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Height and Velocity of the Turbulence Layer at Chajnantor Estimated From Radiometric Measurements

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Dedication

This ALMA memo is dedicated to our dear friend Roberto Rivera, who suddenly passed away last September. Roberto provided a major support to the ALMA Site Testing group keeping operational the measurement equipments at the altitude of Chajnantor, and doing reduction and analysis of the data gathered there. Until his last days he showed a deep interest and enthusiasm for the project. Roberto promoted ALMA and Astronomy science at the Universities and amateur level in Antofagasta and San Pedro de Atacama. He was also a dedicated and exemplary father, husband, brother and son.

We will always remember his joy and friendship.

Abstract

The height of the turbulence layer above Chajnantor was determined using two Water Vapour Radiometers (WVR) located along a 300m East-West baseline. The radiometers measure the fluctuations in the precipitable water vapour (PWV). The fluctuations are similar in both WVR and thus a cross-correlation of the signal of both radiometers make possible to determine the transit time from the correlation time lag. With a known transit time, and with both beams parallel along the East-West baseline, it is possible to obtain the velocity of the turbulence layer, projected along the baseline. Using the projected turbulence velocity together with a second transit time found with the beams crossed at a given height, we obtained the height of the turbulence layer.

Data were taken during a two-month period in December 2003 and January 2004. The most reliable estimates of the velocity and height of the turbulence layer occurred between 14 and 22 UT, which corresponds to about 38% of a whole day. During this period the median height of the turbulence layer is about 600 m. About 70% of the analyzed time the turbulence layer was below 1000 m. During night-time, the estimate of the height becomes less accurate because the wind speeds are lower, the wind direction changes from East-West towards North-South, and the amount of PWV seems to be very low, which all together is reflected in weaker signals in the radiometers and less amount of strong cross-correlations.

Keywords: Precipitable Water Vapour - PWV, Turbulence Layer, Wind Speed, Phase Correction

1. Introduction

A series of experiments have been carried out at Chajnantor in order to correct for the phase variation introduced by the water vapour in the atmosphere, through the use of linear relations between electric path length and the PWV content estimated from radiometric measurements at 183 GHz [1, 2 and 3].

The first results of the phase corrections experiments [2, 3] showed that the correction is possible up to 70%, but the correction achieved presents variations during the day [3]. This variation has been related to the height of the turbulence layer, which can introduce an effect because of the large far-field distance of the interferometer as discussed in [3]. The suggestion is that the better phase correction results when the height of the turbulence layer is high.

In order to confirm the results suggested in [3] we need a reliable method to continuously estimate the height of the turbulence layer at Chajnantor. Presently there are two methods available at Chajnantor: the first one consists of measured tropospheric profiles obtained from radiosonde launches and the second method uses the two interferometer technique described in [7]. The practical problems of these two methods are well described in [4], where a new method was proposed to estimate the height of the turbulence layer from radiometric measurements at 183 GHz. Assuming a “frozen screen” approximation for the atmospheric fluctuations, the water vapour cells will move from one beam to the other of the two radiometers, if the wind direction is along the radiometer baseline. The signature of these atmospheric disturbances in the PWV variations will be similar in both radiometers and thus a cross-correlation of their signal should show the transit time as the correlation time lag. With a know transit time, and with both beams parallel, we are able to obtain directly the projected velocity of the turbulence layer, along the baseline direction. By crossing the beams of the two radiometers at different heights, in order to find where the time lag of the maximum cross-correlation between the PWV series is zero, it is possible to determine directly the height of the turbulence layer.

Here we have used a variation of the method in order to determine the height of the turbulence layer automatically and with fewer measurements, by observing first with the beams parallel, as Figure 1a shows, to determine the projected velocity of the turbulence layer and then crossing the beams (see Figure 1b) at only one height during a given period, obtaining a second transit time, which can be used to determine the height.

2. Experiment and Cross-Correlation

Radiometric measurements of the brightness temperature of an atmospheric column in the direction of the satellite IS-801 (Azimuth 61.7° and Elevation 41.6°) were obtained with the two WVR located at Chajnantor plateau, from December 3, 2003 to January 31, 2004. During this period the WVR were performing observations in the direction of the satellite direction starting every hour from minute 0 to minute 48 (in order to perform phase correction experiments together with 11.2 GHz interferometric measurements [2][3]). At minute 49 the beams of the two radiometers were crossed at a height about 1500 m (at an elevation of 84.29° and an azimuth +90°/-90° for the West and East radiometers, respectively). At minute 59 the beams were moved to continue the observations in the line of sight to the satellite. The sampling rate was 0.5 Hz. During this period, data was taken during about 70% of the time. The rest of the time data was lost due to communication problems with the radiometers.

The cross-correlation was done by reading a data block of about 10 minutes from the West and East PWV series. A second order polynomial is subtracted from the data block in order to reduce the long term variations. After that, the data blocks are smoothed by a running window of 9 points. These smoothed data blocks are then cross-correlated.

As the time window used to compute the cross-correlation function is about 10 minutes (about 600 sec), we are able to determine a maximum time lag of about ±300 sec. This implies that projected turbulence speeds lower than ±1 m/s cannot be detected. Only those values with maximum cross-correlation coefficients higher than 0.6 and projected speeds lower than 100 m/s are considered in the calculations. Examples of strong and weak cross-correlations are showed in Figure 2. Projected wind speeds were limited to 100 m/s because higher speeds lead to illogical results, such as negative heights. In some cases data with cross-correlation coefficients lower than 0.6 were included in the calculations due to the similarity of the series which is not detected with the automatic process of the cross-correlation. The total data reconsidered was 1565 data blocks of 10 minutes, which represents about 28% of the total data blocks.

3. Methodology and Results

The height of the turbulence layer is determined in two steps. The first step consisted in computing the projected (along the East-West baseline) velocity of the turbulence layer from the observations done when the radiometers’ beams are parallel (Figure 1a), by using the cross-correlation method described before.

The time lag Δt_a between the time series of data blocks gathered from the two WVRs, was determined from the delay at which the maximum of the cross-correlation peak has its highest value. The determination of this time lag together with the fixed baseline b (300 m), made it possible to calculate the projected velocity of the turbulence layer as $v = b/\Delta t_a$. A positive value of the wind speed means the wind blows from West to East. A negative value means the wind blows in the opposite direction.

The data blocks from minute 40 to 49 of an hour, and from minute 0 to 10 of the next hour, are used to compute the corresponding projected velocities v of the turbulence layer. If the absolute difference between these velocities is lower than 20 m/s, then the average of these two velocities will be the effective projected velocity v_{eff} used in the computation of the height of the turbulence layer, as explained below.

In the second step, the height of the turbulence layer is computed by combining the projected velocity v_{eff} (derived in the first step) with a second time lag Δt_b computed from the cross-correlation of the PWV series corresponding to the data block gathered from minute 49 to 59, when the beams are crossed at a height about 1500 m.

According to the geometry shown in Figure 1b, when the turbulence is at a height lower than 1500 m, the beams will not be crossed and the projected wind speed will have a positive sign when the wind blows from the west. If the turbulence layer is higher than 1500 m, the beams will cross below the turbulent layer and thus the measured direction will be opposite to the real direction. In both cases the height of the turbulence layer can be determined geometrically from:

$$h = \frac{b - v_{eff}\ \Delta t_b}{2} \tan \alpha_1, \tag{1}$$

where h is the height of the turbulence layer, b is the baseline length (300 m), v_{eff} is the projected velocity of the turbulence layer computed in the first step, α_1 is the elevation angle (84.29º) and Δt_b is the transit time of the turbulence measured in the second step.

Applying this method to all useful data, a daily cycle for the velocity of the turbulence layer was obtained. Figure 3 shows the mean daily cycle (one sample for the blocks corresponding to the minutes 40-49 and 49-59 of an hour, and 0-10 of the next hour) for the projected velocity of the turbulence layer measured with the radiometers and the projected wind velocity gathered at ground level. Between about 0 UT and 12 UT there is a high dispersion in the mean velocity computed for the turbulence layer. This can be due to the low intensity of the emission and fluctuations from the PWV bubbles during night time, which diminishes the signal to noise ratio in the radiometers data series. It can also be due to a decrease in wind speed and a change of wind direction as can be seen in Figure 4.

Between 12 UT and the 22 UT the dispersion in the calculated speed of the turbulence layer is small. During this time the wind blows predominately from West to East, as it was found in [6], suggesting that this is the best period to measure the velocity and height of the turbulence layer with the present setup.

Figure 5 shows the computed height of the turbulence layer for each hour of the available data obtained during the period of the experiment. The heights showed in this figure are higher than 0 m and lower than 4000 m. It can be observed that during night time the amount of available data of heights is less than during day time. This is because of the weak cross-correlations found often during night and because some of the PWV series with strong cross-correlations give negative heights, which are discarded.

Figure 6 shows the distribution of the height of the turbulence layer showed in Figure 5. During the period of the experiment the height of the turbulence layer is typically between 500 m and 600 m above ground level. The quartiles 25%, 50% and 75% are 294 m, 568 m and 1155 m, respectively. Figure 6 also shows that about 70% of time the layer is below 1000 m, which is in agreement with the result found in [4].

Figure 7a shows the mean daily variation computed for the height of the turbulence layer. Each sample corresponds to the mean value with standard deviation computed for each hour. Figure 7b shows the amount of available data points used in the computation of the mean value of the height for each hour. Between 10 UT and 11 UT the turbulence layer seems to have a jump in its height. These correspond to the 6 and 7 hours in local time, when the main turbulence layer starts to go down below Chajnantor (i.e. below 5000 m) so is possible that what the WVR are observing from 11 UT to 15 UT is the upper turbulence layer. Before 11 UT the wind speed is lower than after this hour, as was found in [5], and also the wind direction change, as can be seen in Figure 4. These two effects caused the wind velocity projected along the baseline becomes very slow (see Figure 3) and hence the variations of the PWV. So the observation period of 10 minutes used when the beams are crossed could not be long enough for observing the turbulence layer structure with both radiometers. As a result, there is less available data during night time than during day time, as can be seen in Figure 7b.

4. Discussion

The results obtained in this work are in agreement with the relation found in [4] between the cross-correlation and the wind direction, indicating that the method does not work well when the wind blows from a slightly perpendicular direction with respect to the baseline. This is a natural limitation of the setup because when the wind blows, for example, from North-West to South-East, the structure of the turbulence layer seen by the West radiometer at a given time is unlikely to be observed by the East radiometer at a later time. The probability that both radiometers will observe the same water vapour cell at a different time depends both on the beam width of the radiometers at a given height and the size of the water vapour cells that make up the layer.

In [4] radiosonde data gathered during November 1999 was used to obtain information about the height of the turbulence layer. Here we also use that radiosonde data in order to analyse the behaviour of the wind direction with the height. Figure 8 is extracted from [4] and has been used here only for completeness purposes. This figure shows the cross-correlation computed in [4] for days 6 and 7 of November 1999, when the beams were parallel. Also it can be seen the wind direction gathered at ground level. In grey are emphasized the periods about 4 and 8 UT of both days in order to see the clear relation between the cross-correlations and the wind direction. This correlation with the wind direction obtained at ground level is in agreement with the wind direction profiles showed in Figure 9, which shows the wind direction profile for days 6 and 7 of November 1999, at 4 UT. The wind profile for November 7 shows a more stable wind direction, within a band near the baseline direction, than the profile for November 6. This explains the strong cross-correlation saw in Figures 8 for day 7, before and during 4 UT. The wind direction profiles of Figure 9 imply that wind direction can change with height and, hence, a relation between the turbulence layer velocity and the wind velocity at ground level not always can be reliable.

Besides the wind direction changes at night time, it is possible that during this time the PWV fluctuations are actually strong over a range of heights [8] and that the stability of the lower layer has a short term life due to the dominant mechanical turbulence (wind shear) at the lower heights [5]. Hence it could not be considered as a frozen layer for the time scale assumed in this experiment.

A possible technical source of error in the method presented here, is the assumption that the radiometer beams are perfectly parallel during the first 49 minutes of the observation cycle or that these are in a perfectly opposite direction (±90 degrees in azimuth) when the beams are crossed. This means the geometries of Figure 1 could not be perfect due to alignment deviations introduced by the terrain effects and the positioning of the radiometers, which are natural limitations of the setup and are unlikely to be improved.

5. Conclusions

The speed and height of the turbulence layer was obtained from radiometric measurements at 183 GHz. The method proposed in this work uses fixed geometry for the radiometers setup. The fixed geometry of the instruments makes this method depending on the direction of displacement of the turbulent layer. The accuracy of the method also depends on the correct alignment of the radiometer beams.

With respect to the displacement direction, the best period of the day to use this method is between 14 and 22 UT, when the calculated velocity of the turbulence layer is correlated with the projected wind velocity gathered at ground level, as can be seen in Figure 3. The velocity of the wind at ground level is not always correlated with the velocity of the turbulence layer because the wind direction can change with height, as is showed in Figure 9.

The results obtained here show that the median height of the turbulence layer is about 568 m and about 70% of the recorded time the turbulence layer is below 1000 m.

Acknowledgments

We are grateful to Alison Stirling and to Angel Otárola for their always useful comments and suggestions.

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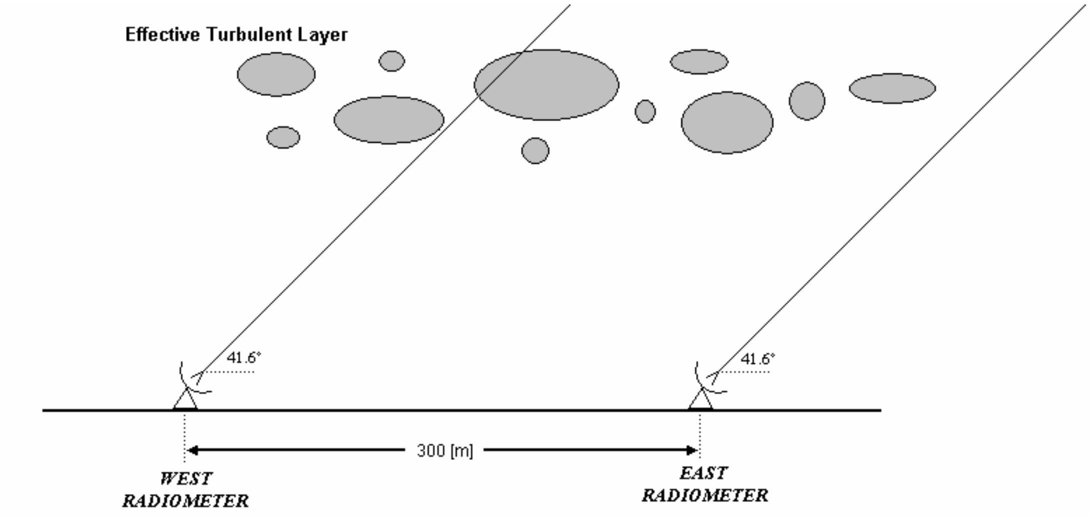
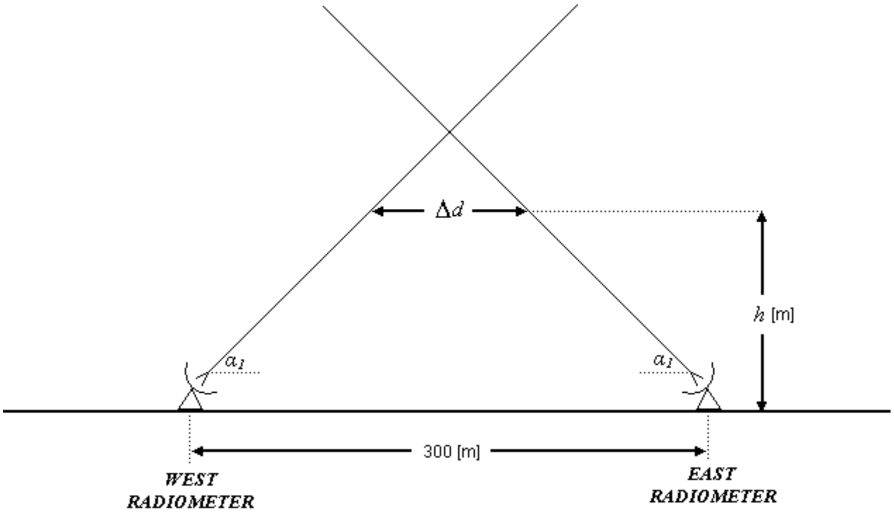


(a)



(b)

Figure 1 Diagram of the geometry used to compute the turbulent layer height from 183 GHz radiometric measurements. (a) The radiometer's beams are pointed to the satellite IS-801 (Azimuth = 61.7º and Elevation = 41.6º) during the first 48 minutes of an hourly cycle. (b) The beams are crossed at an elevation angle of 84.29° from minute 49 to minute 59. This sequence ends at minute 59 when the stepper motors are restarted to resume observations to the satellite.

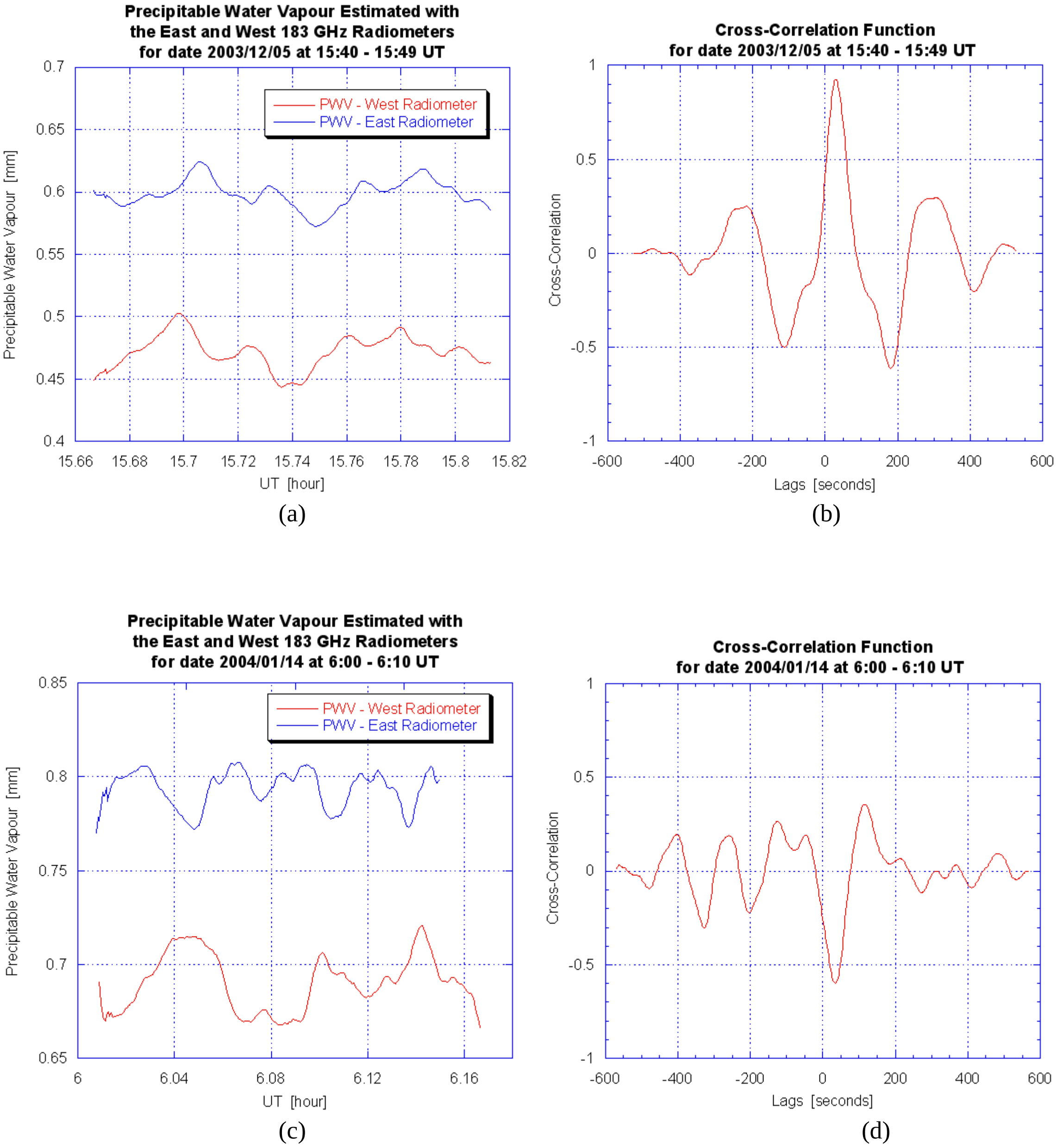


Figure 2 (a) Precipitable Water Vapour estimated with the East and West radiometers, between 15:40 and 15:49 UT of December 5, 2003. (b) Cross-correlation function of the East and West PWV series. This is an example of a strong cross-correlation. (c) PWV estimated between 6:00 and 6:10 UT of January 14, 2004, and (d) the corresponding cross-correlation function. This corresponds to a weak cross-correlation.

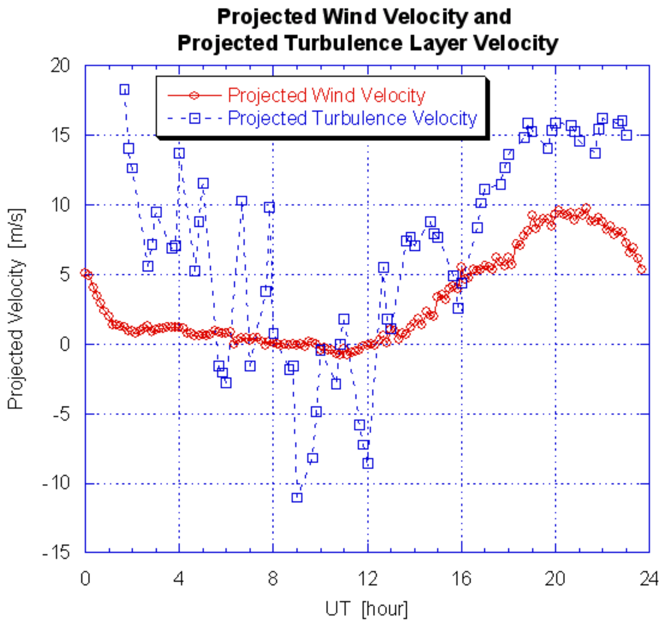
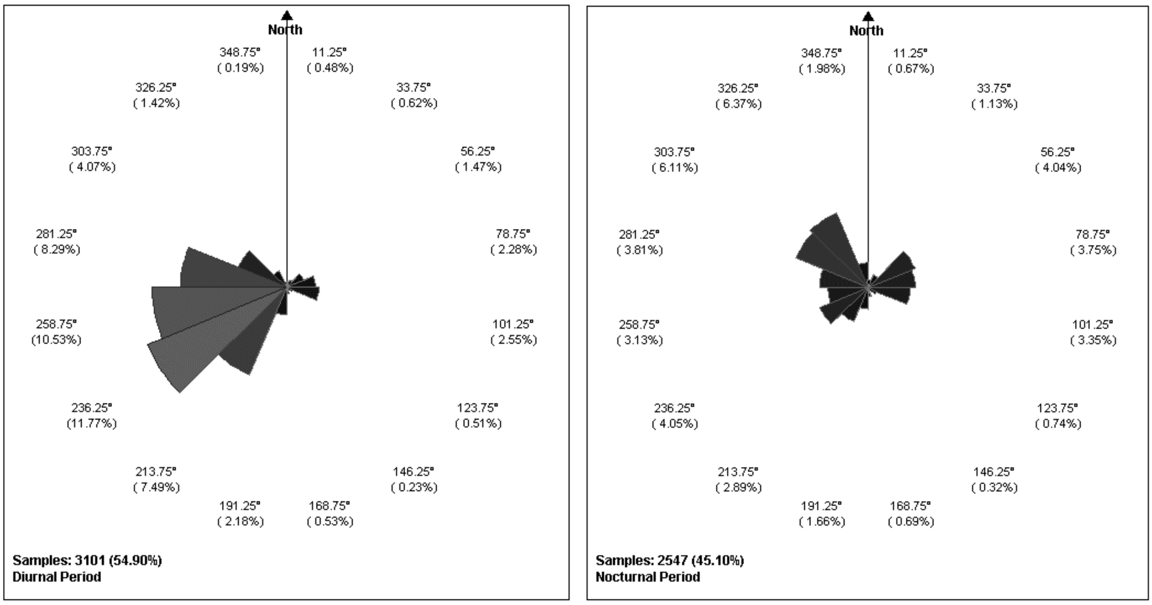


Figure 3 Daily cycle for the wind velocity and turbulence layer velocity computed with whole the useful data gathered during the period corresponding to the first experiment. The series shows a sample about every 10 minutes. Each sample corresponds to the mean value computed for that minute. Positive values of the wind velocity mean the wind blows from west to east. Negative values mean the wind blows in the opposite direction. Values near zero correspond to low wind speeds or the wind blowing in a perpendicular direction respect to the baseline.



(a) (b)

Figure 4 Windroses of the wind direction gathered at ground level during the months December 2003 and January 2004, for (a) diurnal period considered between 11 UT and 24 UT, and (b) nocturnal period considered between 1 UT and 10 UT.

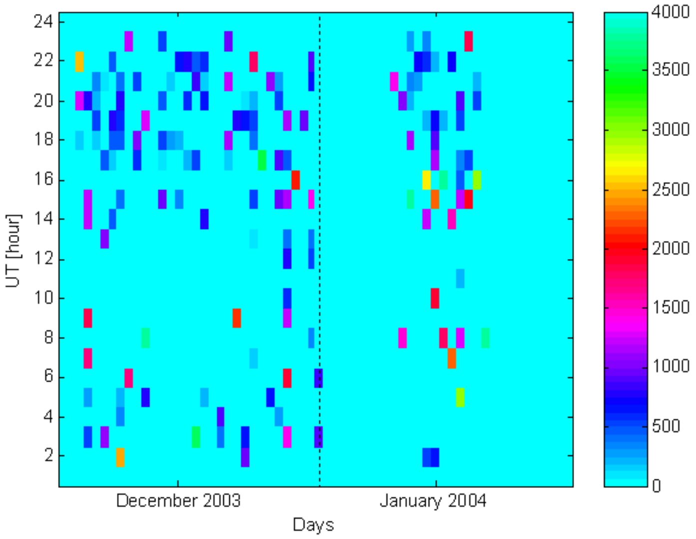


Figure 5 Height of the turbulence layer computed for each hour of the available data gathered during the period of the experiment (from December 3, 2003 to January 31, 2004).

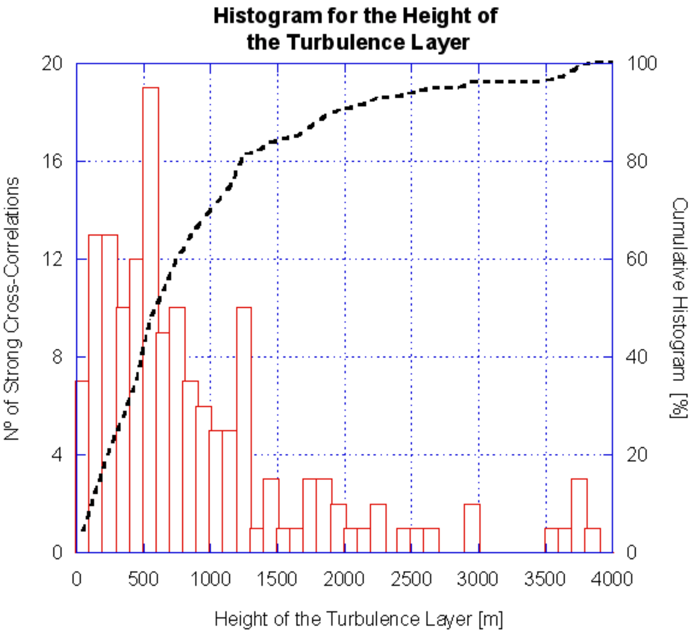
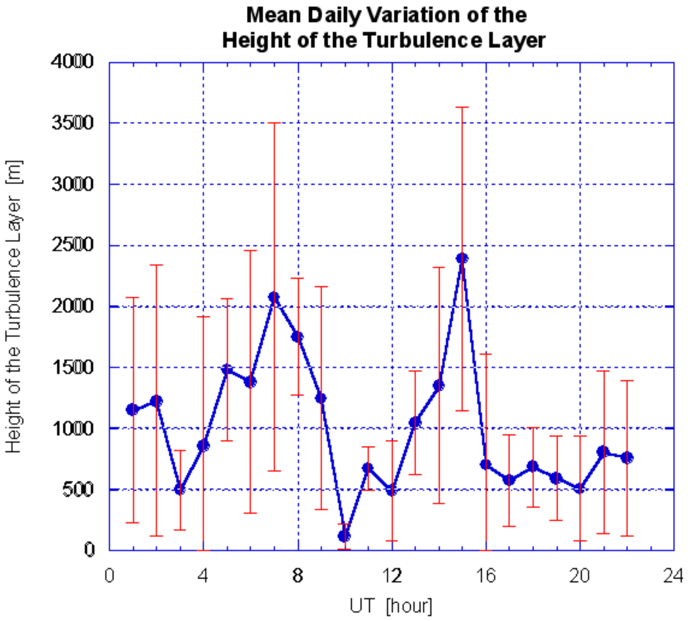


Figure 6 Histogram for the height of the turbulence layer computed with whole the available data. The most frequently height of the turbulence layer is between 500 m and 600 m above ground, while the median is about 600 m. The cumulative histogram indicates that about 70% of time the turbulence layer is below 1000 m. The quartiles 25%, 50% and 75% are 294 m, 568 m and 1155 m, respectively.



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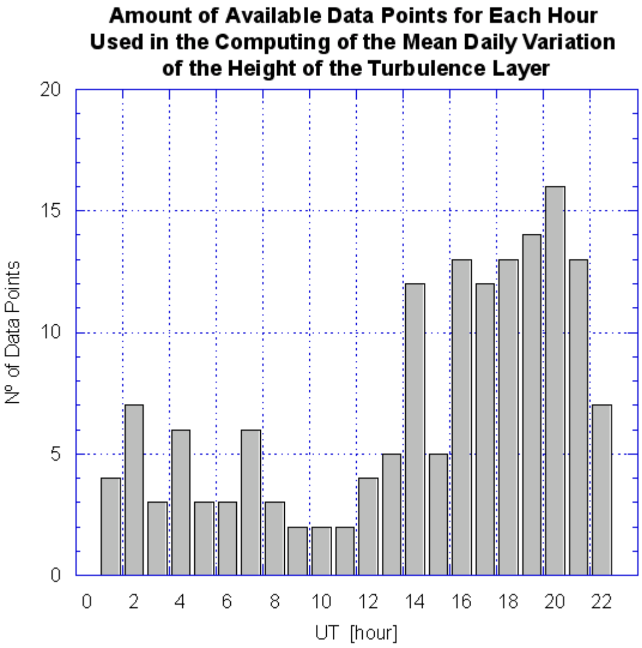

(b)

Figure 7 (a) Daily variation estimated for the height of the turbulence layer. Each sample corresponds to the mean value with standard deviation computed for each hour. The high standard deviation observed can be attributed to the uncertainty introduced by the value of v_{eff} used in the second step of the method for computing the height of the turbulence layer. (b) Number of data points available in the computation of the daily variation of the height. There is less available data during night time because of the wind direction is not as parallel to the baseline as it is during day time.

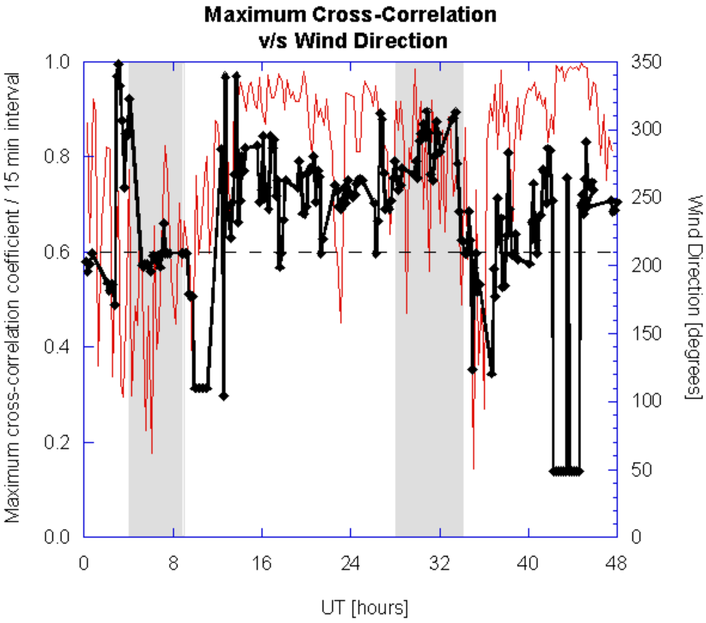

Figure 8 Results of the cross-correlation (thin line) for the days of November 6 and 7, 1999. The solid dots on the black thick line indicate the wind direction gathered at ground level. The time scale is in hours, starting at 0 UT of November 6, 1999. This figure was extracted from [5] and has been used here only for completeness purposes.

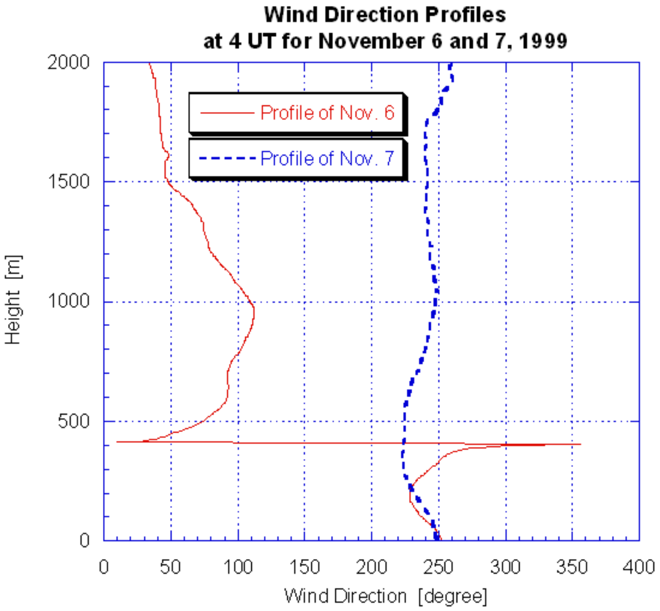

Figure 9 Wind direction profiles for days 6 and 7 of November, 1999. Both profiles correspond to the radiosonde data gathered at 4 UT. The profile corresponding to November 7 shows a more stable wind direction than the one for November 6.