Detecting the planetary boundary layer height from low-level jet with Doppler lidar measurements

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ABSTRACT

The planetary boundary layer (PBL) is an important region of study in the troposphere and one of its more important variable: the PBL height (PBLH) is not easy to detect, mainly in stable conditions due to its complexity. In order to detect the PBLH in stable conditions, in this paper, we apply the low-lev jet (LLJ) method using Doppler lidar measurements, which consists on detecting the LLJ and its maximum velocity height, corresponding to the PBLH. In addition, we analyze this method by comparing and relating it with the variance of horizontal wind and bulk Richardson number (BRN) method from radiosonde data, ensuring the method's efficiency.

Keywords: Planetary boundary layer height, low-level jet, Doppler lidar.

1. INTRODUCTION

According to Stull[1] (1988, p. 2): "we can define the boundary layer as that part of the troposphere that is directly influenced by the presence of the earth's surface, and respond to surface forcings with a timescale of about an hour or less." This layer is responsible for main exchanges of: momentum, energy, and mass between the earth's surface and the atmosphere, which, among other reasons, makes it an important object of study[1,2].

In studies about PBL, a very important variable is the PBLH. This value is a fundamental parameter for several applications, which vary from air quality studies to meteorological modeling[2], however, it is not simple to obtain and/or map this value and its evolution with time. A widespread and well-known tool used to infer the PBLH, is the radiosonde, but it has, as limitation, low temporal and spatial resolutions[3].

In last decades remote sensing devices, which stand out for a better temporal and spatial resolutions, have been applied as an alternative solution for this problem[4] and, in special, lidar systems have been appointed by many authors[5-9] as one of the best tool to obtain these information. In this scenario, two types of lidar are noteworthy: elastic and Doppler.

The elastic lidar has been applied in a lot of works[3,5,6] and it deserves attention for its high vertical range, which allows obtaining the PBLH in metropolis, where these values can reach 2 kilometers or more. One disadvantage is the high overlap height (around hundreds of meters). It impairs to obtain the PBLH in situations where it has lower values[10], often occurring in nocturnal boundary layer (NBL) or stable layer (SL), where PBLH growths slightly, because small convective activity[3].

The Doppler lidar, used in this study, although it is a more recent application, already has been frequently used[7-9]. As opposed to elastic lidar, it has a small overlap height (around dozens of meters), therefore, it is an indicated tool to detect the PBLH in situations mentioned above[8].

Doppler lidar also allows detecting the PBLH by means of different tracers. Wulfmeyer[9], uses the backscatter profile to detect the PBLH, similar technique is applied in elastic lidar, where backscattered signal is availed from mathematics algorithms as: gradient, variance and wavelets method[3]. Alternatively, it is possible to use the signal to noise ratio (SNR) to detect the PBLH, as did Wyngaard[11]. Knowing that the signal received by lidar is coming from inhomogeneities in atmosphere, which are characterized by the refractive index structure parameter C_n^2, and there are a proportionality between C_n^2 and SNR range-corrected[12], the maximum in SNR profile is equivalent to PBLH.

In this study, we used a Doppler lidar to obtain the PBLH from a technique described by Pichugina[8], which is based on the detection of LLJ.

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2. METHODOLOGY

2.1 LLJ method

The LLJ can be defined as a first maximum in the vertical profile of the horizontal winds. In this study according to Stull[1] (1988, p. 521): "we will pragmatically define the LLJ as occurring whenever there is a relative wind speed maximum that is more than 2 m/s faster than wind speeds above it, within the lowest 1500 m of the atmosphere". And it can be used as a parameter to find PBLH, because, in a few words, in stable conditions its maximum is directly associated with minimum of turbulent kinect energy (TKE)[8].

Knowing TKE value can be defined by following equation:

$$TKE = (\sigma_u^2 + \sigma_v^2 + \sigma_w^2) \tag{1}$$

Where σ_u^2, σ_v^2 and σ_w^2 are the variances of zonal, meridional and vertical wind respectively. Some authors[14-16] obtained a relation between standard deviation of these three wind components and frictional velocity (u_*) among which can be highlighted the following[16]:

$$\sigma_u / u_* \approx 2.44 \qquad \sigma_v / u_* \approx 1.92 \qquad \sigma_w / u_* \approx 1.33 \tag{2}$$

which implies in:

$$\sigma_v / \sigma_u \approx 0.79 \qquad \sigma_w / \sigma_u \approx 0.54 \tag{3}$$

so[17]:

$$TKE = 0.5(\sigma_u^2 + \sigma_v^2 + \sigma_w^2) = 0.5(\sigma_u^2 + 0.79\sigma_u^2 + 0.54\sigma_u^2) \rightarrow 0.96\sigma_u^2 \approx \sigma_u^2 \tag{4}$$

Thus in accordance to Equation 4, for stable situations, $TKE = 0.96\sigma_u^2$. From Panofsky[15] and Bergström[14] it is possible to find the following relations respectively: $TKE = 0.95\sigma_u^2$ and $TKE = 0.99\sigma_u^2$ So it can be said that $TKE \approx \sigma_u^2$

Considering a definition of PBL as "a turbulent layer adjacent to the earth's surface"[17], it is possible to find this height using the vertical profile of variance of horizontal wind speed (σ_u^2), where the first minimum of this profile represents the depth of the surface-based turbulent layer[17]. Pichugina[8] detected that in stable situations the maximum of LLJ is equivalent to minimum of σ_u^2 profile (Figure 1).

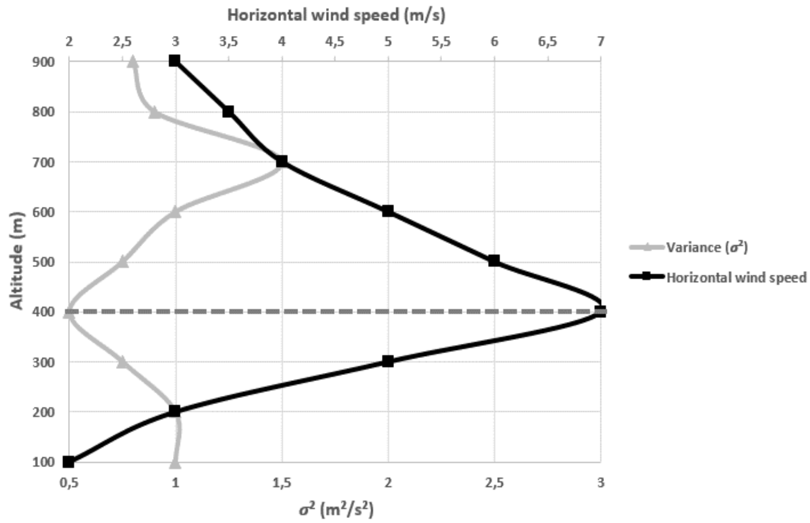

Figure 1. Comparison between the height of LLJ and the minimum σ_u^2, both representing the PBLH (dot line).

2.2 BRN method

The PBL has turbulent activities more intense than free atmosphere, so that, BRN has different values in these layers. Therefore, if the standard value of critical BRN (C_{BRN}), in transition of these layers, is known, it is possible to estimate the PBLH. Although there are some divergences about more precise value, often the range is about 0.25 to 0.30[2]. In this paper, the value adopted is 0.25.

The BRN (Equation 5) is a relation between potential and kinetic energy[2], where $g(m/s^2)$ is the gravity acceleration, $\theta_v(K)$ is the potential temperature, $u(m/s)$ and $v(m/s)$ are the horizontal wind components and $bu_*^2(m/s^2)$ is a constant related to surface friction effects; the suffix *s* and *z* refer to surface and height respectively.

$$BRN = \frac{g/\theta_{vs}\,(\theta_{vz}-\theta_{vs})(z-z_s)}{(u_s-u_s)^2+(v_s-v_s)^2+(bu_*^2)} \qquad (5)$$

2.3 Measurements

The measurement campaign was held in Ressacada's Farm (27⁰40'S, 43⁰30'W) in Santa Catarina State - South of Brazil, during January 2015 and four nights from this period were analyzed. In Figure 2, it is indicated the Doppler lidar position (LIDAR) and the place where radiosonde were launched, the international airport of Florianópolis - Hercílio Luz (SBFL) located 1.62 km northwest from the lidar position.

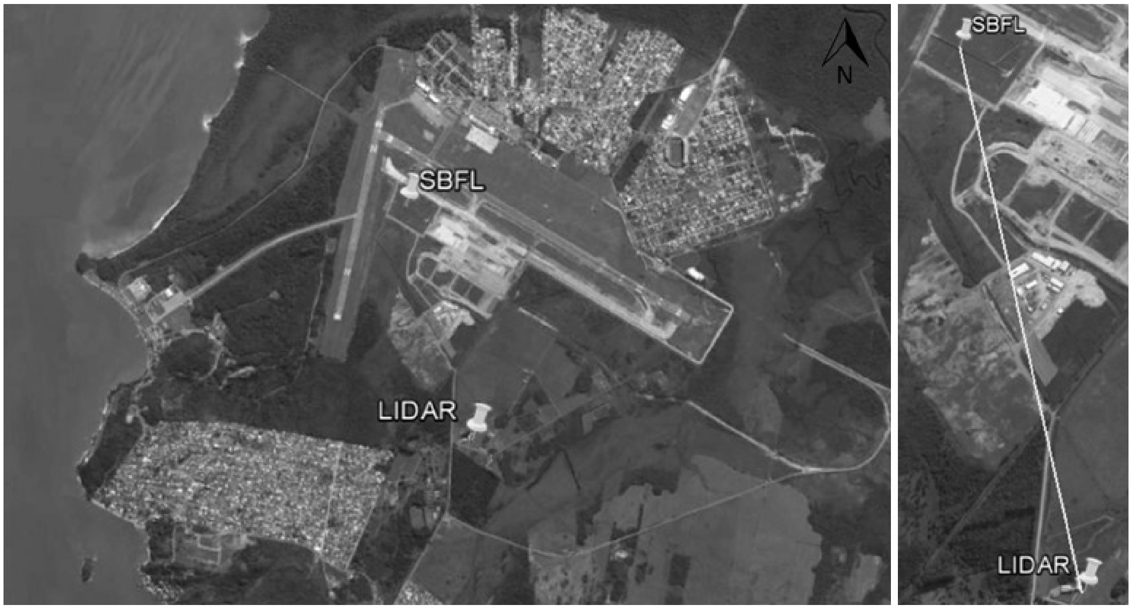

Figure 2. (Left) upper view from the measurement campaign place and (right) the distance between lidar position and radiosonde launching place.

2.4 Instruments

The data were collected by a Doppler lidar, model WLS70 from Leosphere (Figure 3), with a range from 100 up to 1000 m and with vertical resolution of 20 m. It performs a velocity azimuth display (VAD) technique with 14.93^0 conical angle. The data are averaged in 10 min intervals and as an indicator of the measurement quality were used the following parameters: Data Availability (%) defined as the ratio of measurement points accepted by built-in data filters over the complete set of measurement and carrier to noise ratio (CNR), which is equivalent to the SNR. The CNR threshold is set up as -29 dB.

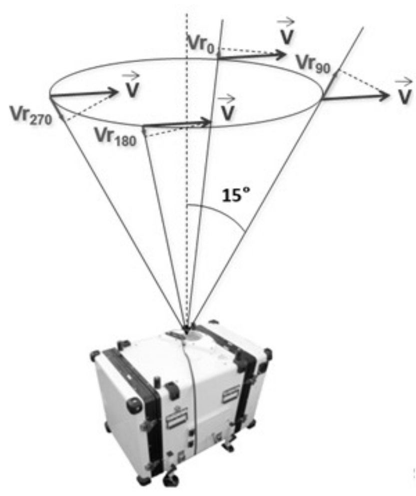

Figure 3. Dopler lidar WLS70 from Leosphere and schematic VAD techinique perfomed by the lidar[18].

The radiosondes are operated by the meteorological network of the aerospace command (REDEMET). They are launched twice a day at 00 and 12 UTC, the second launch is equivalent to 9:00 pm (local time). The balloon rises around 300 m/min, can ascend to over 35 km, drift more than 300 km from the release point and can last 2 hours[19].

3. RESULTS

As mentioned in the previous sections, four nights were analyzed and the values of PBLH were obtained from the LLJ method, compared to the variance values and the PBLH were validated by BRN method obtained from radiosonde measurements. Two horizontal wind speed profiles were used to obtain the maximum of LLJ, profiles around the time of launching of the radiosonde, so this value is relative to the arithmetic mean of the maximum velocity of each profile. The time interval corresponds from 09 until 09:20 pm (local time).

3.1 23th January 2015

The Figure 4 represents the horizontal wind speed profiles obtained at night on 23th January. From this picture, it is possible to observe, clearly, the LLJ. The LLJ method provided a PBLH of 240 m whereas the value obtained from BRN was 228 m, it implies in a difference of 12 m. For this measurement, the mean value of CNR was -13.18 dB.

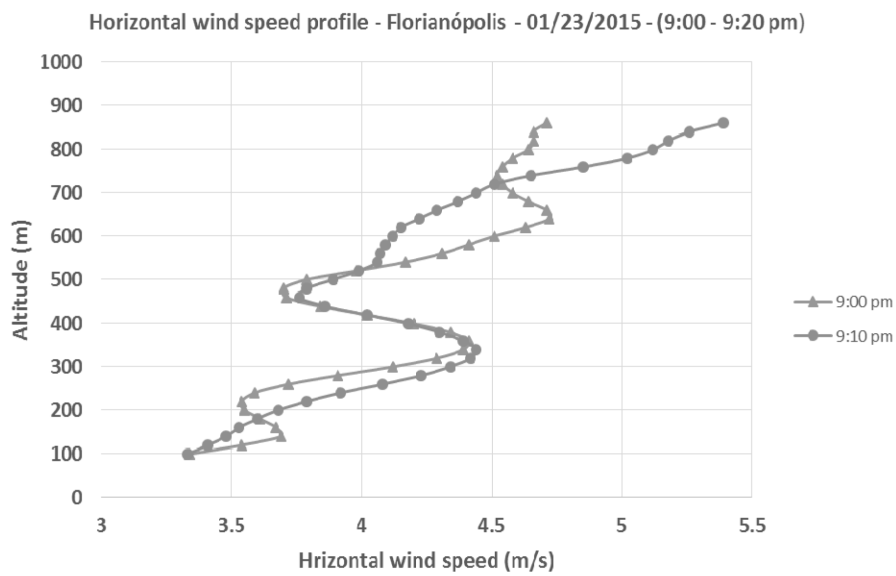

Figure 4. Horizontal wind speed profile from the night on 23th January from 9:00 to 9:20 pm (local time) from Doppler measurements.

3.2 25th January 2015

The wind speed profiles in Figure 5 show the LLJ detected by lidar at night on 25th January. The LLJ method provided a PBLH of 530 m whereas from BRN the value obtained was 546 m. In comparison with previous case, there was a small reduction in proximity between BRN and LLJ method, as well as in mean of CNR, which was -16.70 dB.

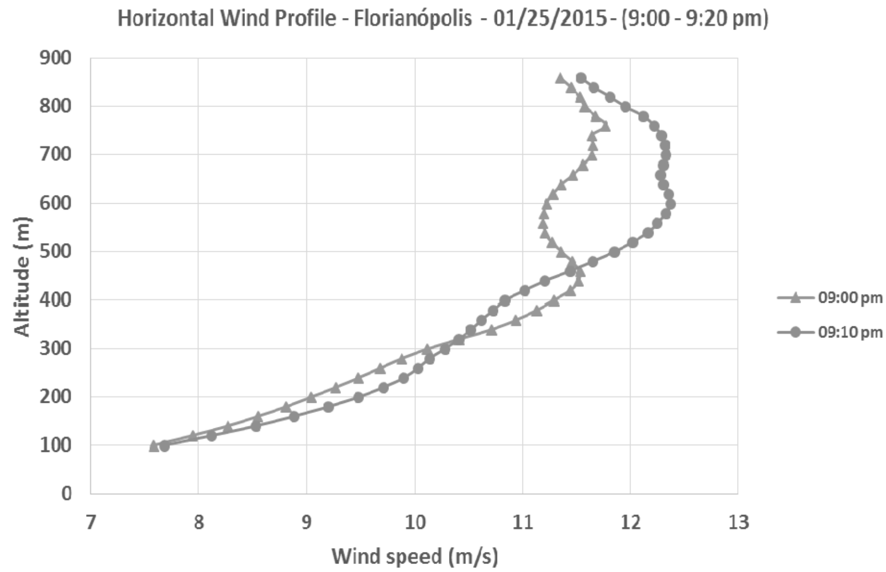

Figure 5. Horizontal wind speed profile from the night on 26th January from 9:00 to 9:20 pm (local time) from Doppler measurements.

3.3 26th January 2015

On 26th January the two wind profiles detected has a similar shape and two LLJ are located in near height (Figure 6). However, the difference between LLJ Method and BRN was bigger than last two cases: 97 m, being that LLJ Method provided a PBLH of 190 m whereas BRN 93 m.

It is noteworthy the small value of CNR (-22.08 dB), which was smallest among all days.

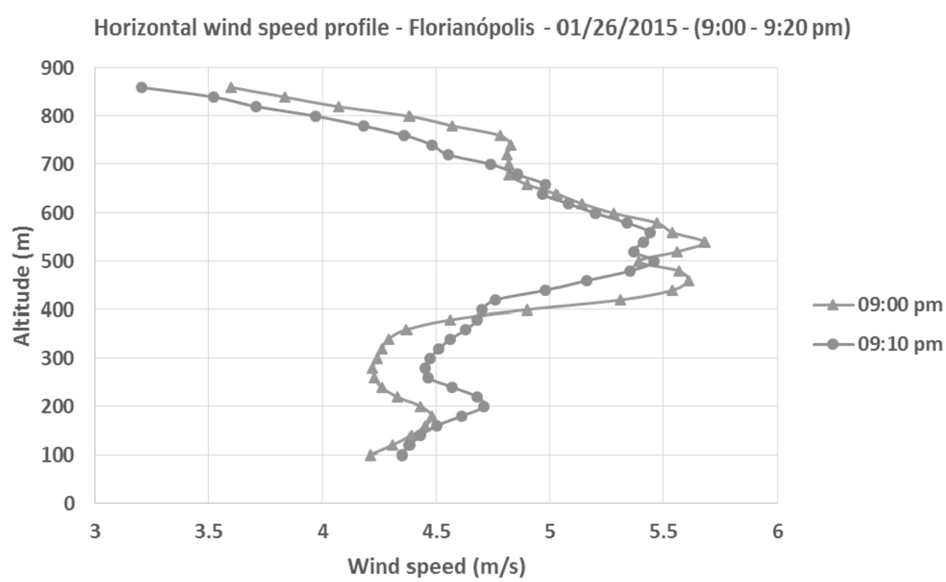

Figure 6. Horizontal wind speed profile from the night on 26th January from 9:00 to 9:20 pm (local time) from Doppler measurements.

3.4 27th January 2015

Figure 7 exhibits the LLJ in wind profiles at night on 27th January. In this night the BRN provided a PBLH of 251 m whereas from LLJ Method the value obtained was 290 m. The difference between these two methods is 41m. The mean value of CNR was -18.02 dB.

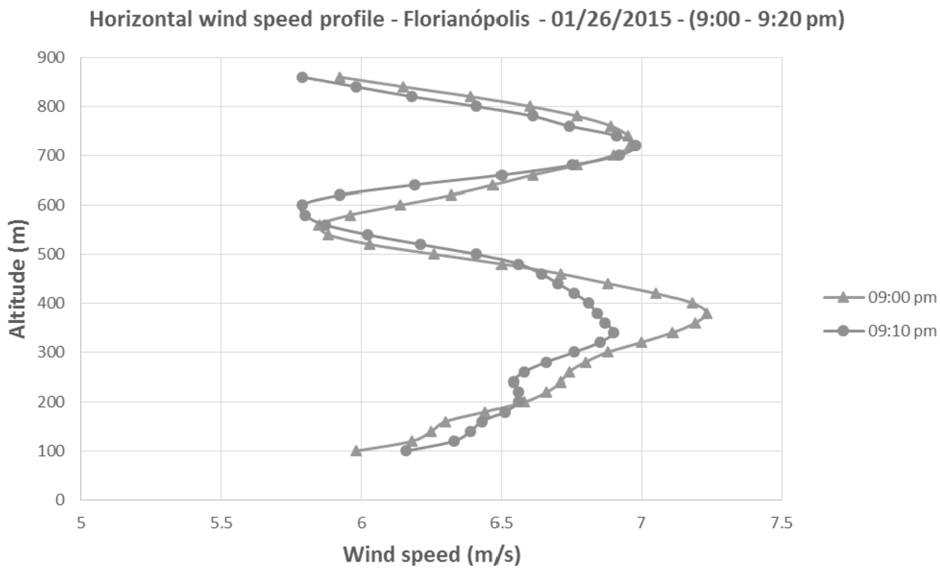

Figure 7. Horizontal wind speed profile from the night on 27th January from 9:00 to 9:20 pm (local time) from Doppler measurements.

3.5 Comparison between LLJ Method and σ² profile

After comparing LLJ method and BRN, in order to understand better the results, it was realized a comparison between the first and the variance of wind horizontal (σ²) profile. It was chosen the first ten minutes of more extreme situations: 23th January (best result) and 26th January (worst result), and from raw data (temporal resolution of 10 seconds) was calculated the variance.

Figure 8 exhibits the comparison between LLJ and σ² profile. The difference between them is 20 m, which is the same value of lidar spatial resolution. This small difference agrees with expected in literature[17].

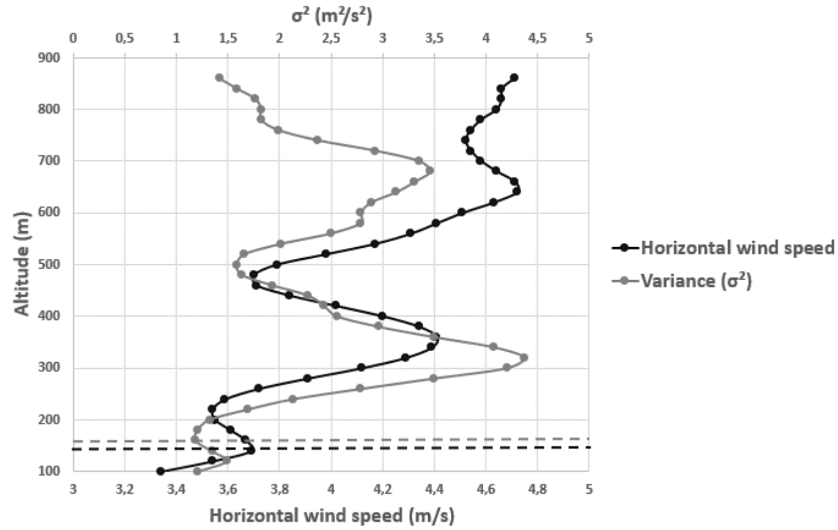

Figure 8. Comparison between the height of LLJ and the minimum σ_u^2, each one representing the PBLH from the night on 23th January.

On 26th January, LLJ Method and σ² profile exhibits a considerable difference (480 m) between the PBLH values provided for each one (Figure 9).

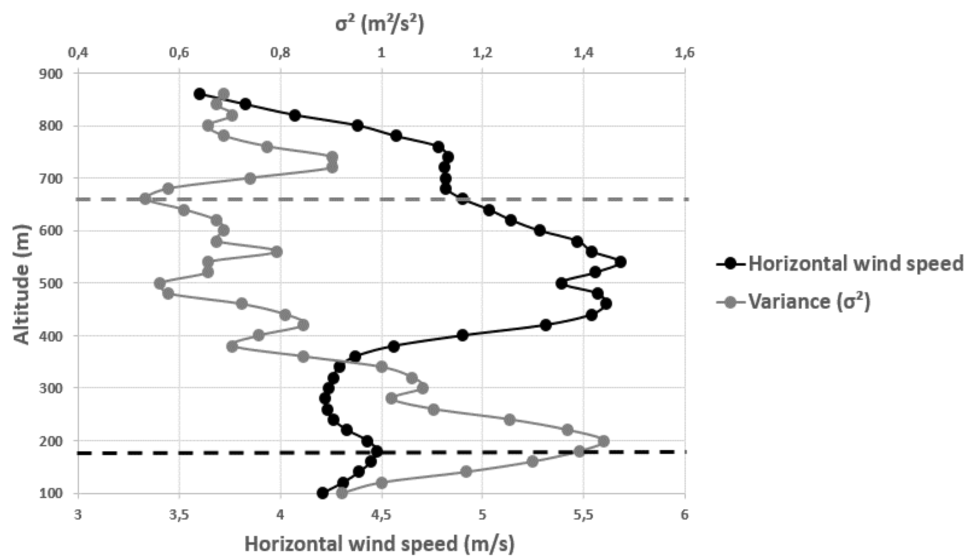

Figure 9. Comparison between the height of LLJ and the minimum σ_u^2, each one representing the PBLH from the night on 26th January.

3.6 Comparison between CNR and confiability of results

From results showed above were possible to observe that LLJ method can detect the PBLH with a high precision (less than lidar spatial resolution). However, it is not a rule for all situation, being that an important factor is the mean value of CNR.

In nights where measured had the large values of CNR, the difference (Δ) between LLJ Method and validation algorithm (σ^2 or BRN) was lower than or equal lidar spatial resolution, but as CNR value decreases, Δ increases. This relation is presented in figure 10 and detailed in Table 1.

Table 1. Resume of comparison between LLJ method and BRN.

Day	Local Time	PBLH (LLJ) [m]	PBLH (BRN) [m]	ΔPBLH (LLJ – BRN) [m]	CNRm [dB]
23/01/2015	9:00 pm	240	228	12	**-13,18**
25/01/2015	9:00 pm	530	546	16	**-16,56**
26/01/2015	9:00 pm	190	93	97	**-22,09**
27/01/2015	9:00 pm	290	251	39	**-18,02**

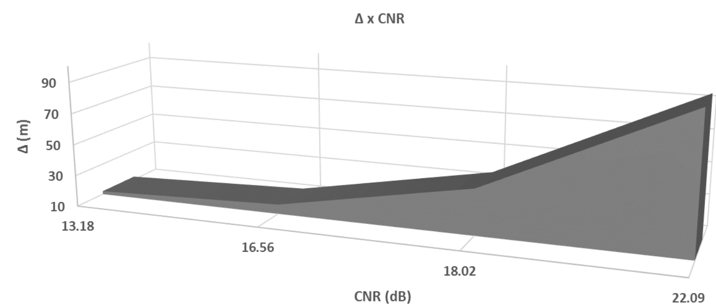

Figure 10. Comparison between CNR value and the difference between PBLH from radiosonde and LLJ method.

4. CONCLUSION

The PBLH is an important value for a lot of studies and it enables a best understanding of PBL behavior and influence of their forcings. However, it is not easy to detect this height, mainly in stable situations. In this paper was presented a manner to detect PBLH in stable situations using Doppler wind lidar by LLJ Method, which consists on detect the maximum of LLJ and this height will be considered the PBLH[8].

Among selected days were possible to observe the direct relation between CNR and efficiency of LLJ Method. In days where CNR value was large, the Δ (difference between LLJ Method and BRN) was less than lidar resolution, but the reduction of CNR value resulted in increase of Δ values. This same relation was obtained when the LLJ Method was compared with σ^2 profile.

Therefore, the LLJ Method can be used as a tool to detect the PBLH in stable situations, but it is very important to pay special attention to CNR values in order to ensure the high quality of data.

In future studies are planned to do similar approaches with meteorological models and other experimental methods to detect PBLH, so that we will can compare a larger period in each night.

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