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Discussions

Interactive comment on "Observing local turbulence and anisotropy during the afternoon transition with an unmanned aerial system – a case study" *by* A. Lampert et al.

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Turbulence anisotropy during afternoon transition

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Answers to Referee 1: Observing local turbulence and anisotropy during the afternoon transition with an unmanned aerial system - a case study

May 6, 2016

The authors would like to thank the anonymous referee for his/her suggestions. According to your and the other reviewers requests, a further analysis of the BLLAST observations during the afternoon and evening transition has been made for 2 July 2011. Now UHF, soundings and tower measurements (all of them in site 1) are taken, apart from observations from M^{2}AV (site 1) and frequent soundings (site 2) already shown in the previous version of the manuscript. Furthermore, results from a high-resolution mesoscale simulations are used to better describe the evolution of the LLJ and the anisotropy ratio during the evening transition of 2 July 2011 in Lannemezan. As a result, find below the main changes in the revised version of the manuscript, some of them directly answering your requests.

- The 3 new co-authors (M.A. Jiménez, J. Cuxart and D. Martínez) have performed the numerical simulations and data analysis, apart from contributing to the discussion of the new results.

- The manuscript has a different organization. The introduction is re-written according to the reviewers' requests (now the turbulence and anisotropy during the evening transition is described, as well as the low-level jet, LLJ). The next section is devoted to the observations and model setup. The atmospheric situation and the features of the observed LLJ are described in sections 3 and 4, respectively, and in section 5 the anisotropy is evaluated. Finally, the discussion of the results is shown in section 6 and the conclusions in section 7.
- The title has now changed into "A study of local turbulence and anisotropy during the afternoon and evening transition with an unmanned aerial system and a mesoscale simulation"

Find below the answer or your requests point by point. The text from the review is given in italic letters, the answers are provided in normal letters. Changes to the text of the manuscript are indicated in quotation marks.

1 Answers to major comments

The use of unmanned aerial vehicles in the study of meteorology is still novel. To this end, manuscripts such as this one are to be encouraged as the scientific potential of UAVs seems to be large.
We are happy that the referee acknowledges the potential of UAS in the field of meteorology and totally agree with the importance of UAS.

However, whilst the manuscript contains some interesting and tantalizing data, and its methodology is sound, its conclusions are not robust because the dataset is too small. This is clear from a basic statistical viewpoint alone.

The UAS data set is forcefully small, due to its mode of operation. Therefore, to supplement it in order to have a broader picture of the events and mechanisms in place, we have tried to use most of the available data during that BLLAST IOP1. Now UHF, soundings and tower measurements (all of them in site 1) are analysed in depth, apart from observations from UAS (site 1) and frequent soundings (site 2) already shown in the previous version of the manuscript. The analysis is complemented by the model outputs from a high-resolution mesoscale simulation obtained from the MesoNH model (model setup is described in section 2.3 and in more detail in Jiménez and Cuxart (2014)). All sources of data are giving consistent results as it is seen in the current Figure 5. The model is able to reproduce the LLJ formation reported from the observations (Figure 2). For the evening transition, there are only UAS observations of turbulence at higher levels (up to 300m AGL) and for this reason this case is taken in this work. The studied case of 2 July is described in section 3 and 4 pointing the similarities and differences to the other IOPs during the BLLAST campaign. Turbulence and anisotropy of the IOPs during the BLLAST campaign are further analysed in Canut et al. (2015) from tethered balloon observations.

In addition, the presence of a low-level jet on this occasion leaves the reader asking: what would have happened to the anisotropy ratio if the LLJ had not been there ? If you can so much as answer this question, then the paper will be vastly improved.
We see that in the daytime the anisotropy ratio (A) provided by the sources are very similar and slightly above 1, in coherence with a dry sheared convective boundary layer. At the evening transition, A takes larger values (a factor between 2 and 5), very likely because the contribution of the convection weakens significantly and the eddies become progressively shallower and more elongated. The beginning of the Inertial Subrange (IS) of the spectrum shifts to the right, and after sunset the eddies have relatively shallow dimensions and are elongated along the main wind direction (Mason and Thomson (1987)), showing large values of anisotropy at these scales. If a LLJ is present (maximum of wind speed at lower levels and close to the top of the temperature

inversion), eddies are even more elongated and therefore A increases. Now Figure 7b shows the anisotropy ratio computed from tower observations of the studied case (2 July) and the one of 1 July (no LLJ during the evening transition). It is found that the anisotropy is larger when the LLJ is present, although in both cases the anisotropy increases during the evening transition when the eddies are more elongated in the wind direction (Mason and Thomson , 1987).

At night the values of A diverge depending on the scale and the source of data (new figure 7a). The model resolved motions at the height of the LLJ is just as anisotrope as in the transition, not feeling significantly the effects of thermal stratification at those levels. Instead, M^{2}AV and the tower, that measure at smaller scales, provide much higher values of anisotropy, indicating that at the smaller scales variability in the horizontal is significantly larger than at the vertical, therefore indicating that thermal stratification may be playing an important role, moving the upper limit of the IS to very small eddies.

If the LLJ was present on all available measurement days, then of course this is important too, and more flight data will in any case boost the statistical base. Fig 10 in particular could be added to and improved. I see from Lothon et al that three other days are potentially available from the M2AV dataset. For this reason, it is probably best to label such a revision as major although it is difficult for me to know how much work is involved.
There are only available observations of turbulence from M^{2}AV during the afternoon and evening transition of the day studied here (2 July). For this reason the data analysis is limited to 2 July. Nevertheless, the results obtained here are compared to those reported from other IOPs where LLJ was not present during the evening transition. It is found that during the IOPs with clear skies and weak wind conditions the anisotropy ratio increases during the evening transition but this ratio increases even more when the LLJ is present (only for IOP10, 2 July). This is further explained in section 6 with the help of the new figure 7.

The conclusions section is also very small, as mentioned below. This should be improved with a larger dataset for a better range of meteorological conditions.
The conclusion section is re-written to incorporate the new analysis (extra sources of data and model outputs). The main findings of the work are: (1) during the afternoon transition, TKE decreases as time progresses and it is minimum close to sunset. Afterwards it increases due to the presence of a LLJ. (2) the shear generated by the presence of a LLJ is the responsible of the increase of the anisotropy during the evening transition, being larger than if no LLJ is present. (3) the anisotropy ratio computed from difference sources of data (model and observations) shows that A depends on the scale (spatial and temporal) of motions included in the data.

A bit of an overhaul of the figures is required too, as described in detail at the bottom of the details below.
We would like to thank the referee for the suggestions. For the revised version, new figures were created, taking into account the additional sources of observations and mesoscale simulation.

2 Answers to minor comments

In general:Stick to either local time or UTC. Do not keep changing from one to the other. But state, both in the abstract and in the main body of the paper, that local time = UTC+2hr.
We will stick to UTC time. As the longitude of Lannemezan is almost the same as Greenwich, in solar time Lannemezan has the same UTC hour as Greenwich. We now comment on this in the manuscript.

Abstract. Line 1 "We analyse airborne observations..." Line 1-2 "directions" Line 2 "turbulently-mixed", "stably-stratified" Use local times in the abstract (but state local= UTC+2hr) Line 5. "...anisotropy ratio, defined here as the ratio of the variance of horizontal to vertical wind speed, changes..." Line 7. "...mean value of about 1 to a mean value of 2 about one..." Line 8. "...a mean value of about 8 one hour after sunset."
We thank the referee for the improvements and changed the text accordingly.

Introduction. Line 28. "...is described in two distinct consecutive phases:" Lines 33-35. Is this typical ? Do you see it here for the case studied ?
Previous works show that the evolution of the TKE during the afternoon and evening transitions can be described in two consecutive phases according to the decrease of the surface heat flux (Steeneveld et al. , 2010). This is now clarified in the introduction: "The combined inspection of observations (LITFASS-2003 experiment) and a mixed layer model performed by Nadeau et al. (2011) show that the TKE decay phase could be separated in two stages: a slow decay of TKE during the afternoon transition followed by a rapid collapse during the evening transition. Similar results were obtained from Rizza et al. (2013) from observations (CASES-99) and LES simulations." Similar results are obtained from the BLLAST dataset (Lothon et al., 2014) and this is now clarified in the results. Observations from M^2AV are not a proper dataset to check this two-phase process (observations available only at some vertical levels during some instants during the afternoon and evening transitions) but results from the mesoscale simulations evidence this decaying of turbulence (see new figure 4d).

Section 2.1 Line 61. The proximity to the Pyrenees I found initially worry because of effects such as gravity waves on the measurements. Given the wind directions during the measurements, this probably isn't an issue. But I would recommend stating the likelihood, or not, of the effect of the mountains on flow. I see gravity waves are not

mentioned in Lothon et al (2014) at all !!
We completely agree with your point. Now the complex terrain area is better described, as well as the organization of the flow at lower levels (new section 3) with a deeper analysis of the observations and the mesoscale simulation during the studied transition (2 July 2011). The general NE flow on 2nd July in the BLLAST site co-existed with the plain-mountain system that generated northerly flows in the daytime over the foothills of the Pyrenees (see for instance new Figure 2a), and the Aure valley -just South of Lannemezan- presented a well developed upvalley wind system. As sunset approached, downslope flows appeared in the Aure valley and generated a down-valley flow which blew underneath the decaying upvalley flow. The down-valley flow will increase its depth and intensity during the first hours of the night and will progress towards Lannemezan reaching it around midnight (Figure 2d). Similar results were obtained by Jiménez and Cuxart (2014). As sunset approached, the wind veered clockwise in the BLLAST site, generating after sunset a well defined LLJ from SE, with maximum wind values around 6 $\mathrm{m\,s^{-1}}$ at heights between 150 m and 300 m AGL. That structure was sampled by the M^{2}AV's last flight.

About your question of the presence of gravity waves, during the first 3 flights, stably stratified conditions were not present yet in the ABL (they are during the afternoon and early evening transition, when surface cooling starts) and therefore no ambient conditions were favourable to develop gravity waves in the ABL. However, during the last flight (about 2100 UTC) cooling is stronger and Román-Cascón et al. (2015) found gravity waves between 2030-2130 UTC close to the surface (they are analysing surface pressure and other atmospheric magnitudes up to 2 m AGL). Figure 8 in Román-Cascón et al. (2015) (vertical profile of the observed Brunt-Vaisala frequency) shows that gravity waves can be found up to about 100 m AGL but not at higher levels (where the M^{2}AV sampled). Later on (from 2100 UTC to midnight), gravity waves could be found but the presence of the LLJ does not allow a strong nocturnal cooling (strongly stably stratified conditions), departing from the favourable conditions for the development of the gravity waves.

The model is not able to capture these observed gravity waves (Román-Cascón et al. , 2015) since they are attached to the ground. In fact, the model does not see this maximum of wind at 2,m AGL that they report since the first grid level is at 1.5 m. A comment on the presence of gravity waves is included in section 4, when the description of the processes during the studied transition is made. We do not consider that the possible presence of Internal Gravity may alter the discussion on the other relevant issues treated in the paper and we just mention them and refer to (Román-Cascón et al. , 2015) for further information.

Line 65. "...with sides about 3-4km long were equipped..." Line 69. "ultra-high" Line 70. "...which provide a measure of the boundary layer depth..."
We changed the text as suggested.

Lines 73-75. No need to describe what a sonde measures, this is standard. State what type of sondes were used e.g. RS92.
We changed the text to: "Standard GRAW and MODEM radiosondes were launched from site 1 during the intensive operation period (IOP) days at least 4 times per day at 0500, 1100, 1700 and 2300 UTC (launching times). In particular, on 2 July, additional radiosondes at 0200 and 2030 UTC were performed. The frequent radiosonde consists of a conventional Vaisala receiver and a global positioning system (GPS) radiosonde RS92SGP, that is tied to a couple of inflated balloons. "

Line 80 "M2AV flight tracks"
OK. Corrected.

Line 84. "...partially controlled..."
We changed the text to "It is started and landed manually, and can be fully controlled

during the mission by an autopilot system. For this case study, most ascents and descents as well as the race track pattern with straight horizontal legs were flown with the autopilot."

Section 2.2 Line 108-109 spelling: "temperature" Line 120 "calculated by two different methods" Line 121 "removing the zero offset and a linear detrend of the time..."
OK. Corrected.

Lines 125-130 gravity waves might be seen in such data. Is there any evidence for this ?
This is already answered in 5 points above.

Line 150. Need to define LLJ in the body text (it was defined only in the abstract).
ok, thank you.

Section 2.3 Line 160. No need to define geostrophic wind, remove words "determined by the...centrifugal force" Line 163. "especially at night" Line 164. "observed LLJ occurrence between 30 and 60 % of all nights" Line 171. "Further, for particular interest for the present study, it creates wind shear..."
OK. Corrected.

Section 3: maybe turn section 3 into Section 2.4 as it?s quite small?
We completely revised the structure of the manuscript. Now it is as follows:
1. Introduction
2. Observations and model setup
2.1 Field site and instrumentation
2.2 M^{2}AV data processing
2.3 Model setup

3. Atmospheric situation
4. The nocturnal LLJ as observed and modelled
5. TKE and anisotropy during the afternoon-evening transition
6. Discussion
6.1 Turbulence properties
6.2 Low-level jet as source of enhanced turbulence
7. Conclusions

Section 4.1 Line 198. What are the typical ascent/descent rates of the UAV ? You can then state the typical SLOPE of the UAV profiles which will help the reader visualise the horizontal distance covered for a given height change.
We included in the text: "The profiles were performed with an ascent rate of about 3.5 m s-1, the descent rate was about 8 m s^{-1}."

Line 217. "For Flights 1 and 2" Line 218. "decreases"
OK. Corrected.

Line 246. Does it really indicate stability and hence also turbulence ?
Now an extended analysis of the turbulence is made at different levels: (1) up to 60m AGL from tower, (2) from 150-300m AGL from M^{2}AV and (3) for the whole ABL from the mesoscale simulation. Besides, the observed and modelled potential temperature in the ABL is inspected. As a result, there is no need to indicate the stability and turbulence with the Ri since the vertical profiles and time series of the modelled and observed TKE and potential temperature are enough. As a result, the definition of Ri in old section 2 is removed, as well as the comments on line 246. However, the stability and turbulence are further described in sections 4 and 5.

Section 4.2 Line 249. Define "Zi" here (you define it on line 299, but it needs to be here).
Right. z_i is now defined the first time that is used (new section 5).

Section 4.3 Line 290-291. Does this refer to the following day ? Best to make it clear.
Right. The observations and model results are restricted from 1200 to 0000 UTC. The information of old section 4.3 is now incorporated in section 4 where it is briefly commented that the LLJ remains in the site until sunrise of the next day (as it is seen from model and observations). But this is beyond the temporal scope of this study.

Section 5.1 Line 309. "In Fig. 9"
OK. Corrected although the number of the figure has changed.

Lines 310-314. This is even more reason for adding more flight data to the analysis, as explained in the main comments section above. Statistically, the analysis given is barely acceptable and firm conclusions cannot be drawn.
With the limited number of flights, all of them corresponding to different flow regimes, it is not possible to make a well-posed statistical analysis. The approach taken, instead, is to analyze case by case, using the UAS data as another source of information together with all others.

Line 322. "flux reduces to zero..."
OK. Corrected.

Section 5.2 Line 327 and 330. No need to put m s-1 in italics. Lines 345-346. "...leads to a thermodynamic decoupling of the air that is in direct contact with the surface from the atmosphere above." Line 353. Do not use "A" notation; use the phrase anisotropy

ratio in full throughout. Line 363. "within the scale of a few km."
OK. Corrected.

Section 6. This section is too short. The use of UAV data for meteorological research is still novel. How can future studies of turbulence and the anisotropy ratio be improved upon in the light of BLLAST ? Would you change the flight patterns or the layout of the ground sites ?
The conclusion section is now re-written to incorporate the new analysis of the observations (UHF, tower and extra soundings) and the mesoscale model results. The main findings of the current work are:
(1) the results presented here show that the use of UAS for meteorological research complements the information given for other sources of data (soundings, tower, ...) to better characterize the lower atmosphere. Furthermore, turbulence measurements in the lower atmosphere can be performed with the M^{2}AV.
(2) M^{2}AV observations provide results consistent to those reported during the BLLAST experimental field campaign (observations from tower, UHF and soundings) and those obtained from a mesoscale simulation.
(3) During the day, a well developed CBL favours the isotropy conditions and the anisotropy ratio remains nearly constant. However, during the afternoon and evening transitions the stably stratified conditions and the general wind favour the elongation of the eddies in the prevailing wind direction, resulting in a loosing of isotropy. Therefore, the anisotropy ratio increases and specially due to the presence of a low-level jet, generated by the interaction between the large-scale winds and the nocturnal mountain-plain circulations.
(4) Once the anisotropy ratio is computed from different sources of observations and model, the spatial and temporal scales included there might induce differences in its value, highlighting which are the relevant processes included in the observations and in the mesoscale simulation results.
Besides, to improve the understanding of anisotropy probably flights well defined along

and across the turbulent elongated structures of longer track would bring much more supplementary information. To do so, efficient use of available information should be made beforehand and determine the high of the flight to use the batteries as optimal as possible to get long tracks within the legally allowed range (surveillance of the aircraft by the safety pilot with the eye, which means a radius of around 1.5 km, or using several safety pilots).

Line 368. "radiosondes" Line 371. "...vertical component coincided with the evolution of a LLJ."
OK. Corrected.

Figures. (i) Fig 1. Add on a distance scale of 1km, or perhaps 5 km, whatever seems best ? The UAV flight patterns here are very small. Could you make the present figure Fig 1a and add a Fig 1b to the right showing a zoom-in of the flights in nice detail ?
We replaced the figure with another two, showing the topography as represented in the model, and superimposed the observation sites and the flight tracks.

(ii) You should combine Figures 3 and 4, using potential temperature (Kelvin) on the x-axis. With suitable line styles/point symbols the distinction between radiosonde and M2AV profiles should be clear. Add profile times to the key for the M2AV data.
We replaced the figures with a new one (now Figure 5, see bellow), consisting of 4 subfigures, showing data of M^{2}AV, sounding, tower and simulations for each time a flight is available.

(iii) You should use "mid-profile times" for all profiles, regardless whether M2AV or radiosonde.
ok

(iv) Fig 8. Use same x-axis as Fig 7. Also add "W", "N", "E", "S" direction labels to the x-axis.
OK. See the changes in the new Figure 5 (two answers above).

(v) Figs 11, 12, 13. I can't help feeling that your interpolated contour plots are disturbing the real data. Please try using "pixel" plots to show true data only.
The plots regarding the UHF observations are improved according to you comment.

(vi) Add annotations showing the astronomical sunrise and sunset times, as appropriate, to Figs 10-13.
We included a vertical black line to indicate the sunset time in the time series and it is properly described in the caption of the figure.

References

Banta, R.M., Pichugina, Y.L„ and Brewer, W.A.: Turbulent velocity-variance profiles in the stable boundary layer generated by a nocturnal low-level jet. J. Atmos. Sci., 63, 2700-2719, 2006.

Canut, G., Couvreux, M., Lothon, M., Legain, D., Piguet, B., Lampert, A., and Moulin, E.: Turbulence measurements with a tethered balloon, submitted to Atmos. Meas. Tech., 2015.

Jiménez, M.A., and Cuxart, J.: A study of the nocturnal flows generated in the north side of the Pyrenees, Atmospheric Research, 145-146, 244-254, doi: 10.1016/j.atmosres.2014.04.010, 2014.

Lothon, M., Lohou, F., Pino, D., Couvreux, F., Pardyjak, E. R., Reuder, J., Vilà-Guerau de

Arellano, J., Durand, P, Hartogensis, O., Legain, D., Augustin, P., Gioli, B., Lenschow, D. H., Faloona, I., Yagüe, C., Alexander, D. C., Angevine, W. M., Bargain, E, Barrié, J., Bazile, E., Bezombes, Y., Blay-Carreras, E., van de Boer, A., Boichard, J. L., Bourdon, A., Butet, A., Campistron, B., de Coster, O., Cuxart, J., Dabas, A., Darbieu, C., Deboudt, K., Delbarre, H., Derrien, S., Flament, P., Fourmentin, M., Garai, A., Gibert, F., Graf, A., Groebner, J., Guichard, F., Jiménez, M. A., Jonassen, M., van den Kroonenberg, A., Magliulo, V., Martin, S., Martinez, D., Mastrorillo, L., Moene, A. F., Molinos, F., Moulin, E., Pietersen, H. P., Piguet, B., Pique, E., Romàn-Cascòn, C., Rufin-Soler, C., Saïd, F., Sastre-Marugàn, M., Seity, Y., Steeneveld, G. J., Toscano, P., Traullé, O., Tzanos, D., Wacker, S., Wildmann, N., and Zaldei, A.: The BLLAST field experiment: Boundary-Layer Late Afternoon and Sunset Turbulence, Atmos. Chem. Phys., 14, 10931-10960, doi:10.5194/acp-14-10931-2014, 2014.

Mason, P. J. and Thomson, D. J.: Large-Eddy simulations of the neutral-static-stability planetary boundary layer. Q.J.R. Meteorol. Soc.,13, 413-443, doi: 10.1002/qj.49711347602, 1987.

Nadeau, D. F., Pardyjak, E. R., Higgins, C. W., Fernando, H. J. S., and Parlange, M. B.: A simple model for the afternoon and early evening decay of convective turbulence over different land sur- faces, Bound.-Lay. Meteorol., 141, 301–324, 2011.

Rizza, U., Miglietta, M. M., Degrazia, G. A., Acevedo, O. C., and Marques, E. P.: Sunset decay of the convective turbulence with Large-Eddy Simulation under realistic conditions, Physica A, 392, 4481–4490, 2013.

Román-Cascón, C. and Yagüe, C. and Mahrt, L. and Sastre, M. and Steeneveld, G.-J. and Pardyjak, E. and van de Boer, A. and Hartogensis, O.: Interactions among drainage flows, gravity waves and turbulence: a BLLAST case study, Atmos. Chem. Phys., 15, 9031-9047, doi:10.5194/acp-15-9031-2015, 2015.

Steeneveld, G. J., Wokke, M. J. J., Groot Zwaaftink, C. D., Pi- jlman, S., Heusinkveld, B. G., Jacobs, A. F. G., and Holtslag, A. A. M.: Observations of the radiation divergence in the surface layer and its implication for its parameterization in numer- ical weather prediction models, J. Geophys. Res., 115, D06107, doi: 10.1029/2009JD013074, 2010.

./FIGURES/figure_7_revisions.pdf

Figure 7. (a) Time series of the anisotropy computed from different sources: M^2AV flight observations during the four flights for different heights (in blue); tower measurements at 60 m AGL every 5 min (in green); and model results averaged between 150 m and 300 m AGL to be close to the altitudes of the M^2AV observations considering a spatial area of 10 km x 10 km centered at Lannemezan (in red). The same in (b) but computed from tower observations during the IOP9 (1 July, no LLJ) and IOP10 (2 July, with LLJ). The time of sunset is represented with a black vertical line. Note the logarithmic scale on the y-axis.

`figure_2.pdf`

Figure 2. Modelled 100 m AGL wind vectors together with wind speed (in colours) and the topography lines (in blue) at different instants (a) 1500 UTC, (b) 2030 UTC, (c) 2130 UTC, (d) 0000 UTC. The 60 m wind vector observed by the tower is plotted with a red arrow.

`figure_5.pdf`

Figure 5. Vertical profiles of wind direction (in °) on the left, wind speed (in $\mathrm{m\,s^{-1}}$) in the center and potential temperature (in K) on the right, from $\mathrm{M^2AV}$ (in violet) for the four flights of 2 July 2011: (a) 1500, (b) 1630, (c) 1900 and (d) 2110 UTC. Vertical lines and dots correspond to instantaneous values from the vertical profiles and to mean values for each horizontal leg, respectively. $\mathrm{M^2AV}$ data are compared against instantaneous observations from UHF (blue squares), tower (black dots), and frequent (red) and standard soundings (black) together with mesoscale simulation results (green). Legend indicates the corresponding times to each data source.