

Analyzing the turbulent Planetary Boundary Layer by remote sensing systems: Doppler wind lidar, aerosol elastic lidar and microwave radiometer *by Gregori de Arruda Moreira et al.*

Author's response.

We thank the anonymous reviewers for their comments, corrections and suggestions, which have helped to improve the quality of the manuscript. According to the referees' reports, the following changes have been performed on the original manuscript and a point-by-point response is included below.

Reviewer 1

The paper has improved significantly. Thank you for the explanations. I understand now much better how the different measurement techniques are applied together in order to gather combined information for analysis of PBL behavior. But I also see now that I was quite distracted by the technical description and I was actually missing a clear overview about the paper's idea. Here some suggestions:

1) It may be helpful to describe in one or two sentences what you mean by "*PBL behavior*". This expression is quite general and leaves a lot of room for interpretation, because it is not well defined and can be interpreted in many differently ways. Maybe you can just add a list of parameters and/or boundary layer properties which you want to derive synergistically. From my current understanding of the paper that would be things like heating/cooling source, aerosol source (ground emission or long-range transport), presence of top down mixing... Those are mentioned in the introduction, but a condensed list of the target parameters would facilitate the understanding of the paper's intention and focus dramatically.

We thank the Reviewer 1 for these comments/suggestions. In order to clarify the question raised on terminology we replaced "*PBL behavior*" by "*analysis of the PBL*", because the main idea is to talk about the different processes that occur in the PBL and use them to characterize this layer. In addition, we replaced the term "*synergy*" by "*combination*". We consider this term more appropriate because the results generated from the different instruments are used in a complementary way leaving the exploitation of synergies for a future work.

The table 2 presents a list of all variables analyzed individually and their respective products.

Table 2 – Products and their respective meaning, provided by each system

Product	System	Meaning
$\tau_{w'}(z)$	Doppler lidar	Measurement in time of length of turbulent eddies
$\sigma_{w'}^2(z)$	Doppler lidar	Turbulent Kinetic Energy
$S_{w'}(z)$	Doppler lidar	Direction of turbulent movements
$PBLH_{Doppler}$	Doppler lidar	Top of CBL obtained from variance threshold method
$\tau_{RCS'}(z)$	Elastic lidar	Measurement in time of length of turbulent eddies
$\sigma_{RCS'}^2(z)$	Elastic lidar	Homogeneity of aerosol distribution
$S_{RCS'}(z)$	Elastic lidar	Aerosol motion ($S < 0 \rightarrow$ Downdrafts, $S > 0 \rightarrow$ Updrafts)
$K_{RCS'}(z)$	Elastic lidar	Level of aerosol mixing ($K < 3 \rightarrow$ Well-Mixed, $K > 3 \rightarrow$ Low Mixing)
$PBLH_{Elastic}$	Elastic lidar	Top of aerosol layer obtained from variance method
$PBLH_{MWR}$	MWR	Top of CBL/SBL layer obtained from Potential Temperature

2) Even better would be a new figure that shows which input parameters are needed for which of these boundary layer properties. It is described in the text, but a figure like this would make the "synergy" and the idea of the work more obvious for the reader.

We thank the Reviewer 1 for this comment. In order to clarify this point, the table 2 (presented above) was added in the main document.

Reviewer 2

General comments

This manuscript presents results from the SLOPE campaign in Granada, Spain, in which the objective was to obtain closure between remote sensing and in-situ measurements. For this manuscript, the focus is on characterizing the planetary boundary layer using a Doppler lidar, multi-wavelength lidar (MULHACEN), and a profiling microwave radiometer, all operating at high temporal resolution (2 seconds). The authors investigate the use of fluctuations in aerosol number density from the elastic system (EL), vertical velocity fluctuations obtained from the Doppler lidar (DL), and potential temperature profiles retrieved from the microwave radiometer (MWR), to identify the boundary layer height (PBLH).

As stated in the first review, some of the methodology is relevant, and the influence of random error introducing extra noise in higher-order moments is explored using suitable techniques, but a major issue was that the manuscript did not have a concrete focus and conclusion, and without these, did not present anything new.

The authors now state that the focus of the paper is 'the synergetic combination of information from different remote sensing systems that are sensitive to different tracers'. This would present something new and useful to the scientific community but there is minimal and insufficient discussion presented in the manuscript in its current state. The comments outlined in the first review have not yet been adequately addressed, and so the manuscript is not yet ready for publication.

We thank the Reviewer 2 for this comment. In order to clarify this point we changed the term “synergy” by “combination”, because we believe that this term is more pertinent. Thus, we show that the combination of different remote sensing systems can provide a detailed picture on the *PBL* turbulent features. In addition, we performed a more detailed discussion about the influence of noise in our results, mainly at 532 nm (Elastic lidar). Some part of the text have been completely re-written and additional results are presented just to show that the focus of the paper is the description of the turbulent behavior of the PBL by means of higher order moments applied to the 2 s profiles retrieved from Doppler Lidar and Elastic Lidar, specially showing the feasibility of Elastic Lidar signals at 532 nm.

Major comments

The authors state that the focus of the paper is on the synergistic combination of different methods to determine PBLH, but there is still insufficient discussion in the main text. There is little suggestion on how the various retrieved parameters could be combined, or how the relative magnitudes of their uncertainties could influence the combination.

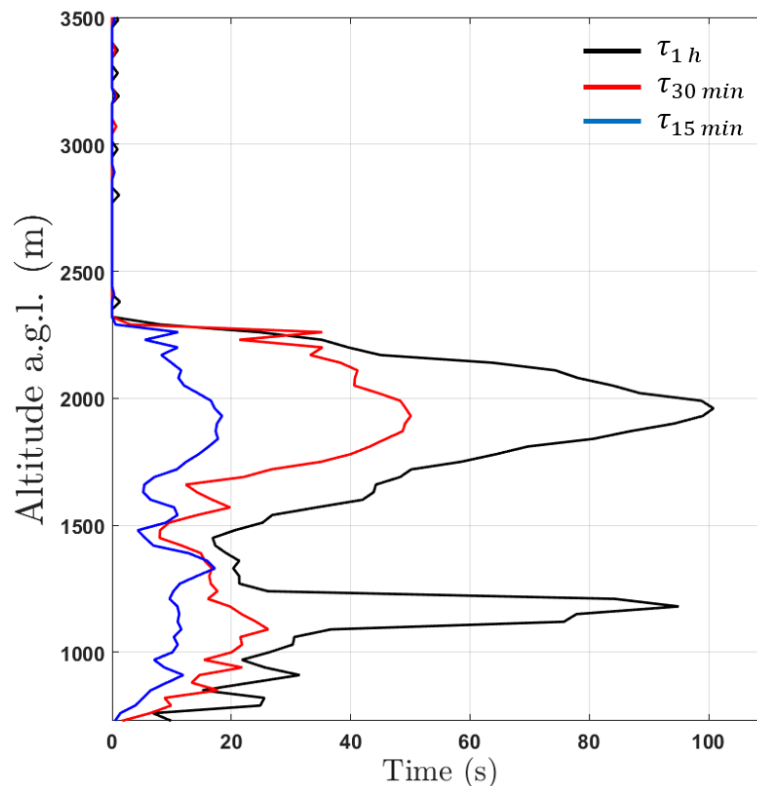
We thank the Reviewer 2 for this comment. In order to clarify this point the term “synergy” was replaced by “combination”, because the results generated from the

different instruments are complementary. We consider this term more appropriate because the results generated from the different instruments are used in a complementary way leaving the exploitation of synergies for a future work. The discussion about the combined variables was rewritten in order to improve the text. (Section 4.2 – lines: 309 – 472)

"The EL and DL parameters are calculated over 1-hour periods. Is this 1-hour timescale suitable during rapidly varying conditions such as during the morning growth of the boundary layer?" This question is asking whether a 1 hour timescale is suitable when, during the morning growth, a particular region may have been calm for 30 minutes, and then strongly turbulent for 30 minutes. If changing the timescales has an impact, then this is important information to include in the manuscript, e.g. how does the noise reduce the integral time scale, and is this SNR-dependent? The abstract states that there is "low influence of noise", so how can both of these statements be correct?

We thank the Reviewer 2 for this comment. The time interval of 1-hour provided us values of integral time scale, considerably higher than 2 s in all situations demonstrated in the main document.

The figure 1 presents the variation of integral time scale to different time intervals. It is possible to observe the influence of interval duration. Thus, as time interval increases, the integral time scale also increases, and only with 1 hour of time interval, all points in integral time scale are at least ten times higher than DL time acquisition. Thus, we keep the study based on 1-hour timescale in order to obtain reliable analyses although in some cases we can miss faster changes of the PBL.



Supplementary Material - Figure 1 – Integral Time Scale obtained from

The influence of noise is shown in figure 5 of the main document. As can be seen there the uncorrected profiles present some underestimation and in this way the application of the corrections, mainly the first lag correction, solve this underestimation.

"What is the impact if you change the averaging period, and why was 1-hour chosen when the MWR data are averaged over 30 minutes?". The authors state that using a different timescale for MWR parameters does not interfere in the analysis, yet the focus is the synergistic combination of the various retrievals? The MWR retrieval is much smoother in time than the lidar retrievals, so what is the likely impact when combining them?

We thank the Reviewer 2 for this comment. The value of $PBLH_{MWR}$ is not combined with high frequency variables. It is only used as indicator of height of CBL and SBL in order to differentiate the sublayers in the PBL region.

The manuscript requires a much more rigorous but short description of the processes driving turbulent mixing in the boundary layer.

We thank the Reviewer 2 for this comment. This section was rewritten in order to improve the discussion. We expect that the new redaction solve the reviewer's criticism.

(lines 331-339)

"The skewness of w' ($S_{w'}$) is shown in Figure 11-C. The $S_{w'}$ is directly associated with the direction of turbulent movements. Thus, positive values (red regions) correspond with a surface-heating-driven boundary layer, while negative (blue regions) ones are associated to cloud-top long-wave radiative cooling. During the stable period, there is predominance of low absolute values of $S_{w'}$. Nevertheless, as air temperature increases (transition from stable to unstable period), $S_{w'}$ values begin to become larger. Air temperature begins to decrease around 18:00 UTC, and there is a reduction of $S_{w'}$, so that, the generation rate of convective turbulence decreases. Therefore, the turbulence cannot be maintained against dissipation, then the CBL becomes a SBL covered by the RL. So, the reduction observed in the $PBLH_{MWR}$ is due to the SBLH detection."

(lines 383-391)

"The positive values of S_{RCS} , observed in the lowest part of profile and above the $PBLH_{Elastic}$ represents the updrafts aerosol layers. The negative values of S_{RCS} , indicates the region with low aerosol concentration due to clean air coming from free troposphere (FT)."

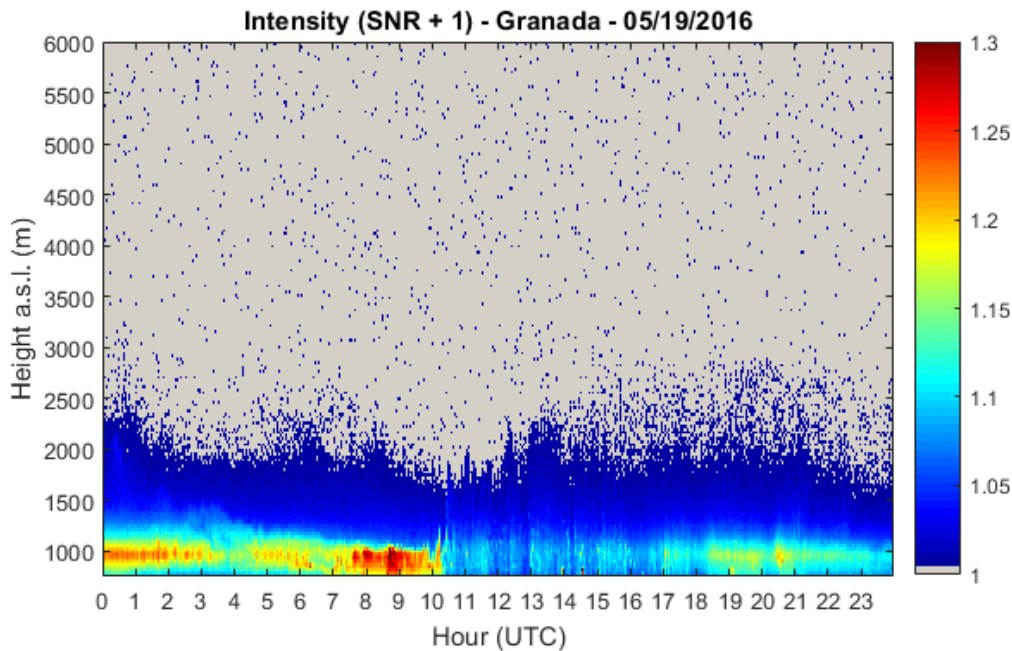
The response from the authors does not satisfy this requirement, is far too long, and contains many factual errors. For instance, air temperature is not directly related to RN and Sw' . The abstract states (lines 22-24) "Furthermore, we show how some meteorological variables such as air temperature, aerosol number density, vertical wind speed, relative humidity and net radiation might influence the turbulent PBL dynamic" but the main text does not discuss how any of these parameters influence the PBL, and in any case it is not clear to me how, in most situations, the aerosol number density would influence the turbulent PBL dynamic.

We thank the Reviewer 2 for this comment. Such text was removed from the document. We apologize for this misinterpretation.

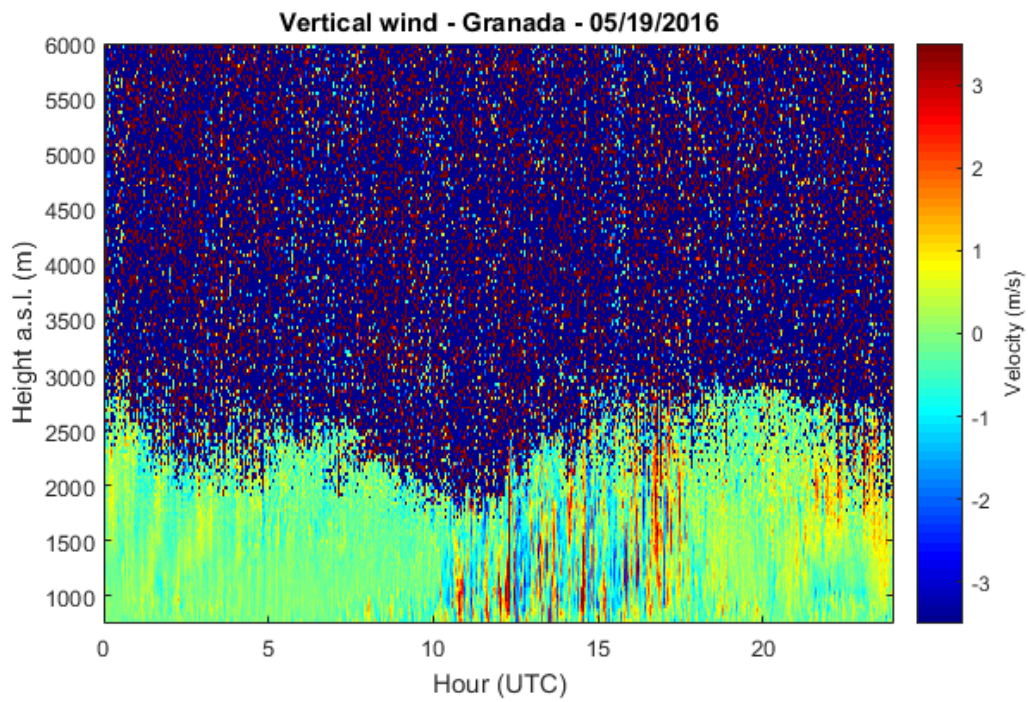
Minor comments

DL analysis: The time-height plots provided in the supplementary material are not satisfactory. The upper panel displays vertical velocity, not wind speed and appears to have been drastically smoothed or averaged compared to the lower panel, which is not backscatter but potentially attenuated backscatter. From the system configuration information provided by the authors (telescope focus) it is unlikely that the 'attenuated backscatter' field has been corrected for the telescope focus, hence the request to provide the signal (SNR+1) instead. Please plot both the vertical velocity and signal (SNR+1) at the original resolution without averaging. If you plot the SNR, you can then see that all velocity data above about 2 km is likely to be noise.

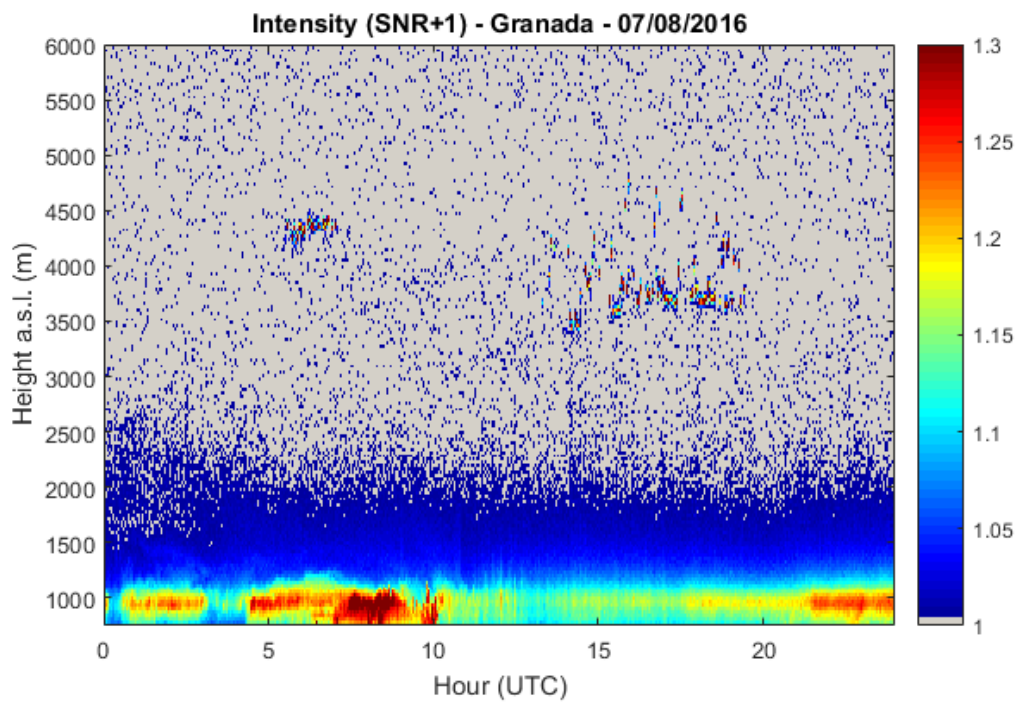
We thank the Reviewer 2 for this comment. In the figures 2-5, presented below, the background correction was applied (Manninen et al., 2016).



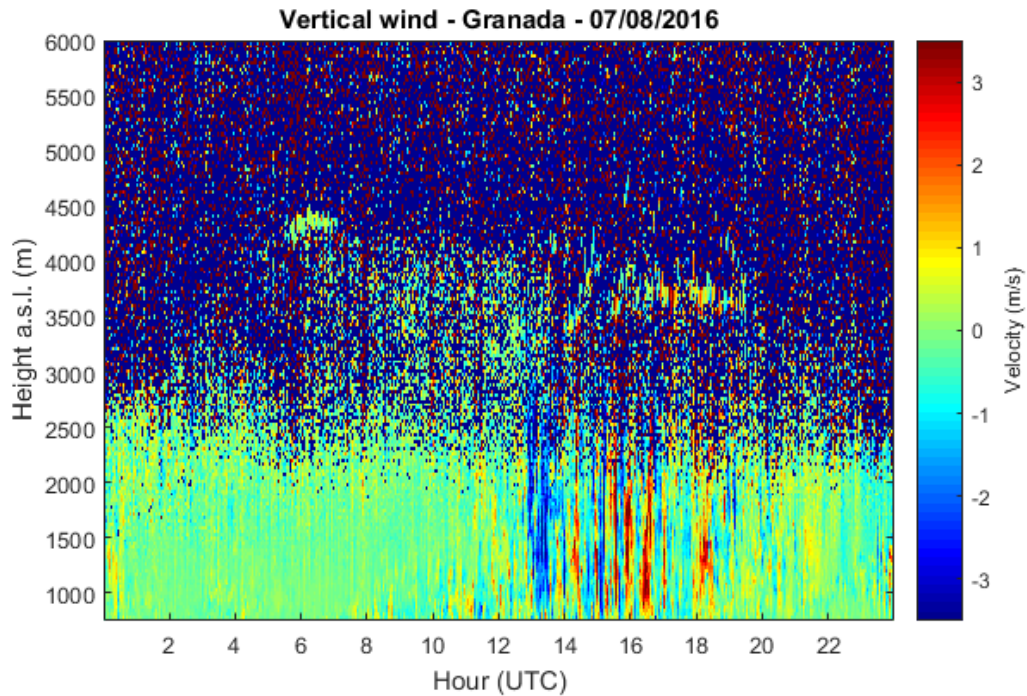
Supplementary Material - Figure 2 – Doppler lidar SNR+1 Intensity



Supplementary Material -Figure 3 – Vertical wind Speed obtained from Doppler lidar



Supplementary Material - Figure 4 – Doppler lidar SNR+1 Intensity



Supplementary Material - Figure 5 - Vertical wind speed obtained from Doppler lidar data

The criterion used to select the regions where our methodology presents valid results is based on the value of the integral time scale, as described in lines 296-298 of main document:

“The gray areas represents the region where τ_w , is lower than the acquisition time of DL and, therefore, in this region it is not possible to analyze the turbulent processes.”

Thus, despite the gray regions have values of vertical wind speed (supplementary material figures 3 and 5, respectively), these regions were disregarded in our analysis about turbulence because the values of integral time scale are lower than the acquisition time of the DL. This criterion has certain similarities with choosing velocities (supplementary material figures 3 and 5, respectively) with SNR+1 more than a certain threshold (supplementary material figures 2 and 4), as suggested by the referees.

"EL analysis: 'Is it safe to assume the two-way transmittance is negligible?' and 'what are the typical molecular, aerosol and total extinction values for the cases shown here?'" The two-way transmittance at a wavelength 532 nm is less than 0.98 by 2 km above sea level from molecular extinction alone. The AOD is also > 0.1 for 19th May 2016, and over 0.3 for 8th July 2016 (at a wavelength of 500 nm, from AERONET data). These values are not negligible. They may not be sufficient to impact the results, but whether this is the case should be discussed. Does this attenuation impact the noise characteristics and the integral time scale? The new figures 10 and 14 do not aid the interpretation and are not necessary for the manuscript.

We thank the Reviewer 2 for this comment. In order to clarify this point, we present in

the revised version of the manuscript the comparison between the analyses based on the use of the wavelengths 1064 and 532 nm, in the sub-section 4.1. In this discussion we use the analyses based on the wavelength of 1064 nm as a reference, considering the negligible influence of the extinction and the molecular component of the backscatter coefficient (figure 10). The comparison between the autocovariance functions derived for 1064 and 532 nm (figures 6 and 7, respectively) evidences the larger noise impact on the wavelength of 532 nm. This larger noise value is due to the impact of the molecular signal at 532 nm, but also in this case because of the extinction by aerosol up to this height. We have estimated two-way transmittances (accounting for both aerosol and molecules) for the two studied cases, obtaining 0.85 and 0.79 respectively.

This characteristic affects the values of high order moments present in figure 9, however, in the same picture is evidenced that the application of the proposed corrections, mainly first lag correction, can significantly reduce the influence of noise and provide results rather comparable to those obtained using the wavelength of 1064 nm in the turbulence analyses.

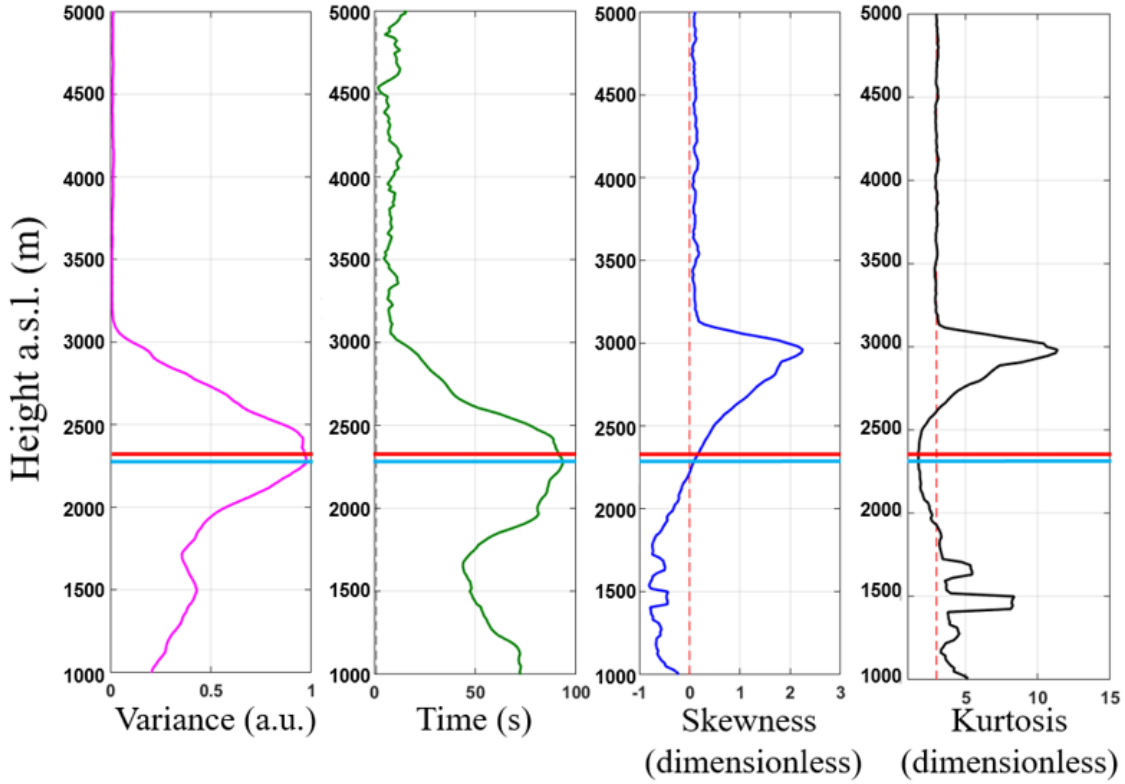
We included this discussion in the manuscripts, lines 282 – 288:

“It is evident the larger contribution of $\beta_{Aerosol}^{1064}$ to the total β at 1064 nm in comparison with the behavior at 532 nm, generating the higher values of noise at 532 nm in comparison with 1064 nm. This higher noise values are also due to higher extinction (by both aerosol and molecules) at 532 nm, producing a lower two-way transmittance. As we used Elastic lidar technique, we could not calculate aerosol extinction profiles, but an estimation of these transmittances was done on the basis of Klett method (Klett, 1985). With this method, a constant lidar ratio value was constrained for each profile using the AOD derived from a collocated AERONET Sun-photometer [Guerrero-Rascado et al., 2008]. Using these constrained lidar ratios, the transmittances were calculated together with aerosol backscatter profiles, integrated up to 2.5 km. The estimated two-way transmittance was 0.85 for the case analyzed in this subsection (19th May).”

Supplementary material, Figs. 5 and 6, do not show time-height plots, only two profiles, so it is still not possible to evaluate whether these parameters provide a reliable guide to the boundary layer development.

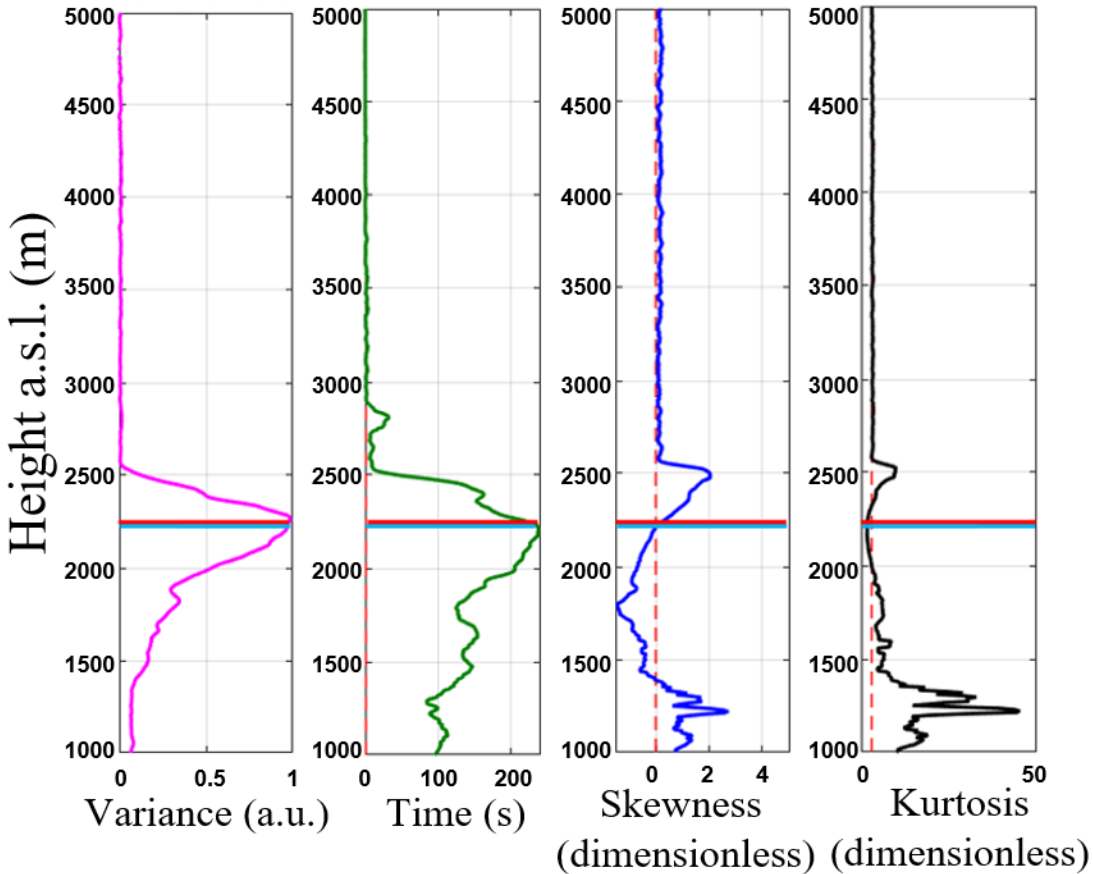
We thank the Reviewer 2 for this comment. In order to clarify this point we provided 4 hours (4 figures) of the profiles of high order moments.

From the variance profiles is possible to observe the evolution of top of aerosol layer ($PBLH_{Elastic}$), which is practically coincident with CBL height in the first two hours (Supplementary Material Figure 6 and Main document figure 7), but due to the presence of lofted aerosol layer at 14 UTC, the $PBLH_{Elastic}$ and CBL move away, as can be observed in main document figure 12. From the skewness profiles it is possible to follow the ascension of the entrainment zone (inflection point in skewness profile), as well as, the regions dominated by downdrafts and updrafts, which influence directly in the profiles of next hour. The kurtosis profiles show the variation of level of mixing, so that the region with low level of mixing due to entrainment of air from FT follows the ascension of PBL , as expected.



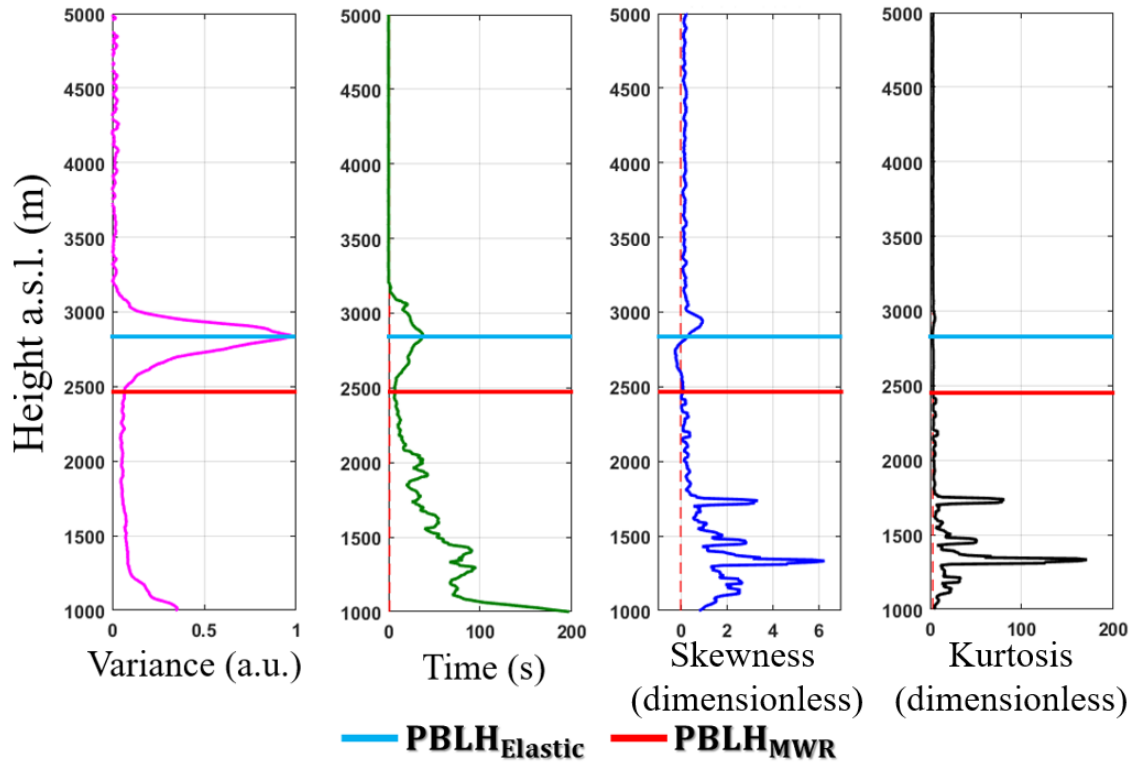
— PBLH_{Elastic} — PBLH_{MWR}

Supplementary Material - Figure 6 - Statistical moments obtained from elastic lidar data at 12 to 13 UTC - 19 May 2016. From left to right: variance [$\sigma_{RCS'}^2$], integral time scale [$\tau_{RCS'}$], skewness [$S_{RCS'}$] and kurtosis [$K_{RCS'}$].

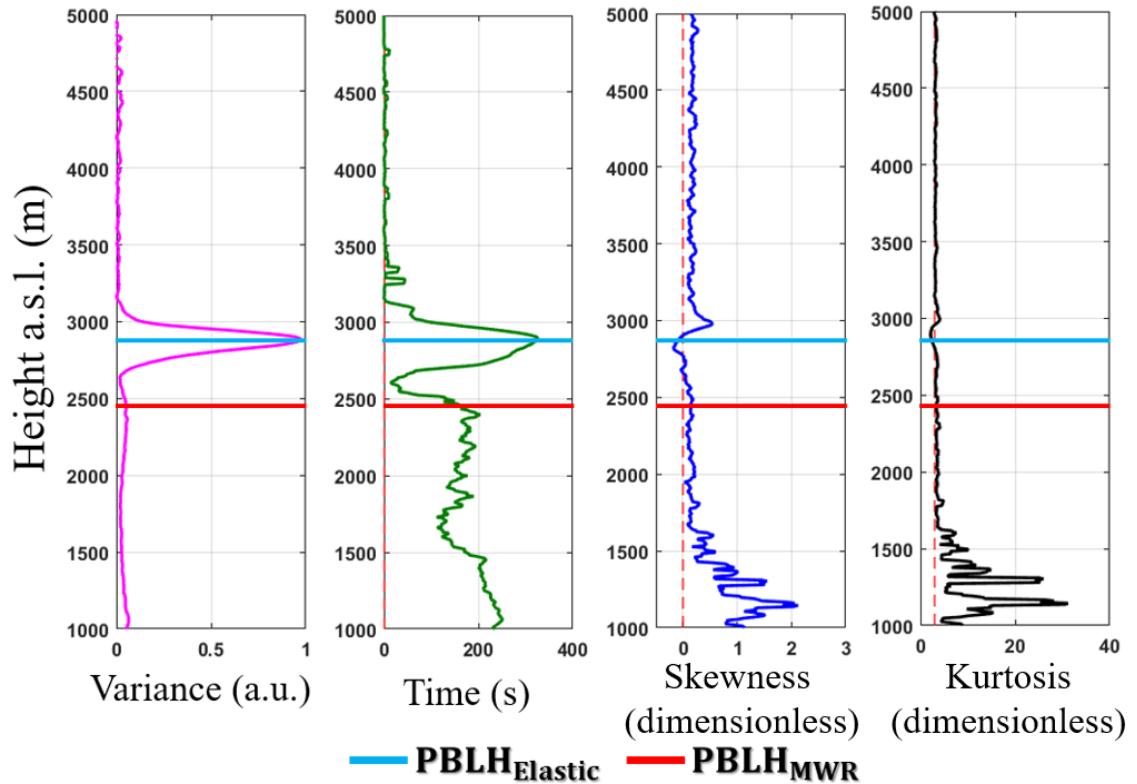


— PBLH_{Elastic} — PBLH_{MWR}

Figure 13 – Statistical moments obtained from elastic lidar data (Mulhacen) in Granada at 13 to 14 UTC - 19 May 2016. From left to right: variance [$\sigma_{RCS'}^2$], integral time scale [$\tau_{RCS'}$], skewness [$S_{RCS'}$] and kurtosis [$K_{RCS'}$].



Supplementary Material - Figure 7 - Statistical moments obtained from elastic lidar data at 14 to 15 UTC - 19 May 2016. From left to right: variance [$\sigma_{RCS'}^2$], integral time scale [$\tau_{RCS'}$], skewness [$S_{RCS'}$] and kurtosis [$K_{RCS'}$].



Supplementary Material - Figure 8 - Statistical moments obtained from elastic lidar data at 15 to 16 UTC - 19 May 2016. From left to right: variance [$\sigma_{RCS'}^2$], integral time scale [$\tau_{RCS'}$], skewness [$S_{RCS'}$] and kurtosis [$K_{RCS'}$].

Doppler lidar and Elastic lidar analysis: Since you make some effort to quantify the influence of noise on the statistical parameters derived from these two systems, it would be beneficial to discuss how this impacts your interpretation, e.g. include time-height plots of the correction factor or relative correction, relative importance in determining PBLH, how much temporal averaging is required to obtain good results. You state that your objective is 'to approach a synergetic combination', hence discussing how the influence of noise impacts your interpretation is vital, otherwise there is nothing new presented in this manuscript.

We thank the Reviewer 2 for this comment. In order to clarify this point the sub-section 4.1 have changed as follow:

“4.1 Error Analysis

The influence of random error in noisy observations rapidly grows for higher-order moments (i.e., the influence of random noise is much larger for the fourth-order moment than for the third-order moment). Therefore, the first step, in order to ascertain the applied methodology and our data quality, we performed the error treatment of DL data as described in Figure 2. For the DL analysis we selected the period 08-09 UTC of 19th May, the same day that presented in Case Study 1. This day is characterized by a well-defined PBL.

Figure 4 illustrates the autocovariance function, generated from w' , at three different heights. As mentioned before, the lag 0 is contaminated by noise (ε), and thus the impact of the ε increases together with height, mainly above $PBLH_{MWR}$ (1100 m a.g.l. in our example).

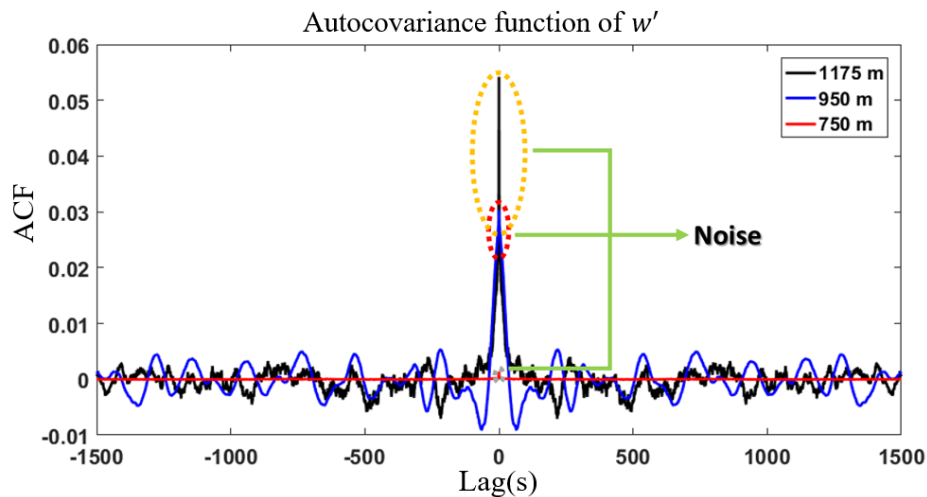


Figure 4 – Autocovariance function (ACF) of w' , obtained from Doppler lidar at three different heights on 19th May 2016 at 08-09 UTC in Granada.

Figure 5-A illustrates the comparison between integral time scale ($\tau_{w'}$) without correction and the two corrections cited in section 3.2. Except for the first height, under the $PBLH_{MWR}$ the profiles have little differences, as well as small errors bars. Above the $PBLH_{MWR}$ the first lag correction presents higher differences in relation the other profiles at around 1350 m.

Figures 5-B and 5-C show the comparison of variance ($\sigma_{w'}^2$) and skewness ($S_{w'}$), respectively, with and without corrections. The profiles corrected by -2/3 law do not present significant differences in comparison to uncorrected profiles. On the other hand, the profiles corrected by the first lag correction have some slight differences under the PBLH_{MWR}, mainly the $\sigma_{w'}^2$ ($S_{w'}$ only in the first 50 m). Therefore, although the presence of ε can change slightly the value of high order moments, it is not enough to distort the observed phenomena, what can be proven by the corrections applied.

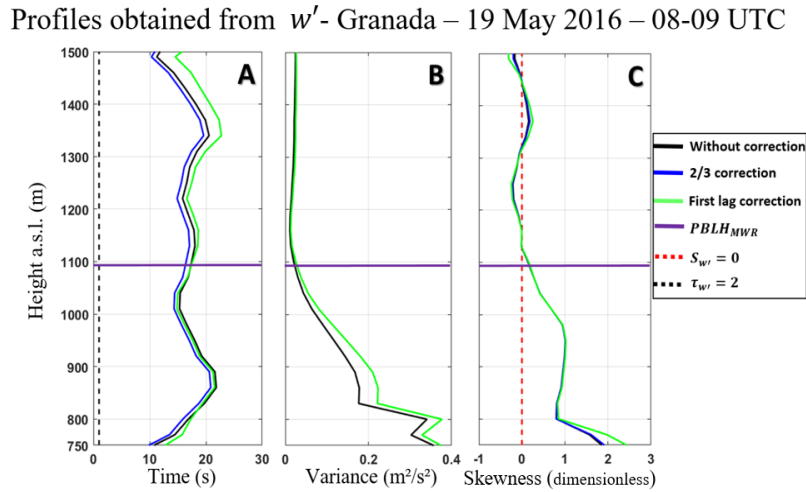


Figure 5 – A - Vertical profile of Integral time scale ($\tau_{w'}$). B - Vertical profile of variance ($\sigma_{w'}^2$). C - Vertical profile of Skewness ($S_{w'}$). All profiles were obtained from Doppler lidar data on 19th May

For EL we use the same procedure for the correction and error analysis that we apply to the DL data. The same day was chosen (19th May), however the period selected is between 12 and 13 UTC, due to the incomplete overlap of Mulhacen lidar. In this sense, we studied the influence of noise at two wavelengths: 1064 nm, that has been previously analyzed by Pal et al. (2010) as presented in the section 2 and adopted as reference (considering the rather low impact of molecular signal and the two ways transmittance shown in 9) and 532 nm, just in order to check the feasibility of this wavelength for turbulence studies considering its spread use in observation network with higher reliability than 1064 nm. Figures 6 and 7 shows the autocovariance function, obtained from RCS'_{1064} and RCS'_{532} , respectively, at three distinct heights. As expected, in both cases the increase of height produces the increase of ε , principally above the PBLH_{MWR}. However, the wavelength 532 nm is more influenced by the noise, what can be verified by the higher peak at lag 0 in figure 7, in comparison with peaks at same lag in figure 6.

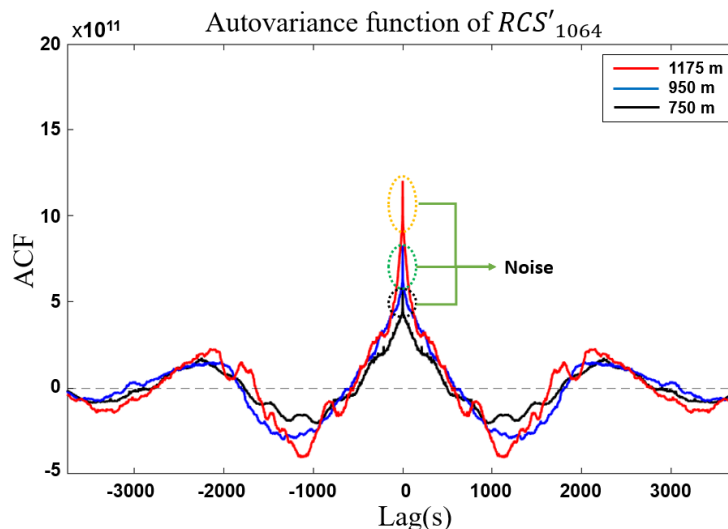


Figure 6 – Autocovariance of RCS'_{1064} obtained from Mulhacen elastic lidar data to three different heights on 19th May 2016 at 12-13 UTC in

Figure 8-A shows the profiles corresponding to molecular backscatter coefficient, $\beta_{\text{Molecular}}$, and backscatter coefficient, β , at 1064 nm ($\beta_{\text{Molecular}}^{1064}$ and $\beta_{\text{Molecular}}^{1064} + \beta_{\text{Aerosol}}^{1064}$, respectively), while figure 8-B shows the same group of profiles at 532 nm ($\beta_{\text{Molecular}}^{532}$ and $\beta_{\text{Molecular}}^{532} + \beta_{\text{Aerosol}}^{532}$). It is evident the larger contribution of $\beta_{\text{Aerosol}}^{1064}$ to the total β at 1064 nm in comparison with the behavior at 532 nm, generating the higher values of noise at 532 nm in comparison with 1064 nm. This higher noise values are also due to higher extinction (by both aerosol and molecules) at 532 nm, producing a lower two-way transmittance. As we used Elastic lidar technique, we could not calculate aerosol extinction profiles, but an estimation of these transmittances was done on the basis of Klett method (Klett, 1985). With this method, a constant lidar ratio value was selected for each profile so that the corresponding AOD coincided with AERONET retrieval. Once we had those optimal lidar ratio values, although approximated, the transmittances were calculated together with aerosol backscatter profiles, integrated up to 2.5 km. The estimated two-way transmittance was 0.85 for the case analyzed in this subsection (19th May).

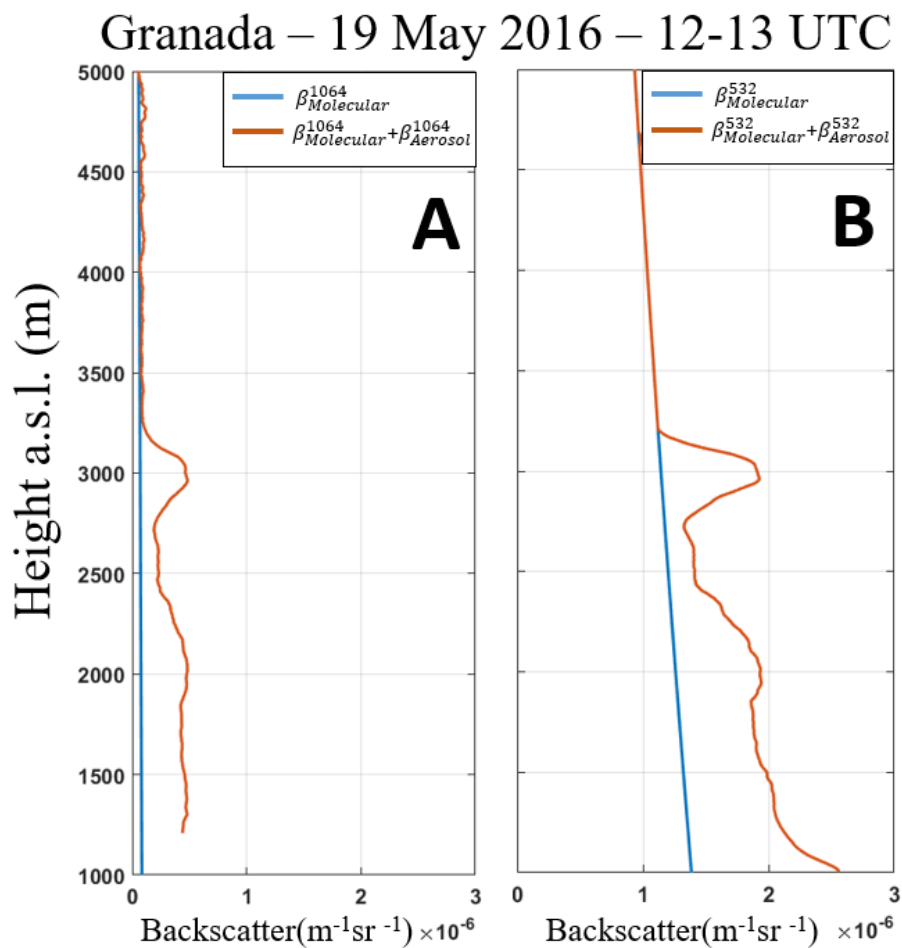


Figure 8 – (A) $\beta_{\text{Molecular}}^{1064}$ (blue line) and $\beta_{\text{Molecular}}^{1064} + \beta_{\text{Aerosol}}^{1064}$ (orange line). (B) $\beta_{\text{Molecular}}^{532}$ (blue line) and $\beta_{\text{Molecular}}^{532} + \beta_{\text{Aerosol}}^{532}$ (orange line). All profiles were obtained from Mulhacen elastic lidar data on 19th May 2016 between 12-13 UTC in Granada.

Figures 9-A, 9-B, 9-C and 9-D show the vertical profiles of $\tau_{RCS'}$, $\sigma_{RCS'}^2$, $S_{RCS'}$, and kurtosis ($K_{RCS'}$), respectively, obtained at 1064 nm, with and without the corrections described in section 3.2. In general, the corrections do not affect the profiles generated from 1064 nm data in a significant way, so that, the higher influence of corrections is observed in the $K_{RCS'}$ profile, which is underestimated in some regions. In the figures 10-A, 10-B, 10-C and 10-D we show same high order moments calculated from 532 nm data. As the complexity of moments increases, it is possible to observe the higher influence of corrections, due to propagation of noise. Nonetheless, the application of the corrections, mainly first lag correction, make these profiles very similar to those generated from the wavelength 1064 nm, so that the same phenomena can be observed in both. This evidences the necessity of applying the corrections, especially the first lag correction, when using the elastic signal at 532 nm in turbulence studies.

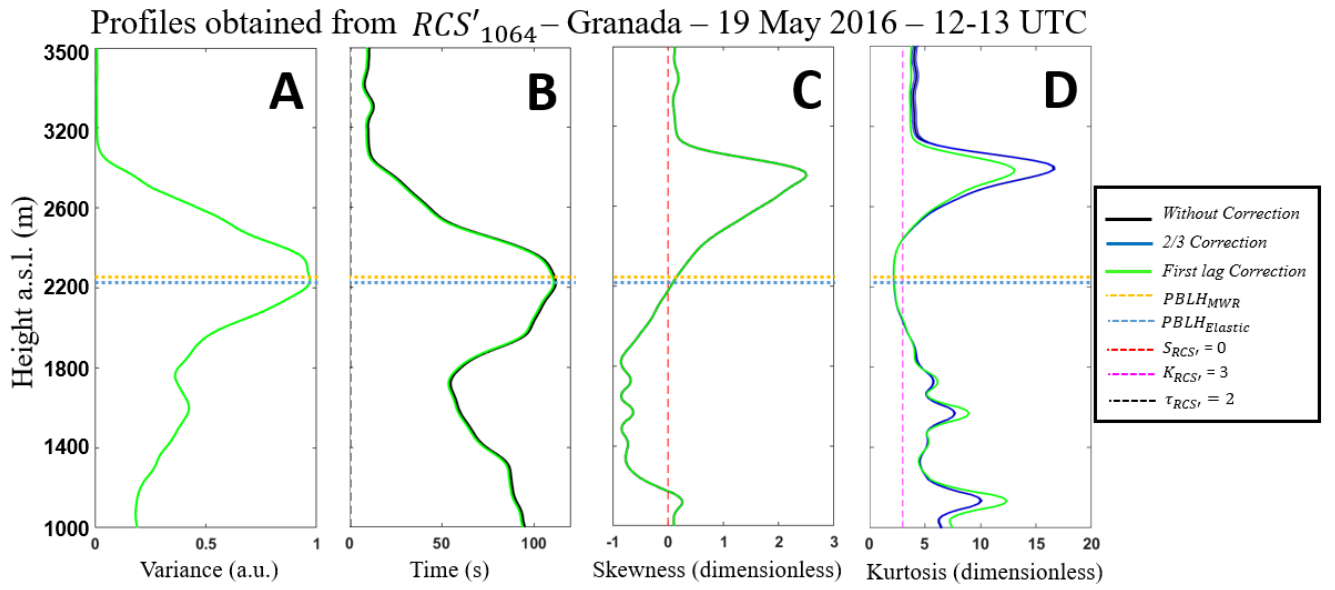


Figure 9 – A-Vertical profile of Integral time scale ($\tau_{RCS'}$). B - Vertical profile of variance ($\sigma_{RCS'}^2$). C - Vertical profile of Skewness ($S_{RCS'}$). D - Vertical profile of Kurtosis ($K_{RCS'}$). All profiles were obtained from Mulhacen elastic lidar data on 19th May 2016 in Granada between 12-13 UTC.

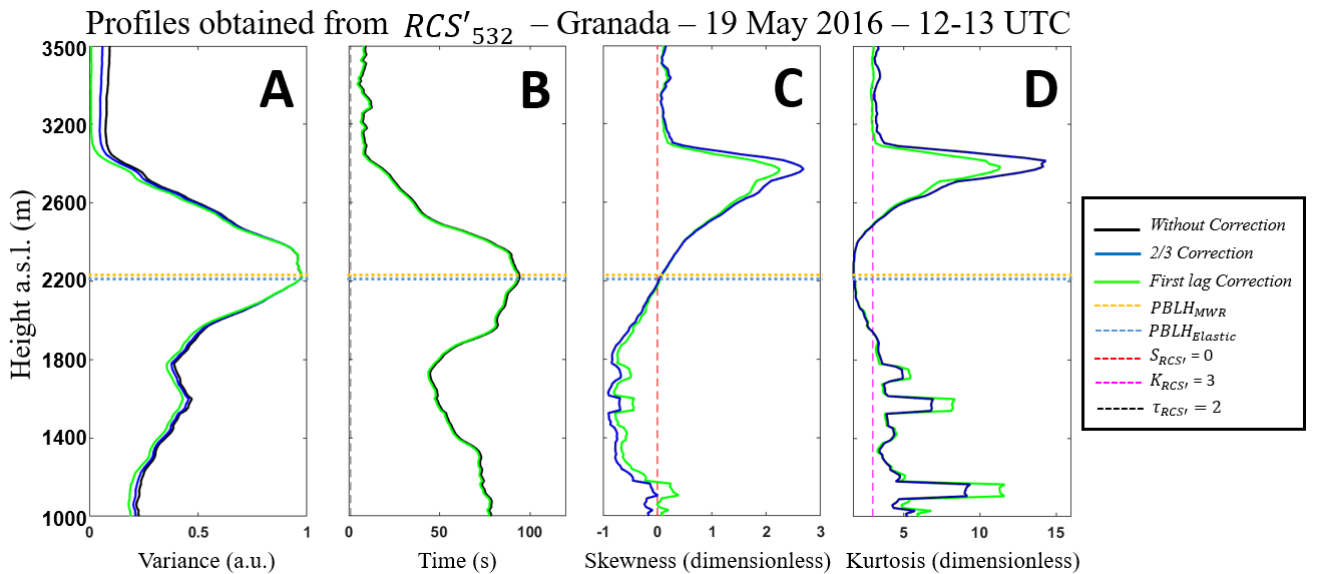


Figure 10 – A-Vertical profile of Integral time scale ($\tau_{RCS'}$). B - Vertical profile of variance ($\sigma_{RCS'}^2$). C - Vertical profile of Skewness ($S_{RCS'}$). D - Vertical profile of Kurtosis ($K_{RCS'}$). All profiles were obtained from Mulhacen elastic lidar data on 19th May 2016 in Granada between 12-13 UTC.

Therefore, in spite of the larger attenuation expected at 532 nm wavelength due to relevant percentage of $\beta_{\text{Molecular}}$ in its composition, which generates noisier profiles in comparison with that ones generated from the reference wavelength, the application of the proposed corrections, mainly the first lag, reduce significantly the influence of noise and enable the observation of the same phenomena detected in the high-order moments obtained from 1064 nm. Consequently, the wavelength 532 nm will be applied in the analysis presented in section 4.2. Due to the first lag correction generates a higher impact on the without correction profiles, we adopted such correction in order to be more careful in the analyses of high-order moments obtained from DL and EL data.”

Case study 2: Did you try cloud-screening EL data before calculating EL parameters? The PBLH from EL would agree much better with PBLH from MWR in Figure 13, and maybe Figure 14 (it is hard to tell with the scales used). Clouds should also be visible in DL data. The authors response is "No, any cloud-screening method was not applied before calculating the EL parameters". What happens if you do attempt a simple cloud screening procedure. This is simple to apply and would presumably be used in any synergetic combination?

We thank the Reviewer 2 for this comment. The problem with PBLH detection by EL in case two is not only because of the clouds, but mainly due to the presence of a Saharan dust layer. As we observe in the manuscript, the usual algorithms for PBLH detection do not work well for these cases. It is shown, for example by Bravo-Aranda et al. (2017), that more sophisticated methods using depolarization information may be able to improve this detection. However, it was not the scope of the present work, since we wanted to show the potential of usual 522 nm EL in the different networks (although they have no depolarization channels).

The cloud-screening algorithms may also give not correct results in this case, where the detected cloud might actually be a more intense dust layer. As suggested by referee, we tried with a simple cloud screening procedure, but it marked as clouds some regions that might not be. We checked this information with AERONET cloud screening (as independent validation) at the same time intervals, and the comparison was confusing.

This analysis reinforces the main idea of this paper, that the combination of different instruments and methods is needed for the study of such complex cases. Moreover, it is shown that with the PBLH detection of the different systems we can separate different layers (e.g. the dust layer from the actual CBL).

If the DL telescope focus is set to 800 m then what method do you use to obtain attenuated backscatter profiles from the (SNR + 1) profile? Therefore, in the supplementary material it would be more appropriate to present the time-height plots of vertical velocity and (SNR + 1), which was what was originally requested.

We thank the Reviewer 2 for this comment. We have not yet implement any focus correction for the DL, as this is not relevant for the retrieved velocities although it is for the attenuated backscatter. Thus, as suggested, intensity (SNR + 1) profiles were included instead of attenuated backscatter.

Line 32: How do the variables interfere in the process?

Lines 40-42: Please check and reformulate these sentences. Surface heating is still unlikely to directly impact the upper troposphere. The convective boundary layer does not reach the upper troposphere.

We thank the Reviewer 2 for this comment. Such text was removed from the document. We apologize for this misinterpretation.

Lines 226-229: The methodologies are not used synergistically, even though this is the focus of the paper, and it is not shown or discussed how each variable 'influences' the turbulent PBL behaviour.

We thank the Reviewer 2 for this comment. In order to clarify this point, as mentioned above, the term “synergy” was changed to “combination”, because we believe that the results of different instruments are complementary. From the combination of the results we retrieved a detailed picture on the *PBL* turbulent features.

Many of the figures still have very short captions without enough information. Please include the instrument name, date and the location in the caption.

We thank the Reviewer 2 for this comment. In order to clarify this point, all figures mentioned below have its captions changed.

Figure 4: Is this autocovariance from DL?

We thank the Reviewer 2 for this comment. In order to clarify this point the caption of this picture was changed as follow:

“Autocovariance function (ACF) of w' , obtained from Doppler lidar at three different heights on 19th May 2016 at 08-09 UTC in Granada.”

Figures 5,7: Profiles from which instrument, and from which location? At what time, and on what day? What height is the surface? Please include this information in the caption

Figures 5, 7-10,12-14: The captions do not state which instrument the data comes from. Please include the instrument names and the location in the caption. Where applicable, state which data comes from which instrument.

Figures 11, 15, 16: The caption states 'elastic lidar data'. Please include the instrument name and the location in the caption.

We thank the Reviewer 2 for these comments. In order to clarify this point the captions of these figures, that now have new numbers, and that have been changed as follows:

Figure 6 – Autocovariance of RCS'_{1064} obtained from Mulhacen elastic lidar data to three different heights on 19th May 2016 at 12-13 UTC in Granada.

Figure 10 – A- Vertical profile of Integral time scale ($\tau_{RCS'}$). B - Vertical profile of variance ($\sigma_{RCS'}^2$). C - Vertical profile of Skewness ($S_{RCS'}$). D - Vertical profile of Kurtosis

(K_{RCS}). All profiles were obtained from Mulhacen elastic lidar data on 19th May 2016 in Granada between 12-13 UTC.

Figure 11 – A – integral time scale obtained from Doppler lidar data [$\tau_{w'}$], B – variance obtained from Doppler lidar data [$\sigma_{w'}^2$], C – skewness obtained from Doppler lidar data [$S_{w'}$], D – net radiation obtained from pyranometer data [R_n], E – Air surface temperature [blue line] and surface relative humidity [RH - orange line] both were obtained from surface sensors. All profiles were acquired on 19th May 2016 in Granada. In A, B and C black lines and white stars represent air temperature and $PBLH_{MWR}$, respectively.

Figure 12 – Time-Height plot of RCS obtained on 19 May 2016 in Granada. Pink stars represent the $PBLH_{MWR}$, black stars represent the $PBLH_{Elastic}$ and blue stars represent the $PBLH_{Doppler}$.

Figure 13 – Statistical moments obtained from 532 nm wavelength data of elastic lidar (Mulhacen) in Granada at 13 to 14 UTC - 19 May 2016. From left to right: variance [$\sigma_{RCS'}^2$], integral time scale [$\tau_{RCS'}$], skewness [$S_{RCS'}$] and kurtosis [$K_{RCS'}$].

Figure 15 - A – integral time scale from Doppler lidar data [$\tau_{w'}$], B – variance from Doppler lidar data [$\sigma_{w'}^2$], C – skewness from Doppler lidar data [$S_{w'}$], D – net radiation from pyranometer data [R_n], E – Air surface temperature [blue line] and surface relative humidity [RH – orange line] from surface sensor data. All profiles were obtained in Granada on 08 July 2016. In A, B and C black lines and white stars represent air temperature and $PBLH_{MWR}$, respectively.

Figure 16 – Time-Height plot of RCS obtained from Mulhacen elastic lidar data on 08 July 2016 in Granada. Pink stars represent the $PBLH_{MWR}$, black stars represent the $PBLH_{Elastic}$ and blue stars represent the $PBLH_{Doppler}$.

Figure 17 - Statistical moments obtained from 532 nm wavelength data of elastic lidar (Mulhacen) in Granada between 11-12 UTC on 08th July 2016. From left to right: variance [$\sigma_{RCS'}^2$], integral time scale [$\tau_{RCS'}$], skewness [$S_{RCS'}$] and kurtosis [$K_{RCS'}$].

Figure 19 - Statistical moments obtained from 532 nm wavelength data of elastic lidar (Mulhacen) in Granada between 12 -13 UTC on 08 July 2016. From left to right: variance [$\sigma_{RCS'}^2$], integral time scale [$\tau_{RCS'}$], skewness [$S_{RCS'}$] and kurtosis [$K_{RCS'}$].

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Analyzing the turbulent Planetary Boundary Layer by remote sensing systems: Doppler wind lidar, aerosol elastic lidar and microwave radiometer

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Abstract

The Planetary Boundary Layer (*PBL*) is the lowermost region of troposphere and endowed with turbulent characteristics, which can have mechanical and/or thermodynamic origins. Such behavior gives to this layer great importance, mainly in studies about pollutant dispersion and weather forecasting. However, the instruments usually applied in studies about turbulence in the *PBL* have limitations in spatial resolution (anemometer towers) or temporal resolution (instrumentation onboard aircraft). Ground-based remote sensing, both active and passive, offers an alternative for studying the *PBL*. In this study we show the capabilities of combining different remote sensing systems (microwave radiometer [*MWR*], Doppler lidar [*DL*] and elastic lidar [*EL*]) for retrieving a detailed picture on the *PBL* turbulent features. The statistical moments of the high frequency distributions of the vertical wind velocity, derived from *DL* and of the backscattered coefficient derived from *EL*, are corrected by two methodologies, namely first lag and -2/3 correction. The corrected profiles, obtained from *DL* data, present small differences when compared against the uncorrected profiles, showing the low influence of noise and the viability of the proposed methodology. Concerning *EL*, in addition to analyze the influence of noise, we explore the use of different wavelengths that usually include *EL* systems operated in extended networks, like EARLINET, LALINET, MPLNET or SKYNET. In this way we want to show the feasibility of extending the capability of existing monitoring networks without strong investments or changes in their measurements protocols. Two case studies were analyzed in detail, one corresponding to a well-defined *PBL* and another one corresponding to a situation with presence of a Saharan dust lofted aerosol layer and clouds. In both cases we discuss results provided by the different instruments showing their complementarity and the cautions to be applied in the data interpretation. Our study shows that the use of *EL* at 532nm requires a careful correction of the signal using the first lag time correction in order to get reliable turbulence information on the *PBL*.

Keywords: Turbulence, Planetary Boundary Layer, Doppler lidar, elastic lidar, microwave radiometer, Earlinet.

38 1 Introduction

39 The Planetary Boundary Layer (*PBL*) is the atmospheric layer directly influenced by the Earth's surface
40 that responds to its changes within time scales around an hour (Stull, 1988). Such layer is located at the
41 lowermost region of troposphere, and is mainly characterized by turbulent processes and a daily evolution
42 cycle. In an ideal situation, instants after sunrise, ground surface temperature increase due to the positive
43 net radiative flux (R_n). This process intensifies the convection, thus, the ascending warm air masses heat
44 the air masses aloft, originating the Convective Boundary Layer (*CBL*) or Mixing Layer (*ML*), which has
45 this name due to a mixing process generated by this turbulent ascending air parcels. Slightly before sunset
46 the gradual reduction of incoming solar irradiance at the Earth's surface causes the decrease of the positive
47 R_n and its change in sign. In this situation, there is a reduction of the convective processes and a weakening
48 of the turbulence. In this process the *CBL* leads to the development of two layers, namely a stably stratified
49 boundary layer called Stable Boundary Layer (*SBL*) close to the surface, and the Residual Layer (*RL*) that
50 contains features from the previous day's *ML* and is just above the *SBL*.

51 Knowledge of the turbulent processes in the *CBL* is important in diverse studies, mainly for atmospheric
52 modeling and pollutant dispersion, since turbulent mixing can be considered as the primary process by
53 which aerosol particles and other scalars are transported vertically in atmosphere. Because turbulent
54 processes are treated as nondeterministic, they are characterized and described by their statistical properties
55 (high order statistical moments). When applied to atmospheric studies such analysis provide information
56 about the field of turbulent fluctuation, as well as, a description of the mixing process in the *PBL* (Pal et
57 al., 2010).

58 Anemometer towers have been widely applied in studies about turbulence (e.g., Kaimal and Gaynor, 1983;
59 van Ulden and Wieringa, 1996), however the limited vertical range of these equipment restrict the analysis
60 to regions close to surface. Aircraft have also been used in atmospheric turbulence studies (e.g., Lenschow
61 et al., 1980; Williams and Hacker, 1992; Lenschow et al., 1994; Albrecht et al., 1995; Stull et al., 1997;
62 Andrews et al., 2004; Vogelmann et al., 2012), nevertheless their short time window limits the analysis. In
63 this scenario, systems with high spatial and temporal resolution and enough range are necessary in order to
64 provide more detailed results along the day throughout the whole thickness of the *PBL*.

65 In the last decades, lidar systems have been increasingly applied in this kind of study due to their large
66 vertical range, high data acquisition rate and capability to detect several observed quantities such as vertical
67 wind velocity [Doppler lidar] (e.g. Lenschow et al., 2000; Lothon et al., 2006; O'Connor et al., 2010), water
68 vapor [Raman lidar and DIAL] (e.g. Wulfmeyer, 1999; Kiemle et al., 2007; Wulfmeyer et al., 2010; Turner
69 et al., 2014; Muppa et al., 2015), temperature [rotational Raman lidar] (e.g. Behrendt et al., 2015) and
70 aerosol [elastic lidar] (e.g. Pal et al., 2010; McNicholas et al., 2015). This allows the observation of a wide
71 range of atmospheric processes. For example, Pal et al. (2010) demonstrated how the statistical analyses
72 obtained from high-order moments of elastic lidar can provide information about aerosol plume dynamics
73 in the *PBL* region. In addition, when different lidar systems operate synergistically, as for example in
74 Engelmann et al. (2008), who combined elastic and Doppler lidar data, it is possible to identify very
75 complex variables such as vertical particle flux.

76 Different works (Ansmann et al., 2010; O'Connor et al., 2010) have evidenced the feasibility for
77 characterizing the *PBL* turbulence by *DL*. Pal et al. (2010) have shown the feasibility for retrieving
78 information on the *PBL* turbulence from high high-order moments of elastic lidar operating at 1064. Such
79 approaches are even more attractive when considering facilities of networks, e. g. European Aerosol
80 Research Lidar NETwork (EARLINET) (Pappalardo et al., 2014), Microwave Radiometer Network
81 (MWRNET) (Rose et al., 2005; Caumont et al., 2016) and ACTRIS CLOUDNET (Illingworth et al., 2007).
82 For these reasons, and having in mind the wide spread of elastic lidar systems operated at other wavelengths,
83 like 532 nm or 355 nm, it would be worthy test the feasibility of these other wavelengths in the
84 characterization of the *PBL* turbulent behavior.

85 The use of simple techniques, applied to the aforementioned remote systems provide robust and similar
86 information on the convective *PBL* height, *PBLH* (see for example Moreira et al, 2018), or a
87 complementary information when the *CBL* is substituted by the presence of the *SBL* and the *RL* (Moreira
88 et al., in preparation). Thus, the combination of information obtained from the active remote sensing
89 systems, *DL* and *EL*, acquired with a temporal resolution close to 1 s, and that provided by *MWR* can
90 provide a detailed understanding about different features of the *PBL*, like structure (*CBL* versus *SBL* and
91 *RL*), height of the layers, rate of growth of the *PBLH* and turbulence.

92 In this study we show the feasibility of obtaining a clear insight on the *PBL* behavior using a combination
93 of active and passive remote sensing systems (Elastic Lidar [*EL*], Doppler Lidar [*DL*] and Microwave
94 Radiometer [*MWR*]) acquired during the SLOPE-I campaign, held at IISTA-CEAMA (Andalusian Institute
95 for Earth System Research, Granada, Spain) from May to August 2016. One of the goals is to show the
96 feasibility of using *EL* at 532 nm, considering the larger reliability of the measurements at this wavelength.

97 This paper is organized as follows. Description of the experimental site and the equipment setup are
98 presented in Section 2. The methodologies applied are introduced in Section 3. Section 4 presents the results
99 of the analyses using the different methodologies. Finally, conclusions are summarized in Section 5.

100

101 2 Experimental site and instrumentation

102 The SLOPE-I (Sierra Nevada Lidar Aerosol Profiling Experiment) campaign was performed from May to
103 September 2016 in South-Eastern Spain in the framework of the European Research Infrastructure for the
104 observation of Aerosol, Clouds, and Trace gases (ACTRIS). The main objective of this campaign was to
105 perform a closure study by comparing remote sensing system retrievals of atmospheric aerosol properties,
106 using remote systems operating at the Andalusian Institute of Earth System Research (IISTA-CEAMA)
107 and in-situ measurements operating at different altitudes in the Northern slope of Sierra Nevada, around 20
108 km away from IISTA-CEAMA (Bedoya-Velásquez et al., 2018; Román et al., 2018). The IISTA-CEAMA
109 station is part of EARLINET (Pappalardo et al, 2014) since 2005 and at present is an ACTRIS station
110 (<http://actris2.nilu.no/>). The research facilities are located at Granada, a medium size city in Southeastern
111 Spain (Granada, 37.16°N, 3.61°W, 680 m a.s.l.), surrounded by mountains and with Mediterranean-

112 continental climate conditions that are responsible for cool winters and hot summers. Rain is scarce,
113 especially from late spring to early autumn. Granada is affected by different kind of aerosol particles locally
114 originated and medium-long range transported from Europe, Africa and North America (Lyamani et al.,
115 2006; Guerrero-Rascado et al., 2008, 2009; Titos et al., 2012; Navas-Guzmán et al., 2013; Valenzuela et
116 al., 2014, Ortiz-Amezcuca et al., 2014, 2017).

117 MULHACEN is a biaxial ground-based Raman lidar system operated at IISTA-CEAMA in the frame of
118 EARLINET research network. This system operates with a pulsed Nd:YAG laser, frequency doubled and
119 tripled by Potassium Dideuterium Phosphate crystals, emitting at wavelengths of 355, 532 and 1064 nm
120 with output energies per pulse of 60, 65 and 110 mJ, respectively. MULHACEN operates with three elastic
121 channels: 355, 532 (parallel and perpendicular polarization) and 1064 nm and three Raman-shifted
122 channels: 387 (from N₂), 408 (from H₂O) and 607 nm (from N₂). MULHACEN's overlap is complete at
123 90% between 520 and 820 m a.g.l. for all the wavelengths, reaching full overlap around 1220 m a.g.l.
124 (Navas-Guzmán et al., 2011; Guerrero-Rascado et al. 2010). Calibration of the depolarization capabilities
125 is done following Bravo-Aranda et al. (2013). This system was operated with a temporal and spatial
126 resolution of 2 s and 7.5 m, respectively. More details can be found at Guerrero-Rascado et al. (2008, 2009).

127 The Doppler lidar (Halo Photonics, model Stream Line XR) is also operated at IISTA-CEAMA. This
128 system works in continuous and automatic mode from May 2016. It operates at 1.5 μm with pulse energy
129 and repetition rate of 100 μJ and 15 KHz, respectively. This system record the backscattered signal with
130 300 gates, being the range gate length 30 m, with the first gate at 60 m. The telescope focus is set to
131 approximately 800 m. For this work the data were collected in stare mode (laser beam is pointed at vertical
132 with respect to the ground surface) with a time resolution of 2 s.

133 Furthermore, we operated the ground-based passive microwave radiometer (RPG-HATPRO G2,
134 Radiometer Physics GmbH), which is member of the MWRnet [<http://cetemps.aquila.infn.it/mwrnet/>]. This
135 system operates in automatic and continuous mode at IISTA-CEAMA since November 2011. The
136 microwave radiometer (MWR) measures the sky brightness temperature with a radiometric resolution
137 between 0.3 and 0.4 K root mean square error at 1 s integration time, using direct detection receivers within
138 two bands: K-band (water vapor – frequencies: 22.24 GHz, 23.04 GHz, 23.84 GHz, 25.44 GHz, 26.24 GHz,
139 27.84 GHz, 31.4 GHz) and V-band (oxygen – frequencies: 51.26 GHz, 52.28 GHz, 53.86 GHz, 54.94 GHz,
140 56.66 GHz, 57.3 GHz, 58.0 GHz). From these bands is possible to obtain profiles of water vapor and
141 temperature, respectively, by inversion algorithms described in Rose et al. (2005). The range resolution of
142 these profiles vary between 10 and 200 m in the first 2 km and between 200 and 1000 m in the layer between
143 2 and 10 km (Navas-Guzmán et al., 2014).

144 The meteorological sensor (HMP60, Vaisala) is used to register the air surface temperature and surface
145 relative humidity, with a temporal resolution of 1 minute. Relative humidity is monitored with an accuracy
146 of ± 3%, and air surface temperature is acquired with an accuracy and precision of 0.6° C and 0.01° C,
147 respectively.

148 A CM-11 pyranometer manufactured by Kipp&Zonen (Delft, The Netherlands) is also installed in the
149 ground-based station. This equipment measures the shortwave (SW) solar global horizontal irradiance data

150 (305–2800 nm). The CM-11 pyranometer complies with the specifications for the first-class WMO (World
151 Meteorological Organization) classification of this instrument (resolution better than $\pm 5 \text{ Wm}^{-2}$), and the
152 calibration factor stability has been periodically checked against a reference CM-11 pyranometer (Antón
153 et. al, 2012).

154 3 Methodology

155 3.1 MWR data analysis

156 The MWR data are analyzed combining two algorithms, Parcel Method [*PM*] (Holzworth, 1964) and
157 Temperature Gradient Method [*TGM*] (Coen, 2014), in order to estimate the *PBL* Height ($PBLH_{MWR}$) in
158 convective and stable situations, respectively. The different situations are discriminated by comparing the
159 surface potential temperature ($\theta(z_0)$) with the corresponding vertical profile of $\theta(z)$ up to 5 km. Those
160 cases where all the points in the vertical profile have values larger than $\theta(z_0)$ are labeled as stable, and
161 *TGM* is applied. Otherwise the situation is labeled as unstable and the *PM* is applied. The vertical profile
162 of $\theta(z)$ is obtained from the vertical profile of $T(z)$ using the following equation (Stull, 2011):

$$163 \theta(z) = T(z) + 0.0098 * z \quad (1)$$

164 where $T(z)$ is the temperature profile provided by *MWR*, z is the height above the sea level, and 0.0098
165 K/m is the dry adiabatic temperature gradient. A meteorological station co-located with the *MWR* is used
166 to detect the surface temperature [$T(z_0)$]. In order to reduce the noise, $\theta(z)$ profiles were averaged
167 providing a $PBLH_{MWR}$ value at 30 minutes intervals. This methodology of *PBLH* detection was selected as
168 the reference due to the results obtained during a performed campaign of comparison between *MWR* and
169 radiosonde data, where twenty-three radiosondes were launched. High correlations were found between
170 *PBLH* retrievals provided by both instruments in stable and unstable cases. Further details are given by
171 Moreira et al. (2018a).

172 3.2 Lidar retrieval of the *PBLH*.

173 The simple processing of *DL* and *EL* data allow to estimate the *CBL* height. Moreira et al. (2018), have
174 discussed this issue in depth, while Moreira et al. (in preparation) have exploited the complementarity of
175 the data obtained from distinct remote sensing systems in order to distinguish the sublayers during the
176 period when the *SBL* and *RL* substitute the *CBL*, as well as, in complex situations, like as, presence of dust
177 layers.

178 The *PBLH* obtained from *DL* data ($PBLH_{Doppler}$) is estimated from variance threshold method. In this
179 method the $PBLH_{Doppler}$ is attributed to height where σ_w^2 is higher than a determinate threshold, which was
180 adopted as $0.16 \text{ m}^2/\text{s}^2$ (Moreira et al., 2018a). For the $PBLH_{Doppler}$ calculations was selected a time interval
181 of 30 minutes. In concerning the *PBLH* obtained from *EL* ($PBLH_{Elastic}$), the variance method is applied.

182 Such method assumes the maximum of σ_{RCS}^2 as $PBLH_{Elastic}$ (Moreira et al., 2015). The σ_{RCS}^2 is obtained
 183 from a time interval of 30 minutes.

184 3.3 Lidar turbulence analysis

185 Both lidar systems, *DL* and *EL*, gathered data with a temporal resolution of 2 seconds. Then, the data are
 186 averaged in 1-hour packages, from which the mean value is extracted [$\bar{q}(z)$]. Such mean value is subtracted
 187 from each $q(z, t)$ profile in order to estimate the vertical profile of the fluctuation for the measured variable
 188 [$q'(z, t)$] (i.e. vertical velocity for the *DL*):

$$189 \quad q'(z, t) = q(z, t) - \bar{q}(z) \quad (2)$$

190 Then, from $q'(z, t)$ is possible to obtain the high-order moments (variance (σ^2), skewness (S) and kurtosis
 191 (K)), as well as, the integral time scale (τ - which is the time over which the turbulent process are highly
 192 correlated to itself) as shown in Table 1. These variables can also be obtained from the following
 193 autocovariance function, M_{ij} :

$$194 \quad M_{ij} = \int_0^{t_f} [q'(z, t)]^i [q'(z, t + t_f)]^j dt \quad (3)$$

195 where t_f is the final time, i and j indicate the order of autocovariance function.

196 However, it is necessary to considerer that the acquired real data contain instrumental noise, $\varepsilon(z)$.
 197 Therefore, the equation 3 can be rewritten as:

$$198 \quad M_{ij} = \int_0^{\tau} [q(z, t) + \varepsilon(z, t)]^i [q(z, t + \tau) + \varepsilon(z, t + \tau)]^j dt \quad (4)$$

199 The autocovariance function of a time series with zero lag results in the sum of the variances of the
 200 atmospheric variable and its $\varepsilon(z)$. Nevertheless, atmospheric fluctuations are correlated in time, but the
 201 $\varepsilon(z)$ is random and uncorrelated with the atmospheric signal. Consequently, the noise is only associated
 202 with lag 0 (Fig. 1). Based on this concept Lenschow et al. (2000) suggested to obtain the corrected
 203 autocovariance function, $M_{11}(\rightarrow 0)$, from two methods, namely first lag correction or -2/3 law correction.
 204 In the first method, $M_{11}(\rightarrow 0)$ is obtained directly by the subtraction of lag 0, $\Delta M_{11}(0)$, from the
 205 autocovariance function, $M_{11}(0)$. In the second method $M_{11}(\rightarrow 0)$ is generated by the extrapolation of
 206 $M_{11}(0)$ at firsts nonzero lags back to lag zero (-2/3 law correction). The extrapolation can be performed
 207 using the inertial subrange hypothesis, which is described by the following equation (Monin and Yaglom,
 208 1979):

$$209 \quad M_{11}(\rightarrow 0) = \overline{q'^2(z, t)} + Ct^{2/3} \quad (5)$$

210 where C represents a parameter of turbulent eddy dissipation rate. The high-order moments and τ
 211 corrections and errors are shown in Table 1 (columns 2 and 3, respectively).

212 The same procedure of analysis is applied in studies with *DL* and *EL*, being the main difference the tracer
 213 used by each system, which are the fluctuation of vertical wind speed (w') for *DL* and aerosol number
 214 density (N') for *EL*. *DL* provides $w(z, t)$ directly, and therefore the procedure described in Figure 2 can be
 215 directly applied. Thus, the two corrections described above are applied separately and finally τ and high-
 216 order moments with and without corrections can be estimated.

217 On the other hand, the *EL* does not provide $N(z, t)$ directly. Under some restrictions, it is possible to ignore
 218 the particle hygroscopic growth and to assume that the vertical distribution of aerosol type does not changes
 219 with time, and to adopt the following relation (Pal et al., 2010):

$$220 \quad \beta_{par}(z, t) \approx N(z, t)Y(z) \Rightarrow \beta'_{par}(z, t) = N'(z, t) \quad (6)$$

221 where β_{par} and β'_{par} represent the particle backscatter coefficient and its fluctuation, respectively, and
 222 $Y(z)$ does not depends on time.

223 Considering the lidar equation:

$$224 \quad P_{\lambda}(z) = P_0 \frac{ct_d}{2} AO(z) \frac{\beta_{\lambda}(z)}{z^2} e^{-2 \int_0^z \alpha_{\lambda}(z') dz'} \quad (7)$$

225 where $P_{\lambda}(z)$ is the signal returned from distance z at time t , z is the distance [m] from the lidar of the
 226 volume investigated in the atmosphere, P_0 is the power of the emitted laser pulse, c is the light speed [m/s],
 227 t_d is the duration of laser pulse [ns], A is the area [m²] of telescope cross section, $O(z)$ is the overlap
 228 function, $\alpha_{\lambda}(z)$ is the total extinction coefficient (due to atmospheric particles and molecules) [(km)⁻¹] at
 229 distance z , $\beta_{\lambda}(z)$ is the total backscatter coefficient (due to atmospheric particles and molecules) [(km-sr)⁻¹]
 230 at distance z and the subscript λ represents the wavelength. The two path transmittance term related to
 231 $\alpha(z)$ is considered as nearly negligible at 1064 nm (Pal et al., 2010). Thus, it is possible to affirm that:

$$232 \quad RCS_{1064}(z) = P(z)_{1064} \cdot z^2 \cong G \cdot \beta_{1064}(z) \quad (8)$$

233 and consequently:

$$234 \quad RCS'_{1064}(z, t) \cong \beta'_{1064}(z, t) = \beta'_{par}(z, t) = N'(z, t) \quad (9)$$

235 where RCS_{1064} and RCS'_{1064} are the range corrected signal and its fluctuation, respectively, G is a constant
 236 and the subscripts represent the wavelength.

237 In this way, Pal et al. (2010) have shown the feasibility of using *EL* operating at 1064 nm for describing
 238 the atmospheric turbulence. However, having in mind the more extended use of lidar systems based on
 239 laser emission at 532 nm in different coordinated networks, e.g., in EARLINET and LALINET (Latin
 240 American Lidar NETwork) around 76% and 45% of the systems include the wavelength of 1064 nm, while
 241 95% of the EARLINET systems and 73% of the LALINET systems operate systems that include the
 242 wavelength 532 nm (Guerrero-Rascado et al., 2016), in this study we perform the validation of the RCS_{532}
 243 in analyses about turbulence using *EL*, following the procedure described in Figure 3, which is basically
 244 the same methodology described earlier for *DL*.

245 4 Results

246 4.1 Error Analysis

247 The influence of random error in noisy observations rapidly grows for higher-order moments (i.e., the
248 influence of random noise is much larger for the fourth-order moment than for the third-order moment).
249 Therefore, the first step, in order to ascertain the applied methodology and our data quality, we performed
250 the error treatment of *DL* data as described in Figure 2. For the *DL* analysis we selected the period 08-09
251 UTC of 19th May, the same day that will be presented in Case Study 1. This day is characterized by a well-
252 defined PBL.

253 Figure 4 illustrates the autocovariance function, generated from w' , at three different heights. As mentioned
254 before, the lag 0 is contaminated by noise (ε), and thus the impact of the ε increases together with height,
255 mainly above $PBLH_{MWR}$ (1100 m a.g.l. in our example).

256 Figure 5-A illustrates the comparison between integral time scale ($\tau_{w'}$) without correction and the two
257 corrections cited in section 3.2. Except for the first height-bins, under the $PBLH_{MWR}$ the profiles have little
258 differences, as well as small errors bars. Above the $PBLH_{MWR}$ the first lag correction presents higher
259 differences in relation the other profiles at around 1350 m.

260 Figures 5-B and 5-C show the comparison of variance ($\sigma_{w'}^2$) and skewness ($S_{w'}$), respectively, with and
261 without corrections. The profiles corrected by -2/3 law do not present significant differences in comparison
262 to uncorrected profiles. On the other hand, the profiles corrected by the first lag correction have slight
263 differences under the $PBLH_{MWR}$, mainly the $\sigma_{w'}^2$ ($S_{w'}$ only in the first 50 m). Therefore, although the
264 presence of ε can change slightly the value of high order moments, it is not enough to distort the observed
265 phenomena as shown by the impact of the corrections applied.

266 For *EL* we use the same procedure for the correction and error analysis that we apply to the *DL* data. The
267 same day was chosen (19th May), however the period selected is between 12 and 13 UTC, due to the
268 incomplete overlap of Mulhacen.

269 In this sense, we studied the influence of noise at two wavelengths: 1064 nm, that has been previously
270 analyzed by Pal et al. (2010) as presented in the section 2 and adopted as reference (considering the rather
271 low impact of molecular signal and the two ways transmittance shown in 9) and 532 nm, just in order to
272 check the feasibility of this wavelength for turbulence studies considering its spread use in observation
273 network with higher reliability than 1064 nm. Figures 6 and 7 shows the autocovariance function, obtained
274 from RCS'_{1064} and RCS'_{532} , respectively, at three distinct heights. As expected, in both cases the increase
275 of height produces the increase of ε , principally above the $PBLH_{MWR}$. However, the wavelength 532 nm is
276 more influenced by the noise, what can be verified by the higher peak at lag 0 in figure 7, in comparison
277 with peaks at same lag in figure 6.

278 Figure 8-A shows the profiles corresponding to molecular backscatter coefficient, $\beta_{Molecular}$, and
279 backscatter coefficient, β , at 1064 nm ($\beta_{Molecular}^{1064}$ and $\beta_{Molecular}^{1064} + \beta_{Aerosol}^{1064}$, respectively), while figure 8-B

280 shows the same group of profiles at 532 nm ($\beta_{Molecular}^{532}$ and $\beta_{Molecular}^{532} + \beta_{Aerosol}^{532}$). It is evident the larger
281 contribution of $\beta_{Aerosol}^{1064}$ to the total β at 1064 nm in comparison with the behavior at 532 nm, generating the
282 higher values of noise at 532 nm in comparison with 1064 nm. This higher noise values are also due to
283 higher extinction (by both aerosol and molecules) at 532 nm, producing a lower two-way transmittance. .
284 As we used Elastic lidar technique, we could not calculate aerosol extinction profiles, but an estimation of
285 these transmittances was done on the basis of Klett method (Klett, 1985). With this method, a constant lidar
286 ratio value was constrained for each profile using the AOD derived from a collocated AERONET Sun-
287 photometer [Guerrero-Rascado et al., 2008]. Using these constrained lidar ratios, the transmittances were
288 calculated together with aerosol backscatter profiles, integrated up to 2.5 km. The estimated two-way
289 transmittance was 0.85 for the case analyzed in this subsection (19th May).

290 Figures 9-A, 9-B, 9-C and 9-D show the vertical profiles of τ_{RCS} , σ_{RCS}^2 , S_{RCS} and kurtosis (K_{RCS}),
291 respectively, obtained at 1064 nm, with and without the corrections described in section 3.2. In general, the
292 corrections do not affect the profiles generated from 1064 nm data in a significant way, so that, the higher
293 influence of corrections is observed in the K_{RCS} profile, which is underestimated in some regions. In the
294 figures 10-A, 10-B, 10-C and 10-D we show same high order moments calculated from 532 nm data. As
295 the complexity of moments increases, it is possible to observe the larger influence of the corrections, due
296 to propagation of noise. Nonetheless, the application of the corrections, mainly first lag correction, make
297 these profiles very similar to those generated from the wavelength 1064 nm, so that the same phenomena
298 can be observed in both.

299 Therefore, in spite of the larger attenuation expected at 532 nm wavelength that increases the noise of the
300 profiles in comparison with 1064 nm, the application of the proposed corrections, mainly the first lag,
301 reduces significantly the influence of noise and enable the observation of the same phenomena detected in
302 the high-order moments obtained from 1064 nm. Consequently, the wavelength 532 nm will be applied in
303 the analysis presented in section 4.2. Due to the first lag correction generates a higher impact on the without
304 correction profiles, we adopted such correction in order to be more careful in the analyses of high-order
305 moments obtained from DL and EL data.

306

307 4.2 Case studies

308 In this section we present two study cases, in order to show how the products indicated in table 2 can
309 provide a detailed description about the turbulence in the *PBL*. The first case represents a typical day with
310 a clear sky situation. The second case corresponds to a more complex situation, where there is presence of
311 clouds and Saharan mineral dust layers.

312 4.2.1 Case study I: clear sky situation

313 In this case study we use measurements gathered with *DL*, *MWR* and pyranometer during 24 hours. The
314 *EL* was operated under operator-supervised mode between 08:20 to 18:00 UTC.

315 Figure 11 (A) shows the integral time scale obtained from DL data ($\tau_{w'}$). The gray areas represents the
316 region where $\tau_{w'}$ is lower than the acquisition time of DL and, therefore, for this region it is not possible to
317 analyze the turbulent processes. However, the gray area is located almost entirely above the $PBLH_{MWR}$
318 (white stars). Thus, the DL acquisition time allows us to observe the turbulence throughout the whole PBL .
319 The gray areas, as well as, the black lines (air temperature), have the same meaning in Figures 11-B and
320 11-C.

321 The $\sigma_{w'}^2$ has low values during the entire period when the SBL is present (Figure 11-B). Nevertheless, as air
322 temperature begins to increase (around 07:00 UTC), the $\sigma_{w'}^2$ increases together, as well as, the $PBLH_{MWR}$.
323 The $\sigma_{w'}^2$ reaches its maximum values in the middle of the day, when we also observe the maximum values
324 of air temperature and $PBLH_{MWR}$. The combination of $\sigma_{w'}^2$ and $PBLH_{MWR}$ provides us a better
325 comprehension about the $PBLH$ growth speed, so that, in the moments where high values of $\sigma_{w'}^2$ are
326 observed, it means higher values of Turbulent Kinetic Energy (TKE), which favor the fast ascension of
327 $PBLH$. In the same way, during the afternoon when the $\sigma_{w'}^2$ begins to decrease, the $PBLH$ growth speed is
328 reduced until the moment where the CBL height is almost constant.

329 The skewness of w' ($S_{w'}$) is shown in Figure 11-C. The $S_{w'}$ is directly associated with the direction of
330 turbulent movements. Thus, positive values (red regions) correspond with a surface-heating-driven
331 boundary layer, while negative (blue regions) ones are associated to cloud-top long-wave radiative cooling.
332 During the stable period, there is predominance of low absolute values of $S_{w'}$. Nevertheless, as air
333 temperature increases (transition from stable to unstable period), $S_{w'}$ values begin to become larger. Air
334 temperature begins to decrease around 18:00 UTC, and there is a reduction of $S_{w'}$, so that, the generation
335 rate of convective turbulence decreases. Therefore, the turbulence cannot be maintained against dissipation,
336 then the CBL becomes a SBL covered by the RL . So, the reduction observed in the $PBLH_{MWR}$ is due to the
337 $SBLH$ detection.

338 Figure 11-D shows the values of net surface radiation (R_n) that are estimated from solar global irradiance
339 values using the seasonal model described in Alados et al. (2003). The negative values of R_n are
340 concentrated in the stable region. The R_n begins to increase around 06:00 UTC and reaches its maximum
341 in the middle of the day. Comparing figures 8-C and 8-D, we can observe similarity among the behavior of
342 $S_{w'}$ and R_n , so that, the joint analysis of these variables reinforces the characterization of this PBL as surface-
343 heating-driven CBL .

344 The increase of R_n causes the rise of surface air temperature, which contributes to the positive latent heat
345 flux from the surface and, consequently, the growth of the $PBLH_{MWR}$ (CBL). The R_n begins to decrease
346 certain time before the air temperature and $S_{w'}$, but the intense reduction of these variables, as well as, the
347 detection of the $SBLH$ occur when R_n becomes negative again, although there can still be a positive sensible
348 heat flux, what is characteristic of early evening in urban regions due to the release of the ground heat flux
349 at that time.

350 Figure 11-E presents the values of surface air temperature and surface relative humidity (RH). Air surface
351 temperature has a pattern of increase and decrease similar to observed in R_n and $S_{w'}$, as expected. On the

352 other hand, RH is inversely correlated with temperature and, thus, with the rest of variables, due to the
353 relative constancy of the water vapor mixing ratio characteristic of our site during the study.

354 Figure 12 shows the RCS_{532} profile obtained from 08:00 to 18:00 UTC. At the beginning of the
355 measurement period (08:20 to 10:00 UTC) it is possible to observe the presence of a thin residual layer
356 (around 2000 m a.s.l.), and later from 13:00 to 18:00 UTC it is evident a lofted aerosol layer. In this picture
357 there are the $PBLH_{MWR}$ (pink stars), the $PBLH_{Doppler}$ (blue stars), obtained from the maximum of σ_{wr}^2 ,
358 (Moreira et al., 2018a), and the $PBLH_{Elastic}$ (black stars), obtained from the maximum of σ_{RCS}^2 (Moreira
359 et al., 2015). In the initial part of measurement, all profiles have similar behavior. However due to distinct
360 $PBLH$ definition and tracer applied by each one, the differences increase as CBL becomes more complex,
361 e.g. the presence of lofted aerosol layer at 14 UTC. The joint observation of the results provided by these
362 three methods can provide us information about the sublayers in the PBL , both in convective and stable
363 situations. Due to low variability of $PBLH$, the period between 13:00 and 14:00 UTC has been selected to
364 be analyzed from the high order moments.

365 Figure 13 presents the statistical moments generated from RCS' of wavelength 532 nm, which were obtained
366 from 13:00 and 14:00 UTC. The red line in all graphics represent the $PBLH_{Elastic}$ (2200 m a.s.l.) and the
367 blue one the average value of $PBLH_{MWR}$ (2250 m a.s.l.), both obtained between 13 and 14 UTC.

368 Due to well-defined PBL , $PBLH_{Elastic}$ and $PBLH_{MWR}$ do not have significant differences (50 m). The σ_{RCS}^2 ,
369 has small and practically constant values between 1000 and 1400m, evidencing the homogeneity of aerosol
370 distribution in this region. From 1400 m the value of σ_{RCS}^2 begins to increase, reaching the maximum value
371 at $PBLH_{Elastic}$, which represents the Entrainment Zone (region characterized by a intense mixing between
372 air parcels coming from CBL and FT , causing a high variation in aerosol concentration). Above $PBLH_{Elastic}$
373 the values of σ_{RCS}^2 decrease slowly due to location of the lofted aerosol around 2500 m. However, above
374 this aerosol layer the value of σ_{RCS}^2 is reduced to zero, indicating a large homogeneity in aerosol distribution
375 at this region, what is expected, because the aerosol concentration at the FT is negligible in this case. The
376 integral time scale obtained from RCS' (τ_{RCS}) has values higher than EL time acquisition throughout the
377 CBL , evidencing the feasibility for studying turbulence using this elastic lidar configuration. The skewness
378 values obtained from RCS' (S_{RCS}) give us information about aerosol motion. The positive values of
379 S_{RCS} , observed in the lowest part of profile and above the $PBLH_{Elastic}$ represents the updrafts aerosol layers.
380 The negative values of S_{RCS} indicates the region with low aerosol concentration due to clean air coming
381 from free troposphere (FT). This movement of ascension of aerosol layers and descent of clean air with
382 zero value of S_{RCS} at $PBLH$ (characteristic of the CBL growing) was also detected by Pal et al. (2010) and
383 McNicholas et al. (2014). The kurtosis of RCS' (K_{RCS}) determines the level of mixing at different heights.
384 There are values of K_{RCS} larger than 3 in the lowest part of profile and around 2500 m, showing a peaked
385 distribution in this region. On other hand, values of K_{RCS} lower than 3 are observed close to the $PBLH_{Elastic}$,
386 therefore this region has a well-mixed CBL regime. Pal et al. (2010) and McNicholas et al. (2014) also
387 detected this feature in the region nearby the $PBLH$. In figure 14 are shown the high-order moments
388 obtained at the same period described above, however from the 1064 nm data (our reference wavelength).
389 It is possible to observe a similarity between the profiles obtained from each wavelength, so that, the same

390 phenomena observed in the profiles generated from 532 nm and described above, also are detected in the
391 profiles obtained from the reference wavelength.

392 The results provided by *DL*, pyranometer and *MWR* data agree with the results observed in Figure 10. In
393 the same way, the analysis of high order moments of *RCS'* fully agree with the information in Figure 8.
394 Thus, the large values of S_{RCS} and K_{RCS} detected around 2500 m a.s.l., where we can see a lofted aerosol
395 layer, suggest the ascent of an aerosol layer and presence of a peaked distribution, respectively.

396 4.2.2 Case study: dusty and cloudy scenario

397 In this case study measurements with *DL*, *MWR* and pyranometer expand during 24 hours, while *EL* data
398 are collected from 09:00 to 16:00 UTC.

399 Figure 15-A shows $\tau_{w'}$, where the black lines and gray area has the same meaning mentioned earlier.
400 Outside the period 13:00 to 17:00 UTC, the grey area is situated completely above the $PBLH_{MWR}$ (white
401 stars), thus *DL* time acquisition is enough to perform studies about turbulence in this case.

402 $\sigma_{w'}^2$ has values close to zero during all the stable period (Figure 15-B). However, when air temperature
403 begins to increase (around 06:00 UTC), the $\sigma_{w'}^2$ also increases and reaches its maximum in the middle of
404 the day. The higher values of *PBL* growth speed are observed in the moments where $\sigma_{w'}^2$ reaches its
405 maximum values. In the late afternoon, as air temperature decrease, the values of $\sigma_{w'}^2$ (and consequently
406 the *TKE*) decrease gradually, until reach the minimum value associated to the *SBL*. Figure 15-C shows the
407 profiles of $S_{w'}$. The main features of this case are: the low values of $S_{w'}$, the slow increase and ascension
408 of positive $S_{w'}$ values and the predominance of negative $S_{w'}$ values from 12:00 to 13:00 UTC. The first two
409 features are likely due to the presence of the intense Saharan dust layer (Figure 16), which reduces the
410 transmission of solar irradiance, and consequently the absorption of solar irradiance at the surface,
411 generating weak convective process. From Figure 15 we can observe the presence of clouds from 12:00 to
412 14:00 UTC. This justifies the intense negative values of $S_{w'}$ observed in this period, because, as mentioned
413 before, $S_{w'}$ is directly associated with direction of turbulent movements that during this period is associated
414 to cloud-top long-wave radiative cooling, due to the presence of clouds (Ansmann et al., 2010).

415 The influence of Saharan dust layer can also be evidenced on the R_n pattern (Figure 15-D), which maintains
416 negative values until 12:00 UTC and reaches a low maximum value (around 200 W/m²). The observation
417 of $S_{w'}$ and R_n between 12:00 and 14:00 reinforce the idea of a case of the cloud-top long-wave radiative
418 cooling in the *CBL*. Air surface temperature and *RH* (Figure 14-E) present the same correlation and anti-
419 correlation (respectively) observed in the earlier case study, where the maximum of air surface temperature
420 and the minimum of *RH* are detected in coincidence with the maximum daily value of $PBLH_{MWR}$.

421 As mentioned before, Figure 16 shows the *RCS* profile obtained from 09:00 to 16:00 UTC in a complex
422 situation, with presence of decoupled dust layer (around 3800 m a.s.l.) from 09:00 to 12:00 UTC and clouds
423 (around 3500 m a.s.l.) from 11:00 to 16:00 UTC. The pink, black and blue stars represent the $PBLH_{MWR}$,
424 $PBLH_{Doppler}$ and $PBLH_{Elastic}$ respectively. Due to the presence of dusty layers and clouds, the difference

425 between the methods is more evident, mainly of the $PBLH_{Elastic}$, which uses the aerosol as tracers. This
426 method only produces results close to the others at 15 UTC, when dust layer is mixed with the CBL .

427 Figure 17 illustrates the statistical moments of RCS' of 532 nm wavelength obtained from 11:00 to 12:00
428 UTC. The $\sigma_{RCS'}^2$ profile presents several peaks due to the presence of distinct aerosol sublayers. The first
429 peak is coincident with the value of $PBLH_{MWR}$. The value of $PBLH_{Elastic}$ is coincident with the base of
430 the dust layer. This difficulty to detect the $PBLH$ in presence of several aerosol layers is inherent to the
431 variance method (Kovalev and Eichinger, 2004). However, the joint observation of $PBLH_{MWR}$ and
432 $PBLH_{Elastic}$, enable us to characterize and distinguish the several sublayers. The values of $\tau_{RCS'}$ are higher
433 than EL acquisition time all along the PBL , evidencing the feasibility of EL time acquisition for studying
434 the turbulence of PBL in this case. The $S_{RCS'}$ profile has several positive values, due to the large number of
435 aerosol sublayers that are present. The characteristic inflection point of $S_{RCS'}$ is observed in coincidence
436 with the $PBLH_{MWR}$, that confirming the agreement between this point and the $PBLH$. From the analysis of
437 $S_{RCS'}$ and S_w is possible to justify this phenomena from the mixing process demonstrated in the earlier case
438 study. The $K_{RCS'}$ has predominantly values lower than 3 below 2500 m, thus shown how this region is well
439 mixed as can see in Figure 16. Values of $K_{RCS'}$ larger than 3 are observed in the highest part of profile, where
440 the dust layer is located.

441 In order to show the feasibility of 532 nm wavelength, in the figure 18 are presented the high-order moments
442 obtained between 11-12 UTC from 1064 nm wavelength data. Although the error of $\sigma_{RCS'}^2$ obtained from
443 532 nm (pink shadow) is considerably higher than the error of same variable obtained from 1064 nm, all
444 profiles are very similar, so that, the same phenomena can be observed in both graphics (figure 17 and 18).

445 Figure 19 shows the RCS' 532 nm wavelength high-order moments obtained from 12:00 and 13:00 in
446 presence of cloud cover. The method based on maximum of $\sigma_{RCS'}^2$ locates the $PBLH_{Elastic}$ at the cloud base,
447 due to the high variance of RCS' generated by the clouds. $\tau_{RCS'}$ presents values larger than EL time
448 acquisition, therefore this configuration enable us to study turbulence by EL analyses. $S_{RCS'}$ has few peaks,
449 due to the mixing between CBL and dust layer, generating a more homogenous layer. The highest values
450 of $S_{RCS'}$ are observed in regions where there are clouds, and the negative ones (between 3500 and 4000 m)
451 occur due to presence of air from FT between the two aerosol layers (Figure 16). The inflection point of
452 $S_{RCS'}$ profile is observed in $PBLH_{MWR}$ region. $K_{RCS'}$ profile has low values in most of the PBL , demonstrating
453 the high level of mixing during this period, where dust layer and PBL are combined. The higher values of
454 $K_{RCS'}$ are observed in the region of clouds. In the same way of the previous analysis, the high-order moments
455 of the period mentioned above were calculated for the wavelength of 1064 nm (figure 20). Although there
456 are some differences in the absolute values of some profiles, the high-order moments generated using 1064
457 and 532 nm have similar profiles, so that, the same phenomena can be observed, demonstrating the viability
458 of 532 nm wavelength in the proposed methodology.

459 5 Conclusions

460 In this paper we perform an analysis about the *PBL* turbulent features from three different types of remote
461 sensing systems (*DL*, *ELand MWR*) and surface sensors during SLOPE-I campaign. We applied two kind
462 of corrections to the lidar data: first lag and $-2/3$ corrections. The corrected *DL* statistical moments showed
463 little variation with respect to the uncorrected profiles, denoting a rather low influence of the noise. The *EL*
464 high-order moments were obtained from two wavelengths: 1064 nm, adopted as reference, and 532 nm, in
465 order to verify the viability to use the last one in turbulence analysis. From this comparison, was possible
466 to observe that the wavelength 532 nm is more affected by noise, in comparison with 1064 nm, due to the
467 large contribution of the molecular component and the lower two ways transmittance at that wavelength.
468 However, the application of proposed corrections, mainly the first lag, can reduce such influence, so that,
469 the same phenomena can be observed in the high-order moments provided from both wavelengths

470 The case studies present two kind of situations: well-defined *PBL* and a more complex situation with the
471 presence of Saharan dust layer and some clouds. In both cases was possible to identify the events describe
472 in table 2. The-combined use of remote sensing systems shows how the results provided by the different
473 instruments can complement one each other, providing a detailed observation of some phenomena, mainly
474 in complex situations.

475 Therefore, this study shows the feasibility of the described methodology based on the combination of
476 remote sensing systems for retrieving a detailed picture on the *PBL* turbulent features. In addition, the
477 feasibility of using the analyses of high order moments of the *RCS* collected at 532 nm at a temporal
478 resolution of 2 s offers the possibility for using the proposed methodology in networks such as EARLINET
479 or LALINET with a reasonable additional effort.

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Table 1 – Variables applied to statistical analysis (Lenschow et al., 2000)

	Without Correction	Correction	Error
Integral Time Scale (τ)	$\int_0^{\infty} q'(t) dt$	$\frac{1}{\bar{q}^{1/2}} \int_{t=0}^{\infty} M_{11}(t) dt$	$\tau \cdot \sqrt{\frac{4\Delta M_{11}}{M_{11}(\rightarrow 0)}}$
Variance (σ_q^2)	$\frac{1}{T} \sum_{t=1}^T (q(t) - \bar{q})^2$	$M_{11}(\rightarrow 0)$	$q^2 \cdot \sqrt{\frac{4\Delta M_{11}}{M_{11}(\rightarrow 0)}}$
Skewness (S)	$\frac{\bar{q}^3}{\sigma_q^3}$	$\frac{M_{21}(\rightarrow 0)}{M_{11}^{3/2}(\rightarrow 0)}$	$\frac{\Delta M_{21}}{\Delta M_{11}^{3/2}}$
Kurtosis (K)	$\frac{\bar{q}^4}{\sigma_q^4}$	$\frac{3M_{22}(\rightarrow 0) - 2M_{31}(\rightarrow 0) - 3\Delta M_{11}^2}{M_{11}^2(\rightarrow 0)}$	$\frac{4\Delta M_{31} - 3\Delta M_{22} - \Delta M_{11}^2}{\Delta M_{11}^2}$

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Table 2 – Products and their respective meaning, provided by each system

Product	System	Meaning
$\tau_{w'}(z)$	Doppler lidar	Measurement in time of length of turbulent eddies
$\sigma_{w'}^2(z)$	Doppler lidar	Turbulent Kinetic Energy
$S_{w'}(z)$	Doppler lidar	Direction of turbulent movements
$PBLH_{Doppler}$	Doppler lidar	Top of CBL obtained from variance threshold method
$\tau_{RCS'}(z)$	Elastic lidar	Measurement in time of length of turbulent eddies
$\sigma_{RCS'}^2(z)$	Elastic lidar	Homogeneity of aerosol distribution
$S_{RCS'}(z)$	Elastic lidar	Aerosol motion ($S < 0 \rightarrow$ Downdrafts, $S > 0 \rightarrow$ Updrafts)
$K_{RCS'}(z)$	Elastic lidar	Level of aerosol mixing ($K < 3 \rightarrow$ Well-Mixed, $K > 3 \rightarrow$ Low Mixing)
$PBLH_{Elastic}$	Elastic lidar	Top of aerosol layer obtained from variance method
$PBLH_{MWR}$	MWR	Top of CBL/SBL layer obtained from Potential Temperature

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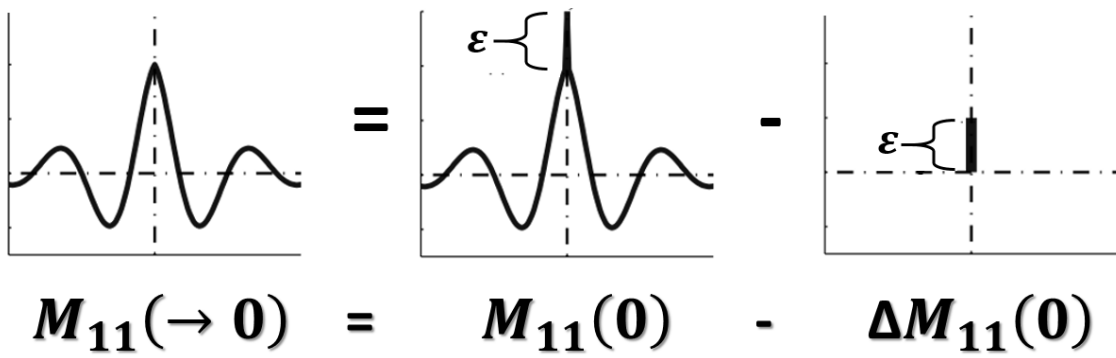


Figure 1 – Procedure to remove the errors of autocovariance functions. $M_{11}(\rightarrow 0)$ – corrected autocovariance function errors; $M_{11}(0)$ - autocovariance function without correction; $\Delta M_{11}(0)$ - error of autocovariance function.

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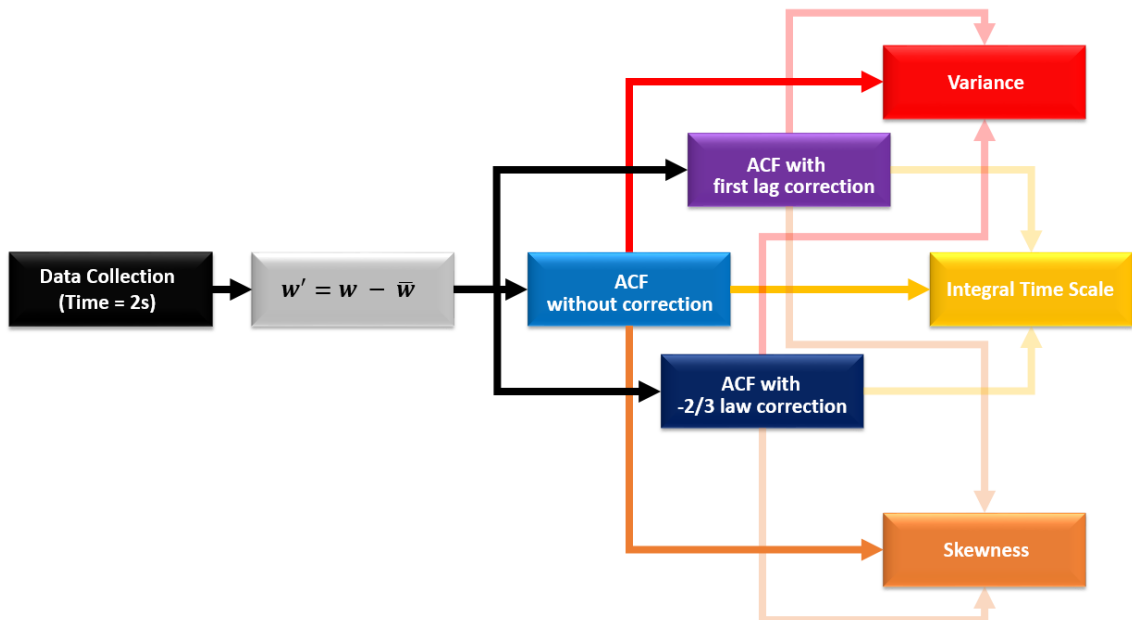


Figure 2 – Flowchart of data analysis methodology applied to the study of turbulence with Doppler lidar

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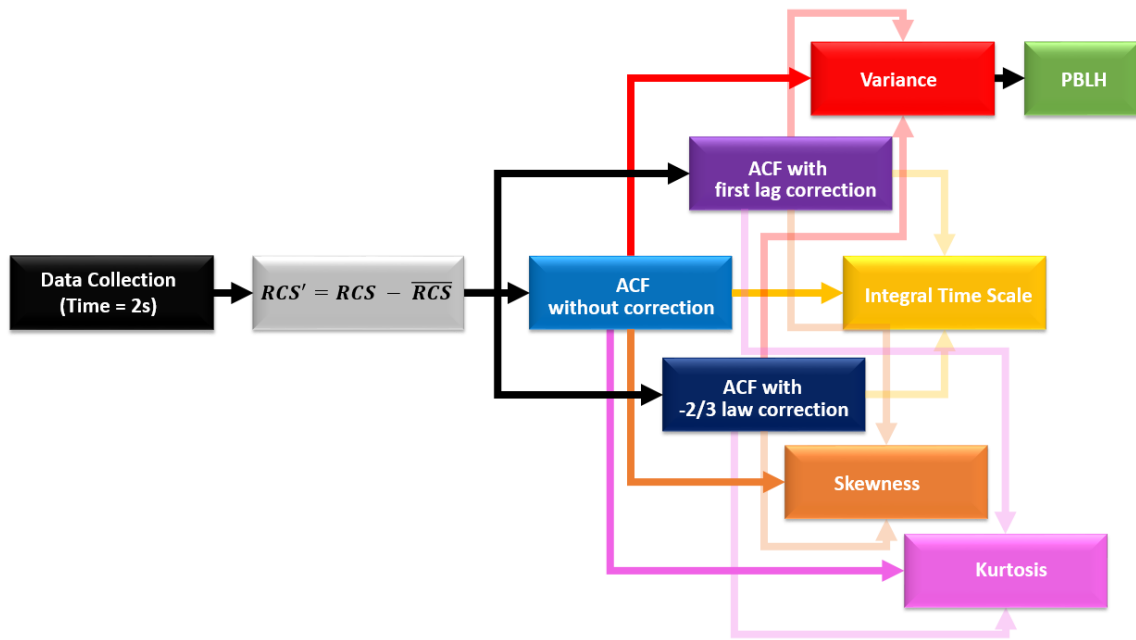


Figure 3 – Flowchart of data analysis methodology applied to the study of turbulence with elastic lidar

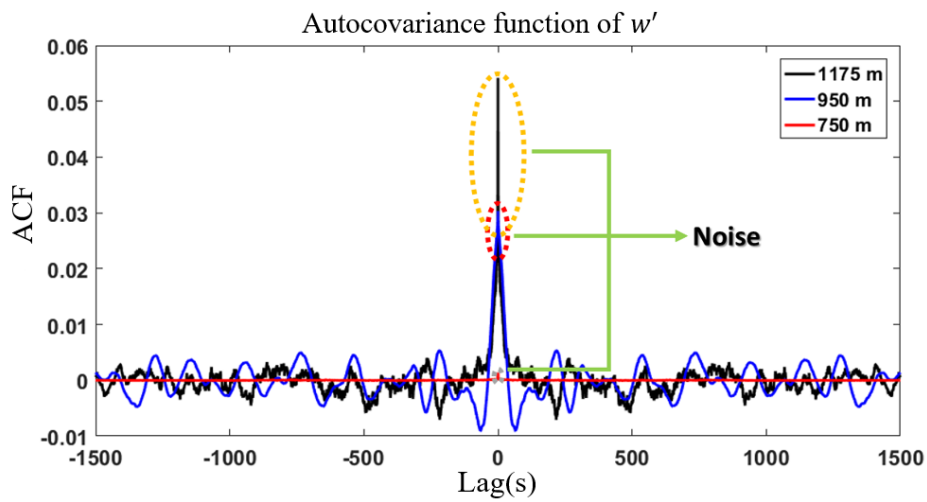


Figure 4 – Autocovariance function (ACF) of w' , obtained from Doppler lidar at three different heights on 19th May 2016 at 08-09 UTC in Granada.

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Profiles obtained from w' - Granada – 19 May 2016 – 08-09 UTC

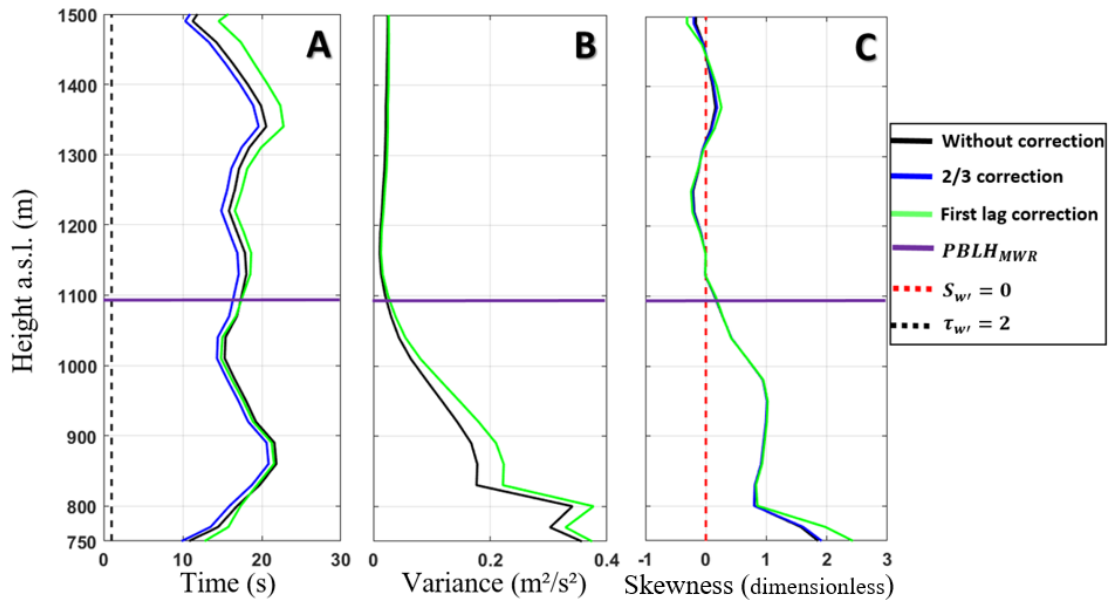


Figure 5 – A - Vertical profile of Integral time scale ($\tau_{w'}$). B - Vertical profile of variance ($\sigma_{w'}^2$). C - Vertical profile of Skewness ($S_{w'}$). All profiles were obtained from Doppler lidar data on 19th May 2016 at 08-09 UTC in Granada.

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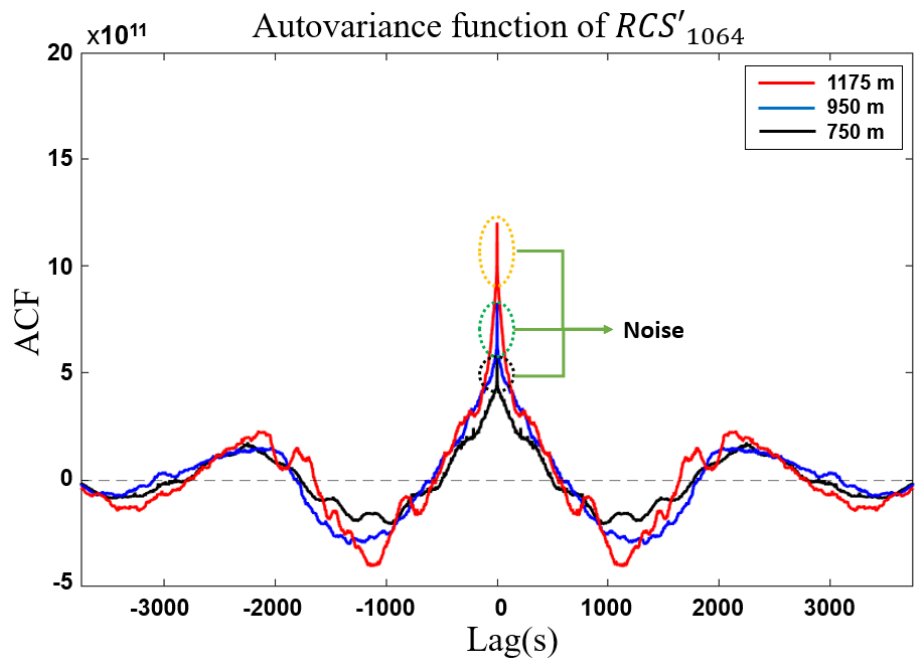


Figure 6 – Autocovariance of RCS'_{1064} obtained from Mulhacen elastic lidar data to three different heights on 19th May 2016 at 12-13 UTC in Granada.

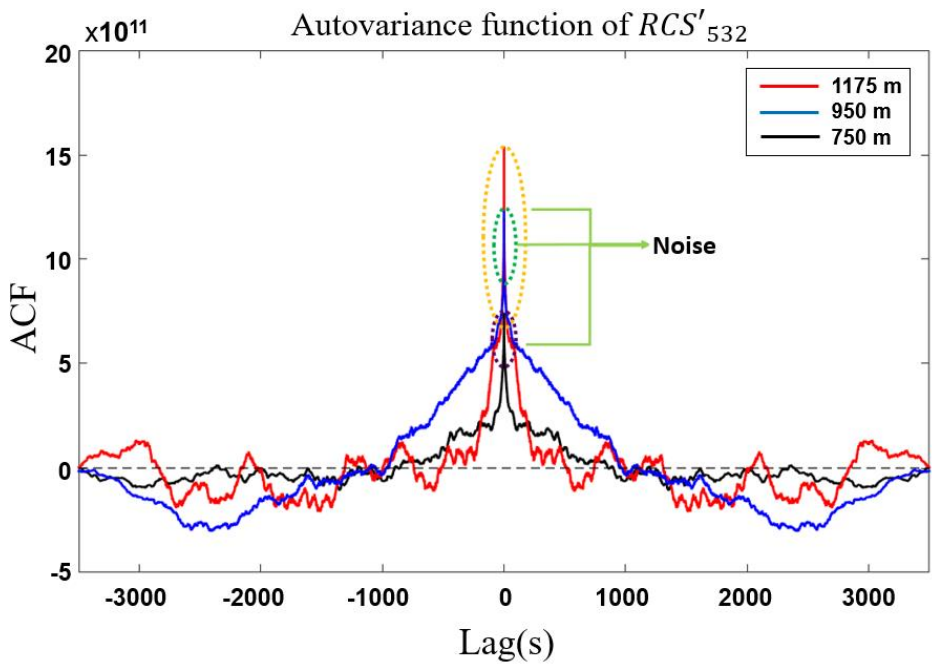


Figure 7 – Autocovariance of RCS'_{532} obtained from Mulhacen elastic lidar data to three different heights on 19th May 2016 at 12-13 UTC in Granada.

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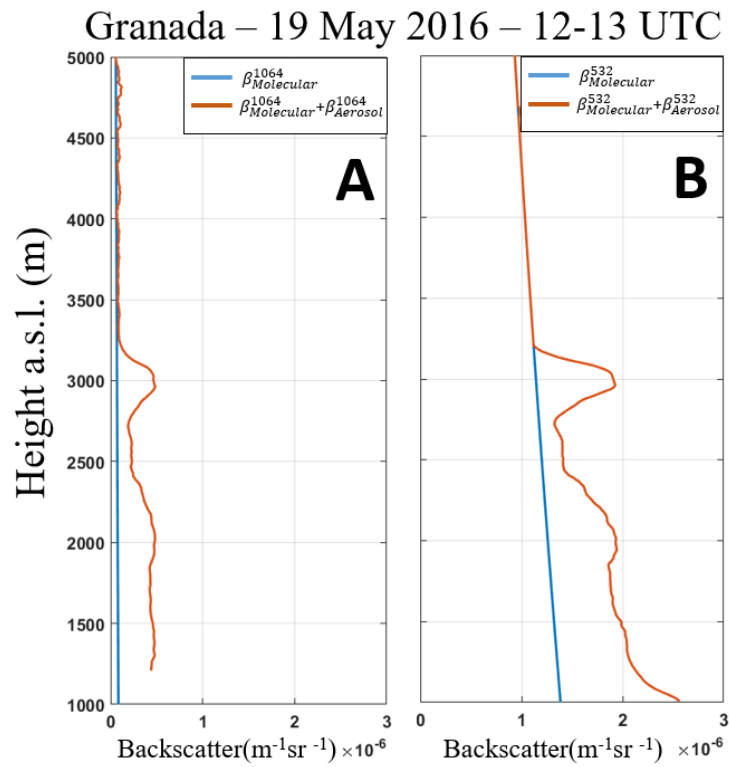
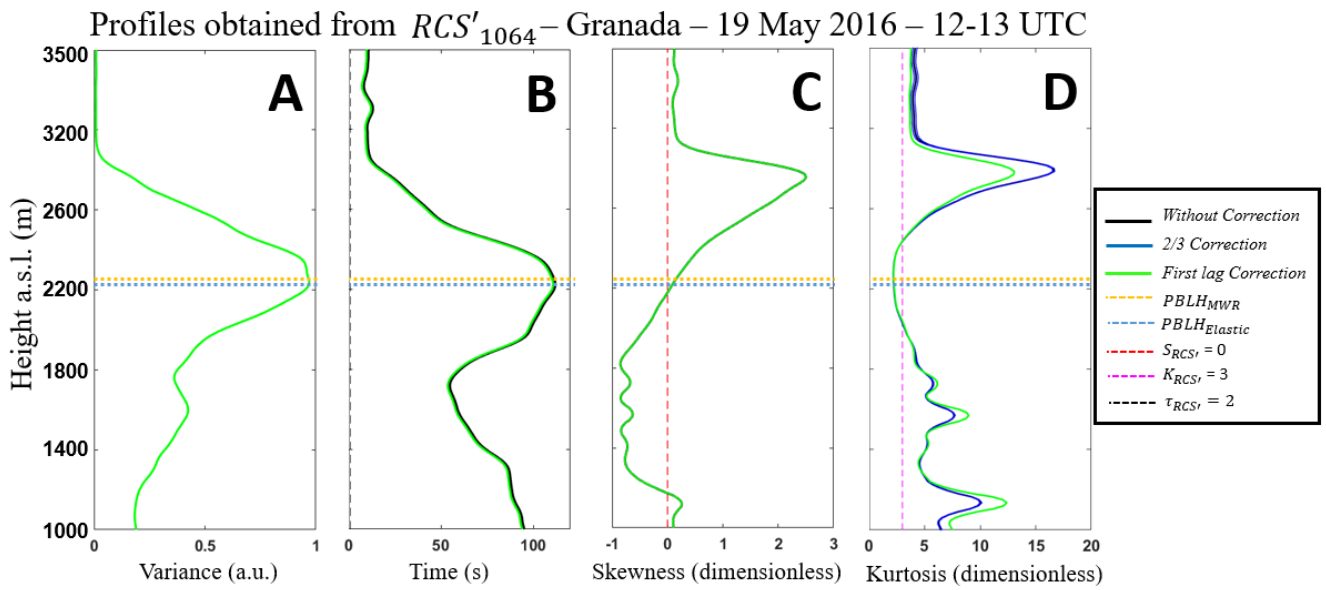


Figure 8 – (A) $\beta_{Molecular}^{1064}$ (blue line) and $\beta_{Molecular}^{1064} + \beta_{Aerosol}^{1064}$ (orange line). (B) $\beta_{Molecular}^{532}$ and $\beta_{Molecular}^{532} + \beta_{Aerosol}^{532}$ (orange line). All profiles were obtained from Mulhacen elastic lidar data on 19th May 2016 between 12-13 UTC in Granada.

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Figure 9 – A- Vertical profile of Integral time scale ($\tau_{RCS'}$). B - Vertical profile of variance ($\sigma_{RCS'}^2$). C - Vertical profile of Skewness ($S_{RCS'}$). D - Vertical profile of Kurtosis ($K_{RCS'}$). All profiles were obtained from Mulhacen elastic lidar data on 19th May2016 in Granada between 12-13 UTC.

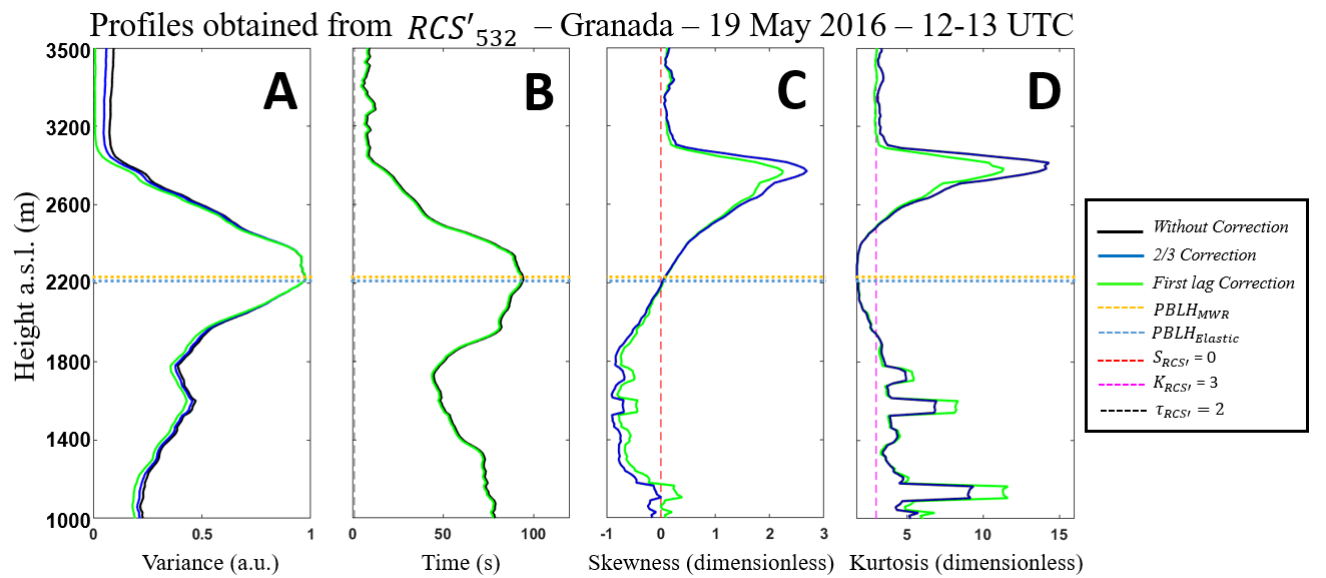
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Figure 10 – A- Vertical profile of Integral time scale ($\tau_{RCS'}$). B - Vertical profile of variance ($\sigma_{RCS'}^2$). C - Vertical profile of Skewness ($S_{RCS'}$). D - Vertical profile of Kurtosis ($K_{RCS'}$). All profiles were obtained from Mulhacen elastic lidar data on 19th May2016 in Granada between 12-13 UTC.

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Granada - 19 May 2016

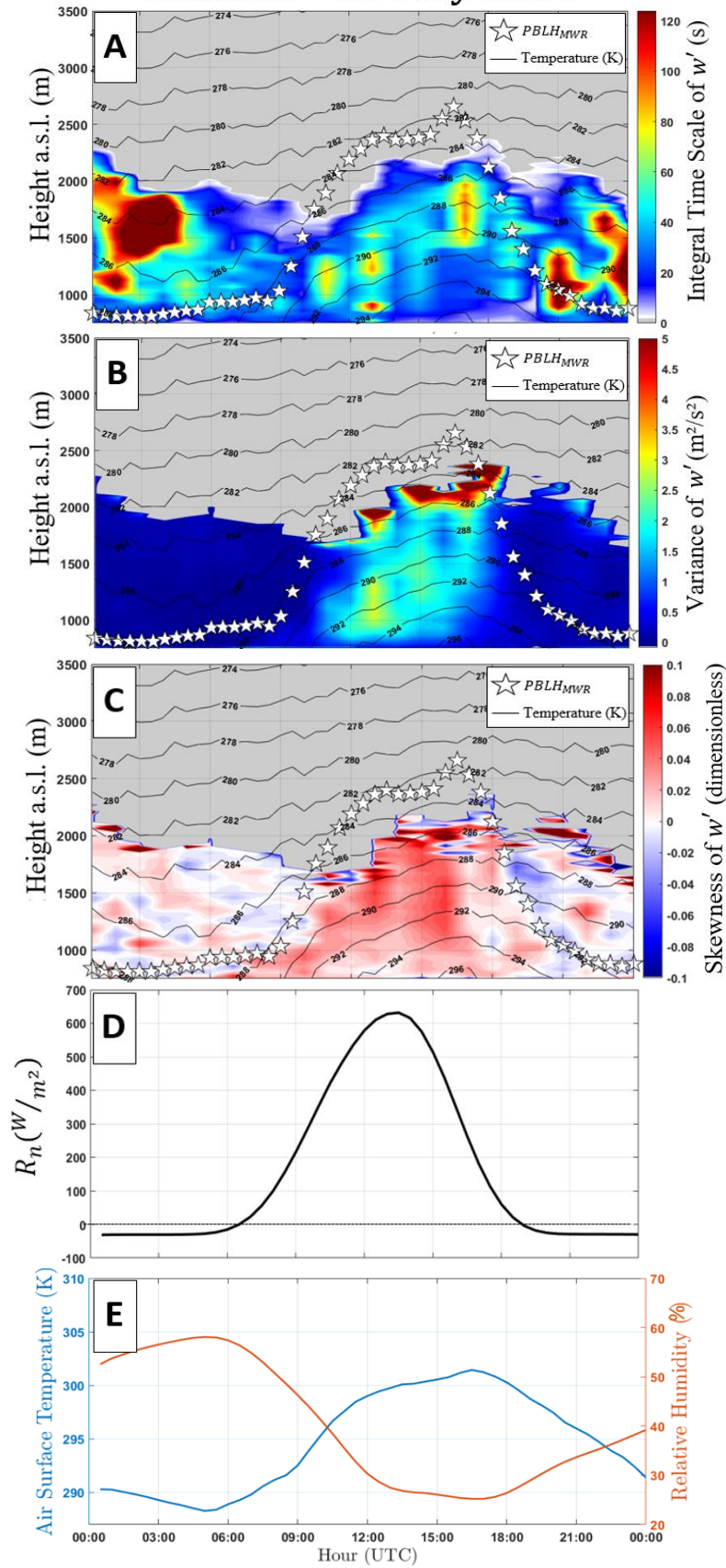


Figure 11 – A – integral time scale obtained from Doppler lidar data [$\tau_{w'}$], B – variance obtained from Doppler lidar data [$\sigma_{w'}^2$], C – skewness obtained from Doppler lidar data [$S_{w'}$], D – net radiation obtained from pyranometer data [R_n], E – Air surface temperature [blue line] and surface relative humidity [RH - orange line] both were obtained from surface sensors. All profiles were acquired on 19th May 2016 in Granada. In A, B and C black lines and white stars represent air temperature and PBLH_{MWR}, respectively.

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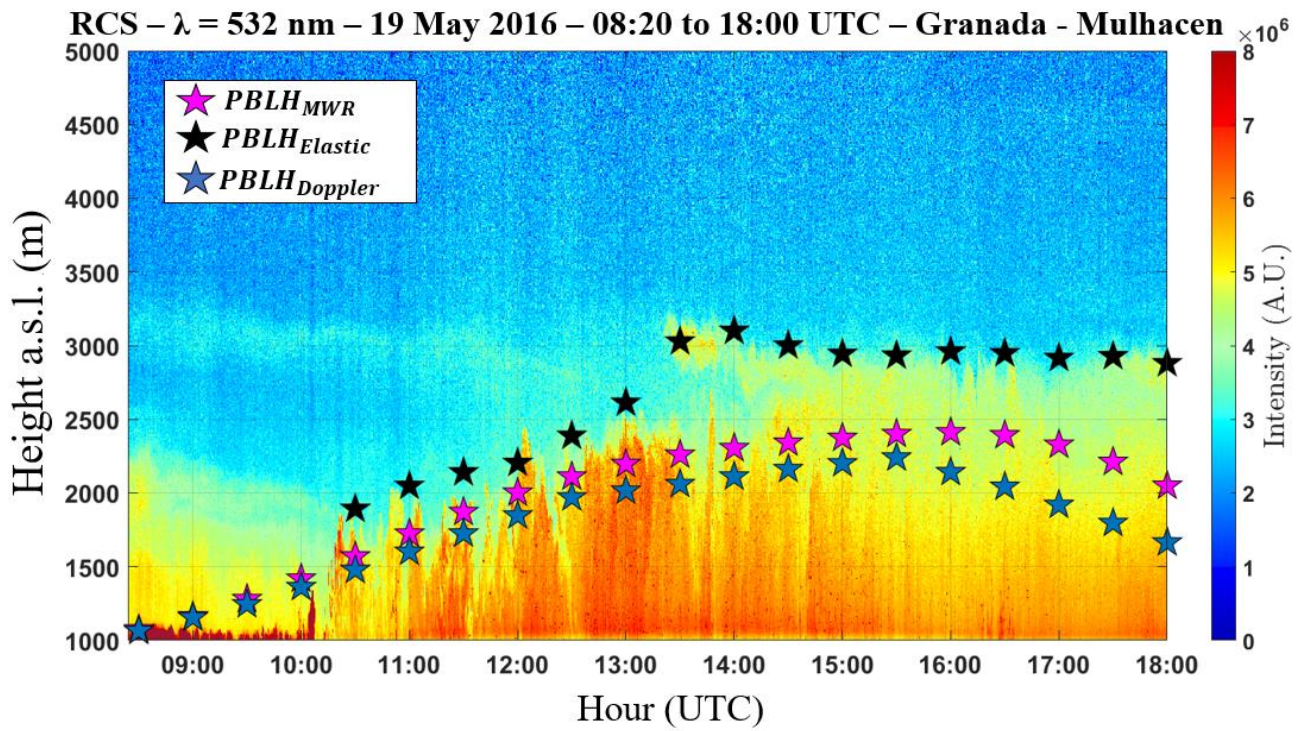


Figure 12 – Time-Height plot of RCS obtained on 19 May 2016 in Granada. Pink stars represent the $PBLH_{MWR}$, black stars represent the $PBLH_{Elastic}$ and blue stars represent the $PBLH_{Doppler}$.

Granada – 19 May – 13-14 UTC

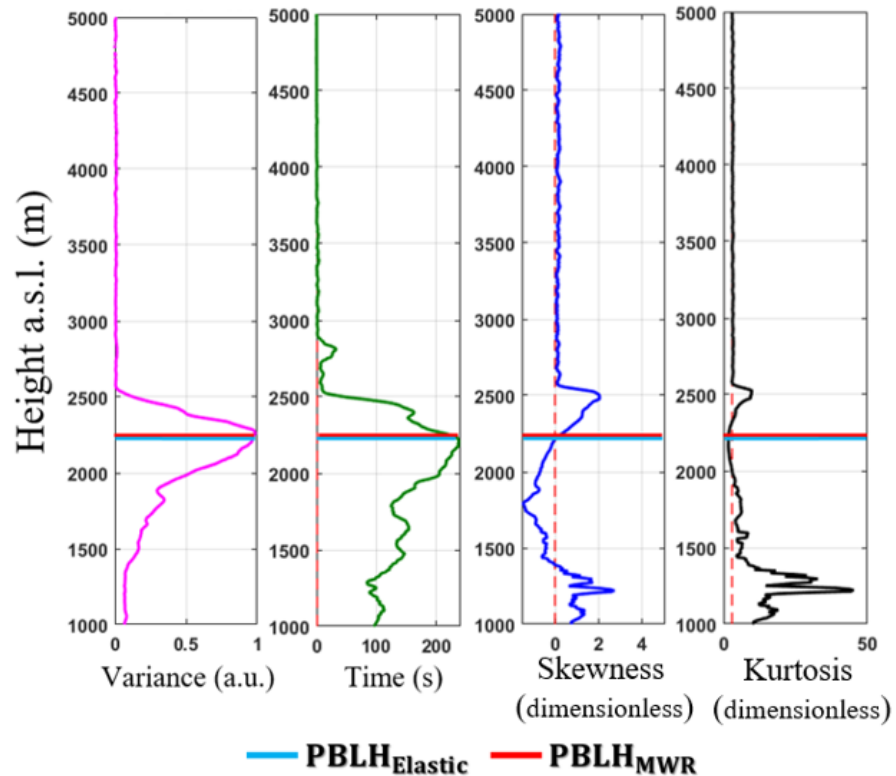


Figure 13 – Statistical moments obtained from 532 nm wavelength data of elastic lidar (Mulhacen) in Granada at 13 to 14 UTC - 19 May 2016. From left to right: variance [$\sigma_{RCS'}^2$], integral time scale [$\tau_{RCS'}$], skewness [$S_{RCS'}$] and kurtosis [$K_{RCS'}$].

Granada – 19 May – 13-14 UTC

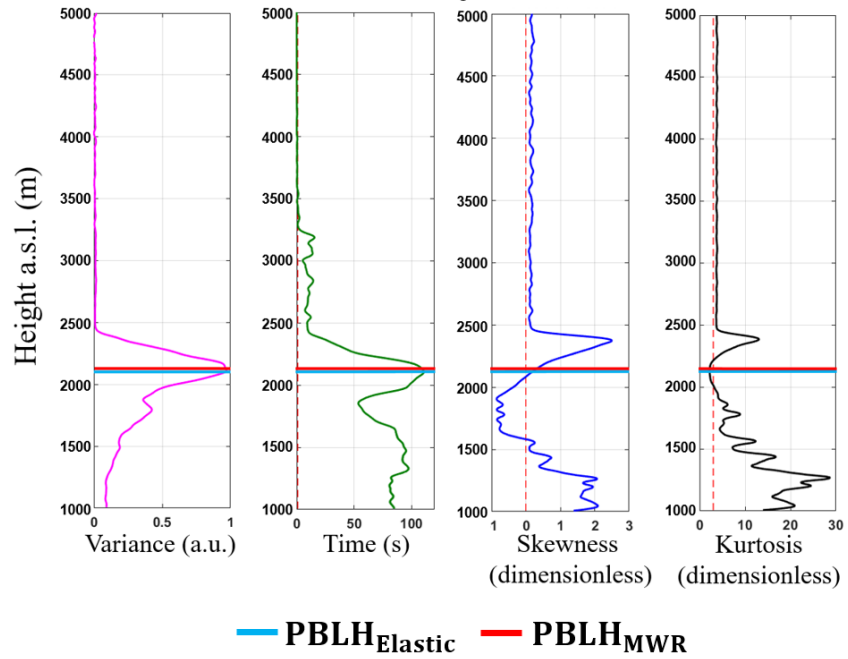


Figure 14 – Statistical moments obtained from 1064 nm wavelength data of elastic lidar(Mulhacen) in Granada at 13 to 14 UTC - 19 May 2016. From left to right: variance [$\sigma_{RCS'}^2$], integral time scale [$\tau_{RCS'}$], skewness [$S_{RCS'}$] and kurtosis [$K_{RCS'}$].

Granada - 08 Jul 2016

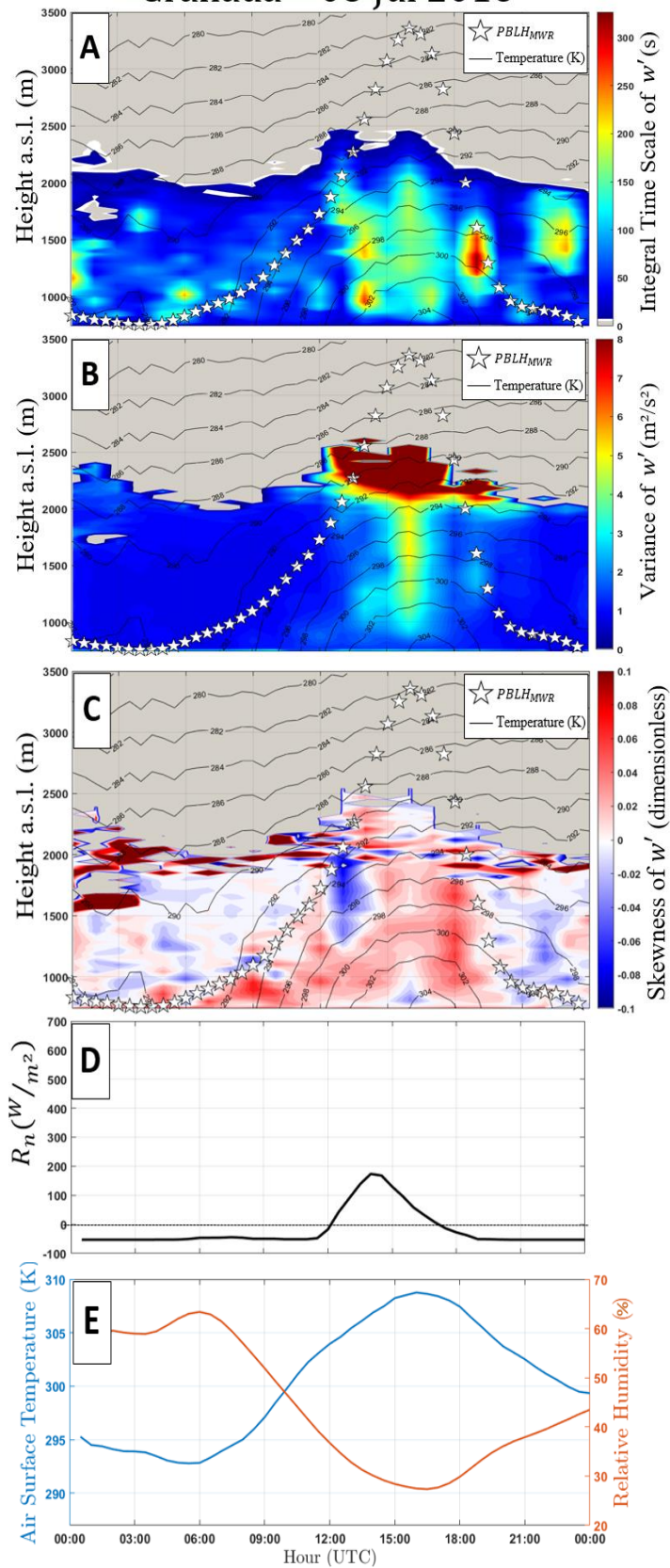


Figure 15 - A – integral time scale from Doppler lidar data [$\tau_{w'}$], B – variance from Doppler lidar data [$\sigma_{w'}^2$], C – skewness from Doppler lidar data [$S_{w'}$], D – net radiation from pyranometer data [R_n], E – Air surface temperature [blue line] and surface relative humidity [RH – orange line] from surface sensor data. All profiles were obtained in Granada on 08 July 2016. In A, B and C black lines and white stars represent air temperature and $PBLH_{MWR}$, respectively.

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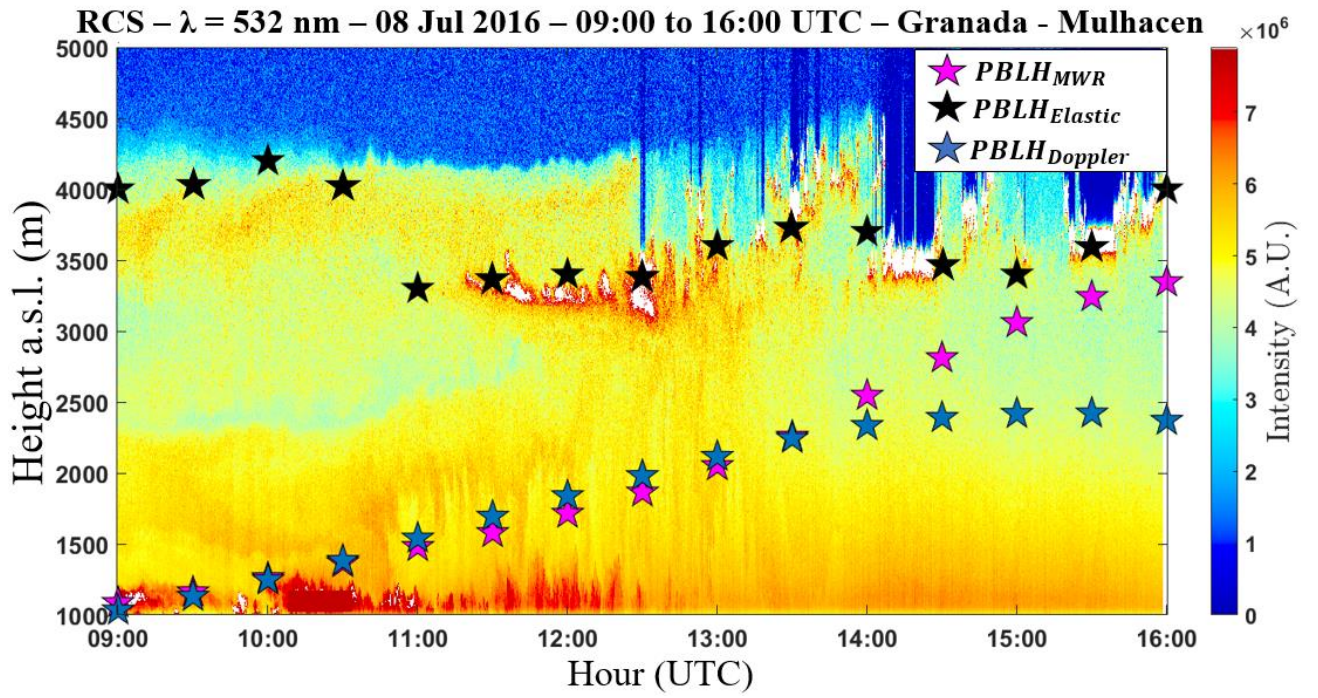


Figure 16 – Time-Height plot of RCS obtained from Mulhacen elastic lidar data on 08 July 2016 in Granada. Pink stars represent the $PBLH_{MWR}$, black stars represent the $PBLH_{Elastic}$ and blue stars represent the $PBLH_{Doppler}$.

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Granada – 08 Jul – 11-12 UTC

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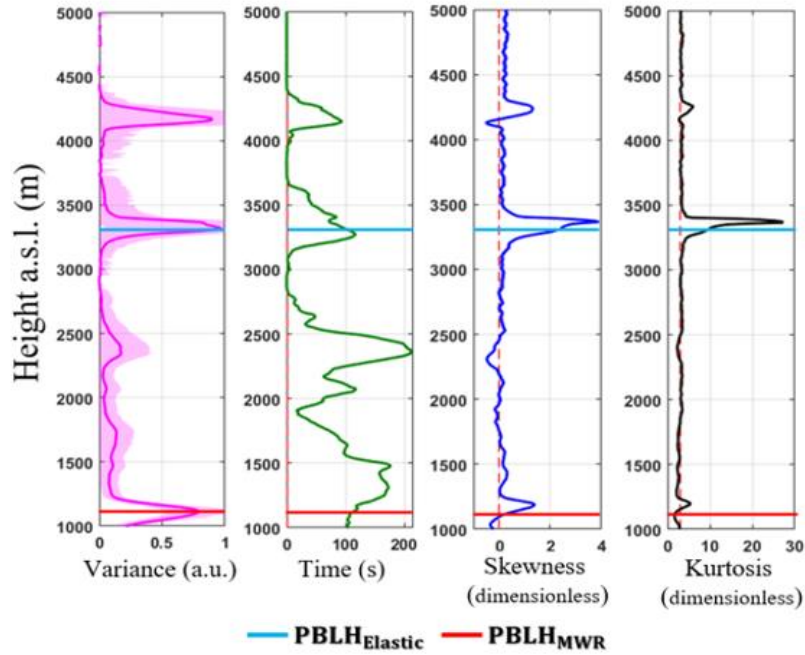
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Figure 17 - Statistical moments obtained from 532 nm wavelength data of elastic lidar(Mulhacen) in Granada between 11-12 UTC on 08th July 2016. From left to right: variance [$\sigma_{RCS'}^2$], integral time scale [$\tau_{RCS'}$], skewness [$S_{RCS'}$] and kurtosis [$K_{RCS'}$].

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Granada – 08 Jul – 11-12 UTC

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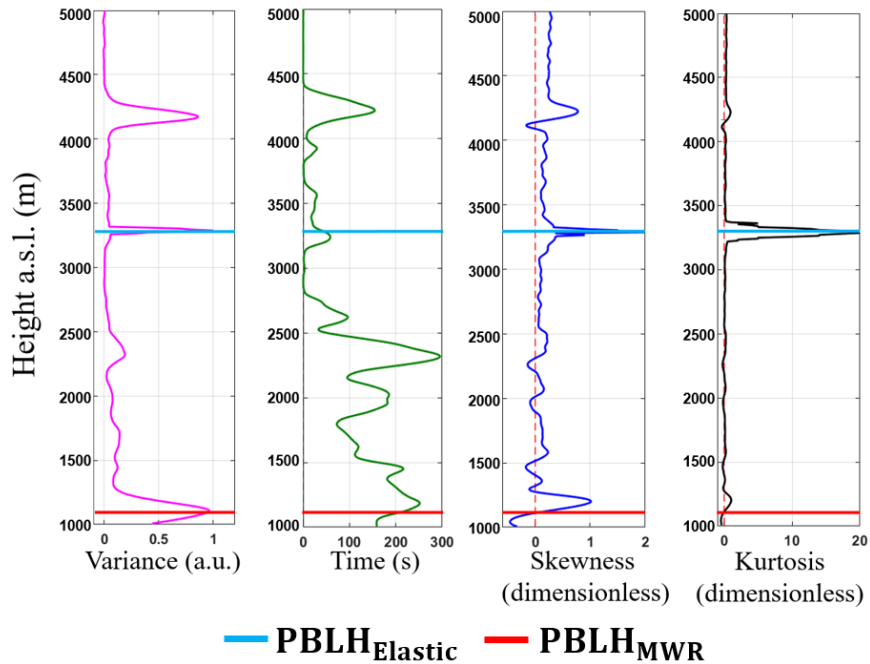
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Figure 18 - Statistical moments obtained from 1064 nm wavelength data of elastic lidar(Mulhacen) in Granada between 11-12 UTC on 08th July 2016. From left to right: variance [$\sigma_{RCS'}^2$], integral time scale [$\tau_{RCS'}$], skewness [$S_{RCS'}$] and kurtosis [$K_{RCS'}$].

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Granada – 08 Jul – 12-13 UTC

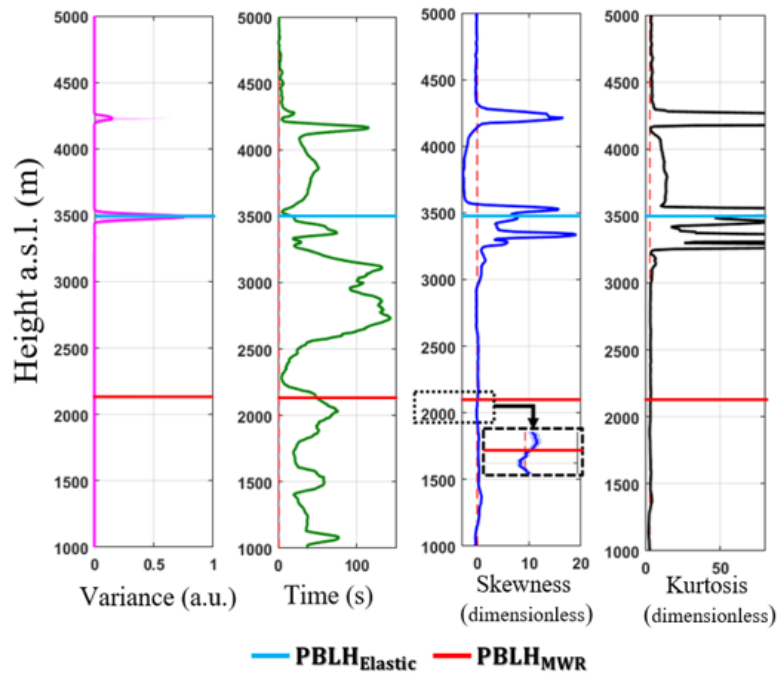


Figure 19 - Statistical moments obtained from 532 nm wavelength data of elastic lidar (Mulhacen) in Granada between 12 -13 UTC on 08 July 2016. From left to right: variance [$\sigma_{RCS'}^2$], integral time scale [$\tau_{RCS'}$], skewness [$S_{RCS'}$] and kurtosis [$K_{RCS'}$].

Granada – 08 Jul – 12-13 UTC

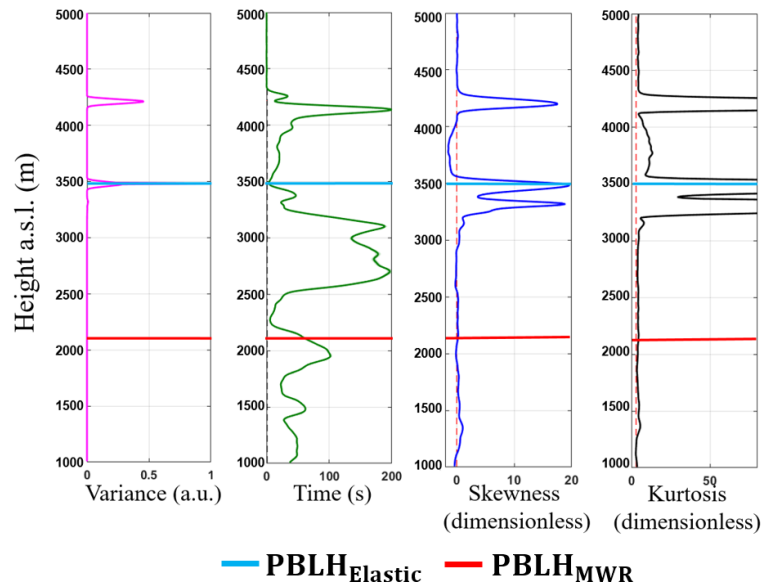


Figure 20 - Statistical moments obtained from 1064 nm wavelength data of elastic lidar (Mulhacen) in Granada between 12 -13 UTC on 08 July 2016. From left to right: variance [$\sigma_{RCS'}^2$], integral time scale [$\tau_{RCS'}$], skewness [$S_{RCS'}$] and kurtosis [$K_{RCS'}$].