the ABL over Medellín city using our automated ABL top detection algorithm, and to compare with both radiosonde and CALIOP space-borne lidar measurements.

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