

Dear Dr. Banakh,

Thank you very much for your positive feedback and constructive suggestions. I appreciate your remarks and am glad to provide more information on each of your comments. This information will be included in the paper.

*1. As the authors formulate, the reason for the considered in the paper task is revealing the possible errors in airborne lidar detection of CAT. At the same time there is no information in the manuscript which method is used for recognition of the CAT areas. There is no analysis of expected variations of lidar echo signal power caused by CAT in comparison with the variations of that because of the pitch effect. It is not clear what is comparative contribution of the CAT and pitch effect to the total echo signal power variations.*

Comparison lidar echo signal caused by CAT and signal variations caused by pitch angle fluctuations should account the fact that pitch angle fluctuations can lead to variations of both turbulence and aerosol signals. When the sensing beam deviates from the forward propagation and goes to the area with different turbulence the lidar echo signal is changing proportionally to ratio between both turbulence on the flight trajectory and turbulence which the strayed beam sense. Similarly, the contribution of aerosol response in the presence of pitch angle fluctuations depends on comparable aerosol density (or backscattering coefficient) in forward and strayed directions. The signal variations due to pitch angle fluctuations can fall down to the background level as presented in simulations and experiment Fig.5(b,f), Fig.6b. Estimations of expected turbulence signal respond based on the assumptions of the value of the structure characteristic  $C_n^2=2.5 \times 10^{-16} \text{ m}^{-2/3}$  were performed by Dr. Vorobiev in the framework of the DELICAT project. Thus, the pitch angle fluctuations can lead to signal level changes from the background level up to level of response of turbulence/aerosol which is present in the area sensed by the strayed beam.

Based on this comment the following information was added to the paper:

“The thorough analysis of CAT detection by DELICAT lidar is given in References (Vrancken et al., 2016; Veerman et al., 2014; Hauchecorne et al., 2016). In a few words, a high-power UV Rayleigh lidar system was installed on an aircraft in a forward-looking configuration as described in detail in (Vrancken et al., 2016). The turbulence area detection was based on the lidar measurements of the fluctuation in density of air associated with the turbulent wind (Feneyrou et al., 2009; Vrancken et al., 2016; Hauchecorne et al., 2016). This idea was tested at first with using of the ground-based lidar (Hauchecorne et al., 2016). Detail discussion of the  $C_n^2$  evaluation method and experimental examples of turbulence lidar signal responses with estimated values of  $C_n^2$  can be found, for example, in the Chapter 4b of the Ref. (Hauchecorne et al., 2016).”

### **References 1**

- Feneyrou, P., Lehureau J.-C., and Barny H.: Performance evaluation for long-range turbulence-detection using ultraviolet lidar, *Applied Optics*, 48, 3750–3759, 2009.
- Veerman, H. P. J., Vrancken, P., Lombard, L.: Flight testing delicat - a promise for medium-range clear air turbulence protection, European 46th SETP and 25th SFTE Symposium 2014, Lulea, Sweden, 2014.
- Vrancken, P., Wirth, M., Ehret, G., Barny, H., Rondeau, P., & Veerman, H.: Airborne forward-pointing UV Rayleigh lidar for remote clear air turbulence detection: system design and performance. *Applied optics*, 55 (32), 9314-9328 2016.
- A. Hauchecorne, C. Cot, F. Dalaudier, J. Porteneuve, T. Gaudo, R. Wilson, C. Cenac, C. Laqui, P. Keckhut, J.-M. Perrin, A. Dolfi, N. Cezard, L. Lombard, and C. Besson: Tentative detection of clearair turbulence using a ground-based Rayleigh lidar, *Applied Optics* 55, 3420–3428, 2016.

*2. Strong inhomogeneity of aerosol concentration is serious problem in interpretation of results of lidar remote sensing the turbulent atmosphere. To exclude the uncertainty in lidar determination of intensity of turbulence caused by variations of aerosol concentration along probing path, two equivalent receiver channels are used [1-5], for example.*

*Some comment on possibility of application of similar approach to avoid impact of pitch effect in airborne lidar detection of CAT may be useful in the paper.*

Based on this comment the following discussion was added in the Introduction:

“There is another technique of CAT detection based on backscattering enhancement (BSE) effect which was initially found in the theoretical research (Vinogradov et al., 1973) and then experimentally confirmed (Gurvich and Kashkarov, 1977). In framework of DELICAT project the idea of possible turbulence strength estimation based on BSE was theoretically analyzed and reported (Gurvich, 2012; Gurvich and Kulikov, 2013). The two channel scheme based on backscattering enhancement (BSE) looks very promising for future airborne applications in light of both thorough theoretical analysis and experimental evidence of success reported in (Banakh and Smalikho, 2011; Banakh, 2011; Banakh and Razenkov, 2016a, b). This technique is also sensitive to the airborne specific noise caused by fluctuations of flight parameters.”

## **References 2**

Banakh, V. A. and Smalikho, I. N.: Determination of optical turbulence intensity by atmospheric backscattering of laser radiation, *Atmos. Oceanic Optics*, 24 (5), 457–465, 2011.

Banakh V.A., A.; Razenkov I. A.: Lidar measurements of atmospheric backscattering amplification, *Optics and Spectroscopy*, 120 (2), 326-334, 2016.

Banakh V.A., Razenkov I.A.: Refractive turbulence strength estimation based on the laser echo signal amplification effect, *Optics Letters*, 41 (19), 4429-4432, 2016.

Vinogradov, A. G., Kravtsov, Y. A. and Tatarskii, V. I.: Backscattering enhancement effect on bodies placed in a medium with random inhomogeneities, *Izv. Vyssh. Uchebn. Zaved., Radiofizika* 16 (7), 1064–1070, 1973.

Gurvich, A. S. and Kashkarov, S. S.: On the issue of scattering enhancement in a turbulent medium, *Izv. Vyssh. Uchebn. Zaved., Radiofizika* 20 (5), 794–800, 1977.

Gurvich, A. S.: Lidar sounding of turbulence based on the backscatter enhancement effect, *Atmospheric and Oceanic Physics*, 48 (6), 585–594, 2012.

Gurvich, A. S., and Kulikov V. A.: Lidar sensing of the turbulence based on the backscattering enhancement effect, *SPIE LASE, Free-Space Laser Communication and Atmospheric Propagation XXV*, pp. 86100U-86100U, International Society for Optics and Photonics, 2013.

*3. It is known (see works by A.S. Gurvich) that at the heights of about 10 km and above the refractive turbulence is strongly anisotropic one and turbulent inhomogeneities have vertical dimensions much less than horizontal ones similar to thin aerosol clusters considered in the paper. These inhomogeneities can cause the refraction of probing beam. Estimation of impact of atmospheric optical refraction on probing beam propagation direction as compared to the pitch angle variations may be useful.*

Following this comment the following discussion was incorporated in the Introduction:

“The atmospheric effects can bend the sensing beam and prevent to lidar turbulence detection based on any principle. The turbulence anisotropy can noticeably bend the light propagated over such long distances (Gurvich and Chunchuzov, 2003; Sofieva et al., 2010). This impact should be almost negligible for short fifteen km optical path; possible laser beam trajectory deviation of about ten meters is small taking into account the thickness of cluster discussed in our paper (100 meters). At the same time, refractive layers can also significantly change the trajectory of optical wave propagation (Werf, 2003; Nunalee et al., 2015). The consideration of such effects can be performed in the framework of geometrical (Southwell, 1982; Werf, 2003; Nunalee et al., 2015) or wave optics (Vorontsov and Kulikov, 2015; Kulikov et al., 2017). Both turbulence anisotropy and possible impact of refractive layers should be considered in the case of extended sensing distances.”

## **References 3**

Gurvich, A. S., and Chunchuzov I. P.: Parameters of the fine density structure in the stratosphere obtained from spacecraft observations of stellar scintillations, *Journal of Geophysical Research: Atmospheres*, 108.D5, 2003.

Sofieva, V. F., Gurvich A. S., and Dalaudier F.: Mapping gravity waves and turbulence in the stratosphere using satellite measurements of stellar scintillation, *Physica Scripta*, T142, 014043, 2010.

Vorontsov, M. A., and Kulikov, V. A.: Framework for analysis of joint impact of atmospheric turbulence and refractivity on laser beam propagation, OSA conference: Propagation through and Characterization of Distributed Volume Turbulence and Atmospheric Phenomena pp. PM4C-1, 2015.

Kulikov, V. A., Basu, S., and Vorontsov, M. A.: Simulation of laser beam propagation based on mesoscale modeling of optical turbulence and refractivity, OSA conference: Propagation Through and Characterization of Atmospheric and Oceanic Phenomena, PTh3D-3, 2017.

Southwell W. H., Ray tracing in gradient-index media, J. Opt. Soc. Am. 72, 908-911, 1982.

der Werf S. Y., Ray tracing and refraction in the modified US1976 atmosphere, Appl. Opt. 42, 354-366, 2003.

Nunalee C. G., He P., Basu, S., Minet J., and Vorontsov M. A.: Mapping optical ray trajectories through island wake vortices, Meteorology and Atmospheric Physics, 127(3), 355-368, 2015.

*4. There is very detailed introduction in the manuscript which contains a lot of information in the paper subject.*

*But part of them is not necessary. For example, it is obviously that nonlinear effects (filamentation) can not be expected for probing nano pulses with pulse energy about hundred of mJs used in typical lidars.*

This information was excluded.

Dear anonymous Referee,

Thank you very much for your comments. I appreciate your suggestions and am glad to update following your comments.

*1. The abstract provides a detailed information however it would be nice to provide also some values from their results.*

The pitch angle fluctuations uncompensated by gyro-platform with residual rms error about 0.1–0.2 degrees in presence of aerosol concentration variations on a scale of 100-300 m can have a significant impact on the level of backscattered signal changing it a few times or even more.

*2. Page 4, line24: Please consider providing reference at the end of this line.*

The analysis of experimental results demonstrated a rapid spatiotemporal evolution of aerosol clusters (Veerman et al., 2014, Fig. 22).

*3. Page 13, line 15: The authors are kindly requested to define if it is full or half angle the corresponding angular beam value that is provided in the manuscript.*

The full angular beam divergence was about of 200 rad. Following your comment this is mention in the paper:

“The lateral dimension  $l_{\perp}$  is determined by the initial diameter  $D_0$  of the sensing beam and full divergence angle”

*4. Page 13, lines 26: I would kindly suggest to the authors to provide the latitude/longitude points with less decimal numbers if possible. Please correct this through the entire manuscript.*

These numbers were corrected through the manuscript.

*5. Page 13, line 30: The authors mention that they choose the spatial window 4-14 km for their experimental study, because it is almost free from other noise factors. Please comment more on this decision.*

The lidar signal correction from molecular attenuation is presented in Fig.17 (Veerman et al., 2014). It mentioned there that the lidar signal is exploitable from 3 km to 15 km due to saturation effect. In order to avoid this problem completely and be sure that noises due to equipment instability do not impact on our research results we chose 4 km as minimal distance for signal analysis.

*6. One line later at the same page (Line 31) they state that the data from Figure 6a are provided with no pitch angle fluctuation and in Figure 6b with pitch angle fluctuation. The authors are kindly suggested to state (in the manuscript and in the corresponding caption of Figure 6) much this fluctuation is.*

At least three aerosol cluster's responds can be found at the Fig.6b. The first two clusters, firstly detected at distances 6 km and 6.5 km, respectively, are weak. It can be seen that there are breaches in the signal which appeared simultaneously in both responds. The breaches demonstrate the same behavior as simulated (see Fig.5) for the case of presence of uncompensated pitch angle fluctuations. The value of observed signal was changed about 3 times.

*7. Figure 6: For reasons of clarity it would be useful for the reader if the color bars of this figure were within the same limits. I would kindly suggest to the authors to provide the z axis with the same min max values and interval.*

Thank you for the suggestion. The limits of color bars are changed.

Dear Dr. Vrancken,

Thank you for your comment. The paper was revised in order to clarify our main statements and highlight foundation for our choice of simulating parameters. For this reason, the data of aircraft measurements of pitch angle fluctuations were included in Section 4. The simulation of the interval of the experimental measurements was also included in the Section 5. The discussion in both simulation and experiment results was expanded. The misprints and misleading places were corrected. The line-by-line answer on your comments is presented below.

*“This paper aims at comparing airborne horizontal lidar measurements of aerosol clusters (or possibly hydrometeor clusters / small clouds) is the presence of beam angle fluctuations obtained during an airborne campaign with numerically modelled lidar signals for the same case.”*

That is what we declared and that was done during the research.

*“The declared purpose (in the abstract) is to give a boundary condition in order to separate lidar signal variations attributed to turbulence (molecular density variations) from variations due to beam angle fluctuations”.*

I would like to provide a detailed answer on this remark, which reappeared a few times through the comment.

The DELICAT system design, namely measuring of two signals with parallel and perpendicular polarizations correspondingly, allows easily distinguishing the signal from non-spherical aerosol and turbulence. The separation of the signal from spherical aerosol, which does not depolarize the incident radiation, from turbulence has difficulties because both turbulence and symmetrical aerosols have the same polarization properties. The aerosol density fluctuations which are expected in the strong turbulence areas can lead to additional signal variations aggravating the turbulence strength estimate.

However, the question of separation of the turbulence and aerosol signal responses was not the goal of our research. The main problem, upon which we focus in this paper, is strong signal variations, such as presented on Fig.6, which have no explanation. Insight into possible reasons of this behavior allows distinguishing these variations from, for example, the temporal evolution of the aerosol along the aircraft path. In our research, we considered a wide range of aerosol clusters' sizes and cluster evolution times and took into account different positions of these clusters ahead the flight direction. Based on our analysis, we can specify the range of possible sizes of the aerosol clusters that can influence the lidar backscattered signal in the presence of pitch angle fluctuations presented in the figures and discussed in the text. Finally, we conclude that the experimental measurements for specific flights contain signal variations with the same type of behavior, corresponding to areas of strong pitch angle fluctuations measured onboard the aircraft.

The research exposed the signal fragments that was outside of the flight trajectory and cannot be used for the turbulence strength estimation without additional assumptions (added to the Conclusions):

*“The signal from the areas with significant pitch angle fluctuations can be used only with additional assumptions due to the fact that the sensing beam deviates from the flight trajectory. We need to assume that turbulence strength does not significantly change at the scale of this deviation which is fulfilled only for the short distances and small angle fluctuations. Otherwise this deviation would lead to the turbulence strength estimation changes which cannot be corrected due to absence of backscattered signal from the*

actual aircraft trajectory. At the same time, the aerosol clusters' evolution in absence of significant uncompensated fluctuations of the pitch angle should not prevent to the turbulence strength estimation. The numerical simulations shown that, for reasonable parameter range, these cases can be distinguished.”

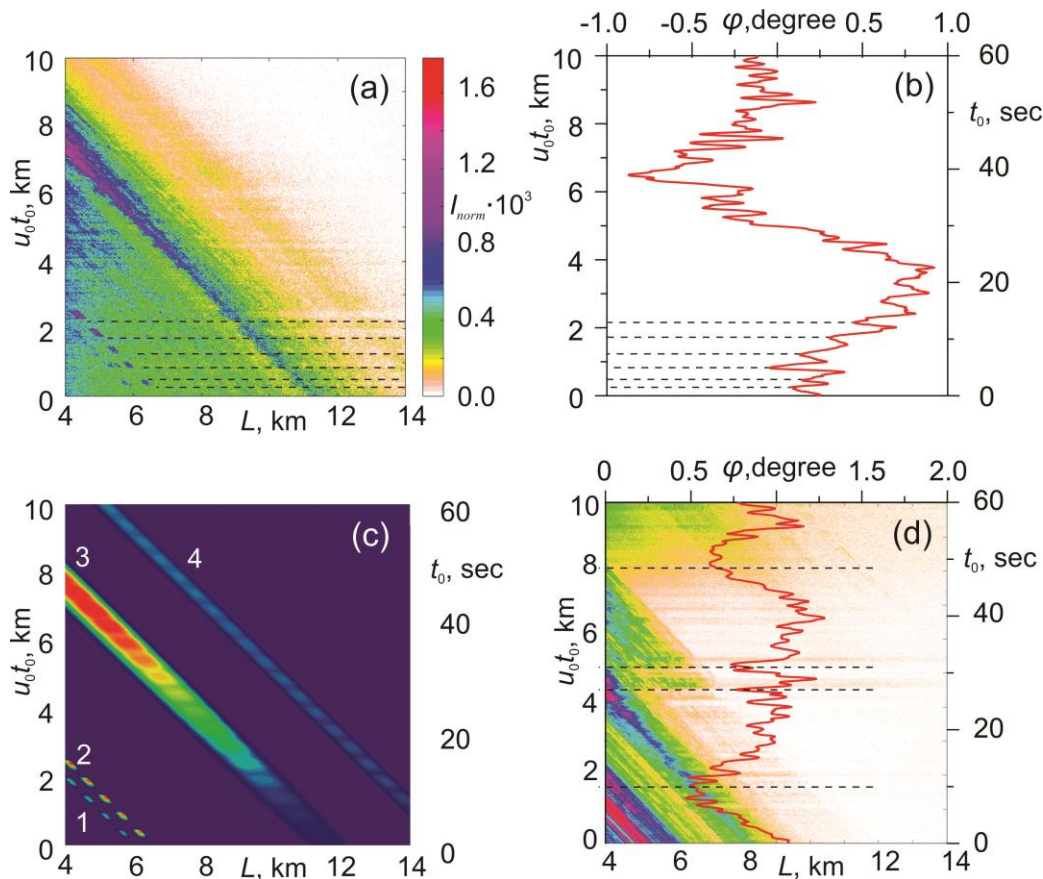
For the sake of clarity, the fourth sentence in the abstract which could be misleading was changed as follows, in order to better specify the research goals:

“In this paper, we discuss possible error sources imminent to this technique, related to fluctuations of the flight parameters, which may lead to strong signal variations caused by the random deviations of the sensing beam from the forward flight trajectory.”

*“The assumptions taken on values of the beam movement are rather arbitrary and not well-founded as are the parameters of the aerosol “clusters””*

The choices of both maximal amplitude of pitch angle fluctuations and cluster's parameters are based correspondingly on the rms of typically used compensation systems and observations of aerosol layers/clusters (detail discussion of quantitative cluster's characteristics with citations is given in Introduction).

In order to make clear our choice of beam movement parameters the new figures (Fig.6 (b) and (d)) presenting on-board measurements of pitch angle fluctuations were incorporated in the paper.



“Fig.6 The experimental data and numerical simulations: (a) the normalized intensity  $I_{norm}$  measured during 1 minute at airborne experiments (20.22-20.23); (b) measured pitch angle fluctuations correspond to (a); (c) simulations of the experiment presented in (a), the clusters are marked by their numbers; (d) the normalized intensity  $I_{norm}$  measured during 1 minute at airborne experiments (20.32-20.33).”

The simulations of the experiment were also performed (Fig.6c). This simulations demonstrate the values of the clusters' characteristics and pitch angle fluctuations which fit the experimental observations. This simulations as well as measured pitch angle fluctuations is now discussed in the experimental section:

“The experimental observations shown in Fig.6 (b) and (d) demonstrate that there are fast and slow pitch angle fluctuations, with the characteristic time scales of 3-4 seconds and about 10-20 sec, respectively. The dotted lines in panels (a), (b) and (b) highlight period of these fluctuations. For the visual convenience only periods of few fast fluctuation in Fig.6 (b) and only few slow fluctuations in Fig.6 (d) are highlighted. The pitch angle fluctuations result in significant changes of backscattered signal. This impact can be seen, for example, in Fig.6a where each signal breach is a result of corresponded pitch angle fluctuations. Two significant signal changes due to slow pitch angle fluctuations can be seen in Fig.6d. The two clusters, first at the  $u_0t_0=5$  km (30 sec) and second at  $u_0t_0=8$  km (50 sec), are suddenly appeared in the field of view due to significant change of the pitch angle presented in the figure by the red curve. In order to resolve the features of backscattered signal caused by the slow pitch angle fluctuations, this type of fluctuations was chosen for the numerical simulation section.

Consider the first and second clusters in Fig.6a which firstly detected at distances 6 km and 14 km, respectively. It can be seen that there are breaches in the signal which appeared simultaneously in both responds. The value of observed signal was decreased by 3 times from the undisturbed value in the breaches. The breaches demonstrate the same behavior as simulated (see Fig.6c) which is typical for the case of presence both uncompensated pitch angle fluctuations and aerosol clusters.

In order to simulate observed in (Fig.6a) effect, we chose four clusters with parameters presented in Table 2. The results of the simulations are presented in Fig.6c. The density of the first and last cluster is twice less than that of the second and third cluster. The first and the second clusters have vertical thickness about 100 meters, while the third and fourth one have thickness about 300 meters. For this reason, the pitch angle effect on the variations of the backscattered signal from the last clusters is weak. The period of pitch angle fluctuations was chosen  $T_\phi = 2:85$  sec in accordance with observed fast fluctuations (Fig.6a). The correcting parameter  $\phi = 0.5\pi$ .

The maximal amplitude  $\phi_0$  of the pitch angle fluctuations in the simulation was 0.6 degree (corresponds to 0.2 degree rms). This parameters of the clusters and pitch angle fluctuations allows to fit the experimentally observed decreasing of the signal level and time interval between the signal reappearance (sizes of the breaches). Based 5 on our numerical analysis we can conclude that the characteristic vertical size of the aerosol clusters provide a noticeable impact on the backscattered signal is about 50-100 meters. The decreasing of vertical size of the aerosol clusters would increase of this estimation.

If we assume that  $\phi_0 = 0:15$  degree (corresponds to 0.05 degree rms), the experimental results can be approximated with the cluster thickness 25-30 m.”

*“Regarding the real airborne measurements, the flight data (from the IS, notably) are not taken into account for reference”*

The flight data were analyzed included all the measured parameters, i.e. changing of altitude during the flight, fluctuations of yaw, roll and pitch angles etc. We did not present these data in the paper, because we arrived at the conclusion that it is only pitch angle fluctuation that really matters, given the reasonable sizes of atmospheric aerosol clusters/layers (discussed in the paper). Based on this comment the discussion of changes of the flight parameters information was expanded in the Section 5:



“The experiment shows that the yaw as well as roll angle fluctuations did not exceed pitch angle ones (excluding few times of significant elevations/descent moments during the flight). The altitude changes during the flight, excluding few areas of the significant elevations/descent, did not exceed a value of about ten meters. In accordance with the sensing geometry under discussion and possible sizes of the aerosol clusters, only pitch angle fluctuations can result in noticeable signal changes. The pitch angle fluctuations presented in Fig. 6b corresponded to the lidar backscattered signal presented in Fig.6a; both backscattered signal and pitch angle fluctuations for the other observation interval are shown in Fig.6d. One can see that backscattered signal breaches appeared simultaneously with the pitch angle fluctuations.”

*“The individual analysis and the respective comparison are performed rather qualitatively and “by eye”, I cite here: page 13, lines 3-4 – “more distorted”, “more intense”. A quantitative statement is lacking here.”*

The goal of our paper was to find a reason of uncontrolled backscattered fluctuations in the presence of aerosol and qualitatively describe it. Since we concluded that this is pitch angle fluctuations in the presence of aerosol clusters, we distinguished ranges of both possible angle fluctuations and cluster characteristics (sizes, evolution times) which can result in noticeable signal level changes. Thus the general conclusion from Fig.5 is that aerosol cluster’s thickness in the range [100-300] m will make a significant impact on the signal level variations for the considered range of correction errors [0.1-0.2] degree rms. This conclusion is based on the quantitative analysis and contains value of parameter ranges.

Following your comment, the additional discussion of intensity variations was added:

“For this reason the images are more distorted at the right side of each pane of Fig. 5.

For example, the backscattered signal at the sensing distance  $L=6$  km at the time corresponding to aircraft trajectory coordinate  $u_0t_0=5$  km in presence of aerosol clusters with thickness  $2\delta_0=100$  m (Fig.5(a,b)) decreased by about 20% (60%) from the level without the pitch angle fluctuations (see Fig.3) for  $\varphi_0=0.3$  degree and  $\varphi_0=0.6$  degree respectively. The signal decreased by about 10% in the presence of aerosol clusters with thickness 300 m for the  $\varphi_0=0.6$  degree and it had no noticeable changes for larger vertical sizes of cluster or smaller angles (Fig.5(c,d)). The backscattered signal from the aerosol layer at the sensing distance  $L=15$  km at the time corresponded to aircraft trajectory coordinate  $u_0t_0=5$  km with thickness 100 m decreased by about 85% for the  $\varphi_0=0.3$  degree and absent (only background level) for the  $\varphi_0=0.6$  degree. The signal decrease about 35% and 45% in presence of aerosol clusters with thickness 300 m for the  $\varphi_0=0.3$  degree and  $\varphi_0=0.6$  degree correspondingly, while for the thickness of the cluster about 900 m the only noticeable change (about 12%) can be found for the  $\varphi_0=0.6$  degree. Similar effects can be found in Fig.5 for each other moment of time (corresponding to flight trajectory coordinate  $u_0t_0$ ).”

“The vertical beam deviation caused by pitch angle fluctuations is about 30 m and 60 m at 6 km distance for maximal amplitude of angle fluctuations  $\varphi_0=0.3$  degree and 0.6 degree, respectively (Fig.4). It increases up to 75 and 150 meters for the 15 km distance. The sensing beam can easily move outside the aerosol cluster with a thickness less than the doubled shift size. Even for a movement with a smaller amplitude the backscattered signal will decrease due to decreasing of the cluster density nearby its edge.”

*“The respective chapters 4 and 5 are very short in content and discussion”*

Following your previous comments discussion in both these sections was expanded.

*“The conclusion effectively is none, because there is no quantitative measure that has been determined”*

The estimation of range of aerosol cluster thicknesses for possible IRS system rms is given in the Conclusions. Since it was the main problem stated in abstract and discussed through the paper, this estimation is the main quantitative result of the paper. Following this comment, the additional estimations are included in the Conclusions:

“The lidar backscattered signal from 15 km sensing distance can disappear (or decrease by about 85%) for compensation of pitch angle fluctuations with 0.2 degree rms (0.1 degree rms) in presence of aerosol clusters with characteristic vertical scale about 100 meters. Aerosol clusters with characteristic vertical scale about 300 meters lead to 45% (35%) signal decreasing for the same sensing distance and pitch angle fluctuations. The signal level fluctuations about 60% (20%) can be caused by pitch angle fluctuations with 0.2 degree rms (0.1 degree rms) at the 5 km sensing distance. Pitch angle fluctuations in presence of aerosol clusters with [100-300] m with angular correction smaller than 0.2 degree rms lead to breaches in the backscattered signal.

Presence of two or more aerosol clusters allows to easily distinguish the areas of significant beam wander due to signal decreasing caused by pitch angle fluctuations.”

In accordance your previous comments the numerical simulation of the experiment was performed. This result is also mention in the Conclusion:

“Simulations of the experiment are performed with assuming the aerosol clusters thickness about 100 meters (1000 m for the large cluster) for the case of pitch angle compensation with 0.2 degree rms. For compensation with 0.05 degree rms noise the corresponded value of the aerosol clusters’ thickness 25-30 meters (about 250 meters for the large cluster).”

*“The only conclusion that is valid is that such pitch variations of the sensing beam does generate fluctuations in the (normalized) signal when encountering a vertically extended object. But this is geometrically obvious.”*

Our conclusion about characteristic range of both pitch angle fluctuations and sizes of aerosol clusters which can significantly impact on the lidar signal have a solid foundation in presented simulations and analysis presented in the text. According to your previous comment the experimental measurements of pitch angle fluctuations were included in the paper for clarification of our choice of simulation parameters. The discussion of both experimental and simulation results was expanded.

*“The promised conclusion on separation of turbulence signal fluctuation (which is on the sub-percent level, Vrancken et al. 2016) from pitch/cluster variation is not given since mere arbitrary color bars are given without any notion on temporal characteristics.”*

This was not a goal of our research. The sentence in the abstract which could mislead to this conclusion was changed (the detail answer is presented on the first page).

*“In addition to above described contentual shortcomings, the text also yields many conceptual mishaps, some of them described here below. Some of them may be founded in language problems, other in hastily written assertions”*

The text was revised based on your comments.

*“In summary, I suggest at least a major revision of this document with not only incorporating the points listed here, but also delivering resilient numbers. This should include a thorough study and analysis of a whole range of possible pitch variations (amplitude/time constant-bandwidth), cluster vertical extent, cluster scattering/concentration distribution and temporal evolution of the latter. This was promised in the abstract and introduction.”*

The study and analyses of the pitch angle fluctuation effect on lidar backscattered signal was announced and performed. Based on your other comments the additional discussion of values presented in Figures were included in the paper. Our model was also used for simulation of the experimental observations (Fig.6c). Below, I shortly review the main paper results.

In this research, we, based on the cited literature, considered a wide range of clusters' sizes and possible evolution times. In the paper we only presented a range of cluster' parameters which can impact on the lidar signal based typical rms values of the compensation systems for the angle fluctuations. The period of the pitch angle fluctuations was based on experimental observations (Fig.6(b,c)).

The clusters' vertical sizes were limited by the range from 100 to 900 meters because the discussed effect disappears for larger sizes in the considered range of possible pitch angle fluctuations. This range was based on the typical errors of compensation systems used in the civil aviation. Maximal amplitude of pitch angle fluctuations changed from zero up to 0.3 degrees (0.6 degrees) which correspond correction with 0.1(0.2) degree rms. The on-board measurements of fluctuations of the pitch angle demonstrate the values about 1-2 degrees. We have no information about the success of the compensation, but the effects (contaminated with the pitch angle fluctuations) are clearly seen in the Figure 6. Therefore, the pitch angle fluctuations were only partially compensated.

We considered the range of aerosol clusters' horizontal sizes from 0.5 up to 2 kilometers. A larger size of clusters results in a wider signal area and does not produce any specific effects. Smaller cluster sizes are highly unlikely. We also considered the time of cluster temporal evolution to be in the range from 10 sec up to 60 sec. It is obvious that the evolution time can be much larger than 1 minute. However, the clusters with such a slow evolution look like time-constant structures during the experimental 1-minute observation. The faster evolution of clusters is doubtful.

Thus, we considered all reasonable ranges for pitch angle fluctuations, time of the clusters evolutions and their horizontal and vertical sizes. Following one of the previous comments, the simulations of the experiment was performed. The simulations showed that the ranges of aerosol clusters' parameters and pitch angle fluctuations, considered in the paper, allow to successful simulation of the effect which was observed experimentally.

*“Regarding turbulence, this aspect has either to be omitted in the abstract or also to be addressed in detail.”*

The misleading sentence in the abstract was changed.

You also mentioned the problem: (page 6, line 25): *“Because the shot frequency is taken to be less than  $I=t_{max}$ , we may use the approximation of delta-pulses, assuming, therefore, the backscattered signals to be independent for each pulse.”*

These sentences were changed following your comments below in the “Specific issues” for the page 6.

Answer for “Specific issues” section

“Abstract:

- line 3: *“the difficulties encountered” – which difficulties do you mean? It sounds like a reference to some known issue. Please specify if so, otherwise express differently.”*

We referred to signal variations such as presented in the Fig. 6. This sentences was changed:

“However, the strong variations of signal level sometimes, which were observed during the DELICAT measurements but not explained, indicated the need of a better understanding the observational errors due to geometrical factors”

“*“Uncompensated” – Within the DELICAT setup, a compensating beam steering device was used.”*

We meant the part of the signal which was not compensated (due to error limits of the using system). The sentence was changed:

“The part of pitch angle fluctuations uncompensated by the beam steering device in the presence of aerosol concentration variations can lead to noticeable signal variations that can be mistakenly attributed to wind shear, turbulence or fast evolution of aerosol layer.”

“*The subject “turbulence” is not addressed again within the whole paper”*

We focus on the unexplained strong signal variations observed in the airborne sensing. The impact of pitch angle fluctuations on the turbulence estimation was shortly formulated according to your comment (the detail answer is presented on the first page).

“Introduction: Page1:

- lines 17-19: *The given references are not related to DELICAT, please refer here to Vrancken et al. Appl. Opt. 2016 - line 19”*

These sentences were reformulated. Instead “Recently, a medium range lidar was developed, built and tested in the framework of the DELICAT (DEmonstration of LIdar based Clear Air Turbulence detection)” it says now:

“Recently, a medium range lidars were developed, built and tested [References]. One of these systems was developed in the framework of the DELICAT project (DEmonstration of LIdar based Clear Air Turbulence detection) [Vrancken et al. Appl. Opt. 2016]”.

“line 19: *No, they are not focused”*

The word “focused” was changed on “are designed to work up to”:

“Medium range systems are designed to work up to 20-30 km sensing distance, which corresponds to 2–10 minutes of warning time for typical flight speed of airplane and helicopter correspondingly.”

“line 21: *in future”*

This misprint was eliminated.

“line 22: *air density fluctuation: the right reference would be Feneyrou et al. Appl. opt 2009, or Vrancken et al. Appl. Opt. 2016”*

The cited work is also discuss possibility of turbulence sensing based on air density fluctuation. Following your comment the references were added.

*“line 23: “absence of >particle< scatterers” – evidently, without any scatterers (as molecules), there would be no return”*

This misleading term was changed on the “aerosol scatterers”.

*Page2:*

*- line 1-2: Unclear. What “filtration” are you talking about? Why should it be impossible to cut responses from all “types” of aerosol? Filtration by interferometric methods may reduce the aerosol part to an insignificant level, filtration by molecular (I2, e.g.) or atomic absorption (Cs, e.g.) to an even lower level. This is not addressed in the given references. Veerman et al 2014 (and in more detailed description Vrancken et al. 2016) only use depolarization, which is by no means a filtration method but rather a “hint” to depolarizing aerosols (as the respective authors state).”*

The sentences were changed:

*“The signal filtration is a good method to exclude undesirable contributions. For example, Hair and co-authors used an extremely narrowband iodine vapor (I2) absorption filter to eliminate the aerosol returns and pass the wings of the molecular spectrum (Hair et al., 2008). At the same time, in the DELICAT system the depolarization was used (Vrancken et al. 2016).”*

*“- line 4-5: What do you mean by “signal at the background level”?”*

This sentence was changed and the misleading term is excluded:

*“The presence of atmospheric aerosol should not be a critical problem for turbulence detection.”*

*“line 11 “significant concentration changes in the could split” – phrase fraction – revise!”*

The sentence was revised:

*“Clouds could be split up into numerous small clusters at the horizontal scale of one or several kilometers. Such splitting was observed for different types of aerosol.”*

*“lines 14-15: “GW also impact CAT” – the relationship between GW and CAT clearly is more complex than just “impacting” – please revise!”*

The sentence was revised:

*“Gravity waves are one of the reasons of CAT and new results suggest that turbulence was most strongly forced at the scale of about 700 m.”*

*“line 15: Reference Fritts and Alexander, 2003 refers to the Middle Atmosphere, there are more appropriate references than this one, also by the same author.”*

The paper (Fritts and Alexander, 2003) contains information for the altitude range from 10 to 110 km. Since the flight altitude is about 10 km at the longest part of the typical aircraft flight, we believe that (Fritts and Alexander, 2003) is appropriate here. The second work which we cited in this place is (Nappo, 2013) which is a book and contains a lot of information about gravity waves in wide altitude range.

*“line 24: “Strong laser pulses may indicate a non-linear interaction with the medium, resulting in the filamentation effect (Kosareva et al., 2006; Kandidov et al., 2009).” – This effect is of no relevance for lidar, please suppress!”*

This discussion was excluded.

*“lines 32-33: “Variations of sensing angles for lidars mounted on gyro-platform should be within the error limits of these compensating systems” – unclear what you mean by this.*

*“mounted on” ?? What exactly do you mean by gyro-platforms? Aircraft IRS? This measures the angles, laser-gyros are more precise and accurate than mechanical ones. A compensating platform steers the laser beam in order to “compensate” the pitch and yaw angles of the aircraft. It also features some*

*“noise”, as does the estimation algorithm. This adds up to the fluctuations you refer to. Vrancken et al. 2016 have shown a combination of laser-gyro IRS and mechanical beam steering with an pitch/yaw “noise” of <math><0.05^\circ</math> rms (within a certain dynamics bandwidth).”*

We take into account the typical range of the laser-gyros (0.1-0.2 rms) which is close to DELICAT gyros compensation error (0.05 degrees rms). We discuss values of the angle fluctuations which are in the limits of compensation errors. Following your comment the sentence was included in the numerical simulations’ discussion (section 4):

“Lidar images computed in the presence of pitch angle fluctuations in the typical range of the laser-gyros (0.1-0.2 rms) are presented in Fig. 5.”

Following your comment the angle compensation with the 0.15 degree rms was considered in the simulations. The following sentence was added to the Section 5:

“If we assume that  $\theta = 0.15$  degree (corresponds to 0.05 degree rms), the experimental results can be approximated with the cluster thickness 25-30 m.”

Since such aerosol cluster’s thickness is not commonly observed, the values of the standard rms of the gyro-systems (0.1-0.2 degree rms) were hold in the numerical simulation section with the corresponding vertical sizes of the aerosol clusters (100-300 m).

*“Page 3:*

*- lines 8-9: I wonder if the Klyatskin references refer to the lower atmosphere, as you state or not to some very general flow.”*

The Klyatskin theory can be applied to the lower atmosphere (source: cited books and personal conversation of the authors with Dr. Klyatskin in 2015).

*“- lines 10-14: This refers to the VERY special case of a volcano eruption – this does not describe the occurrence of such clusters in general. I suggest removing this phrase.”*

The aerosol clusterization depends on atmospheric conditions (wind, humidity, pressure etc.) and aerosol layer parameters. Even though the discussed aerosol is specific (volcanic), it still presents an example of an aerosol cluster and typical at least for the volcanic aerosol. At the same time we considered a lot of different aerosol types in Introduction which presents other examples of aerosol clusters with similar parameters.

*“Page 4:*

*- line 5: “distinguish impact from the natural changes caused by wind or time evolution. “ ?? What do you mean by wind or time evolution” Evolution of what?”*

This place was changed: “distinguish of pitch angle fluctuation impact from the evolution of aerosol clusters”.

*“2 Observation model and typical scales*

*Page 4:*

*- lines 12-13: The particle <math>>concentration</math> does not scatter the beam, please revise!”*

The sentence was changed:

“The laser beam scatters on thermodynamic fluctuations of air density (Fabelinskii, 2012) and particles of solid or liquid aerosol (Bohren and Huffman, 2008).”

*“Page 5:*

*- line 1: Wrong. The position is defined by  $x, y, z$ . The <math>>attitude</math> is defined by roll, pitch, yaw.”*

The sentence changed:

“The fluctuations of the sensing direction during the flight can be defined by fluctuations of three angles: roll, yaw and pitch.”

“line 10: References Huffaker and Hardesty, 1996; Inokuchi et al., 2009; have nothing to do with DELICAT.”

This misprint was corrected.

“lines 11-12: “suggest that it may be possible to observe aerosol clusters with evolution time smaller than that of the measurement time interval.” Not logic. How could that be possible to observe a phenomenon that is faster than the measurement frequency? Possibly you mean something different, but please revise!”

When we said “measurement time interval” we meant the time interval during which the cluster can be observed until the aircraft flight over it. This time is defined as maximal sensing distance divided by the aircraft speed. The evolution time is defined as a time during which a cluster significantly changes (Eq. 6 provides exact definition). Thus evolution can be seen if the observation time is larger than interval of time changes. Otherwise the layer/cluster looked as having constant characteristics. In order to avoid misunderstanding the sentence was revised:

“Airborne lidar measurements in the flight direction suggest that it may be possible to observe evolution of the aerosol clusters with evolution time smaller than the observation time.”

“- line 14: “imaging” is perhaps not the best notion”

The “imaging” was changed on “lidar observations”:

“In this paper, we simulate and discuss the influence of airplane pitch angle variations on the lidar backscattered signal from the aerosol clusters.”

“- line 16: “volume is large  $L_{\sin(..)}$ ” – omit “large””

The “large” was omitted.

“- line 19: “technical requirement”? for what purpose exactly? Within DELICAT or similar (JAXA Inokuchi, e.g.) the requirement is NOT proper sensing of aerosol clusters.”

The sentence was reformulated:

“In order to avoid the signal variations caused by the pitch angle fluctuations the condition  $L_{\sin(\varphi/\delta_0)} < 1$  on the maximal acceptable beam angle deviation  $\varphi$  should be fulfilled in presence of aerosol clusters with vertical size about  $\delta_0$ .”

“Page 6:

- line 10: What do you mean with the max. distance scale  $L_{\text{ext}}$ ? How is it defined by mol. extinction (which depends on mol. scattering)?”

We meant that the molecular extinction distance  $L_{\text{ext}}$  is longer than the maximal sensing distance  $L_{\text{max}}$ . The  $L_{\text{ext}}$  was moved from the end of the sentence:

“Assuming that the molecular scattering is negligibly weak and neglecting molecular absorption, we may accept the length of molecular extinction  $L_{\text{ext}}$  to be the maximum distance.”

“- line 12: How is  $L_{\text{max}}$  defined? What value is reached by intensity  $I$ ?”

According to your comment the following explanation is included in the text:

“Distance  $L_{\text{max}}$  is defined as the maximal distance for which we are still able to register backscattered signal. Specifically, in our simulations we limited by signal registered with time delay corresponded to 16 km distance suppose that the signal from longer distance cannot be registered due to the noise.”

“line 15: repeated mention of  $\tau=10\text{ns}$  typical for lidars (cf. line 13)”

The repeated information was excluded.

*“line 17: the “sensing path” does not end somewhere ( $L_{max}$ ), only the intensity further drops with  $L^2$ .”*

We define the sensing path as the path during which the experimental equipment is able to register backscattered lidar signal. Thus, based on our definition, the sensing path ends when we cannot resolve backscattering signal from the background light or errors of signal registration. The sentence was change in order to avoid misunderstanding:

“We define the sensing path as the path during which the experimental equipment registers the backscattered lidar signal.”

*“- line 19: well, usually it is the employed laser technology that sets a limit to the repetition rate. Theoretically, the definition (which is not clear to me) of an  $L_{max}$ , sets the upper bound for a high rep system.”*

Following your comment the sentences was rewritten:

“For the value of  $t_{max}$  is about 0.1 milliseconds, the distance  $L_{max} = 15$  km.”

*“lines 25ff. Therefore, you state, the used repetition rate should be  $<10$ kHz; granted.*

*How does this allow for the assumption of “delta-pulses” (and what are delta-pulses?), you possibly mean Dirac function, but this assumption has nothing to do with the repetition rate, BUT with the shortness of the pulse. 10ns/1.5m is short in comparison to the considered spatial scales (of turbulence or your clusters) here → thus it is a valid assumption. You conclude another time: “assuming, therefore, the backscattered signals to be independent for each pulse”. Again, this has nothing to do with the former, but with lack of coherence between the pulses (if and only if there is no coherent relation between the pulses; true for a Q-switched laser in the case of DELICAT. Not true for some other laser types.).”*

This part is revised according your comment:

“Based on the absence of coherent relation between pulses we assume the backscattered signals to be independent for each pulse.”

“Because the lidar pulse is short (10 ns) in comparison to the considered spatial scales, we can use the Dirac function which significantly simplifies the analytical solution.”

*“- General: So far, there is no consideration at all, of how fast the sensing laser beam can move from position 1 to 2 within ( $t_2-t_1$ ). This is an important topic, since for shorter time scales the residual pitch “noise” of a compensated platform (based on an angle-resolving IRS) surely is lower than when looking on longer time scales. Reasons: The movement of the aircraft itself is not erratically abrupt, but follows its own inertia (so essentially it depends on its mass/distribution). The movements of the compensating platform also have a certain bandwidth. Where is this aspect considered in your study?”*

This aspect was considered in our study in the framework of presented equations and shown in Fig.4. Fig. 4 presents the dependence of laser beam movement from the aircraft trajectory as a function of time and distance from the aircraft. The time was shown as  $u_0t$  (distance of aircraft flight). Taking into account the discussed aircraft velocity (170 m/sec) and distance (20 km) the whole observation time here is evaluated to about 2 minutes. According to your comment, the discussion of the results presented in Fig. 4 is expanded:

“The distance  $u_0t_0=20$  km corresponds to 2 minutes of airborne observation (for aircraft speed 170m/sec). Beam displacement is changing from 0 to 160 m (from 0 to 80 m) for  $\varphi_0=0.3$  degree ( $\varphi_0=0.6$  degree) for about of 10 sec. The speed of movement was defined by period  $T_\varphi=20$  sec”.

This discussion also answered one of your comments below about the utility of Figure 4.

According your previous comment the another  $T_\varphi=2.8$  sec was considered (Fig.6c).



*“3 Modeling of an aerosol cluster lidar image*

*Pages 7 and 8: The derivation of a lidar signal has been published very often, there is no need to perform this in this detail here, I suggest to considerably shorten it.”*

We did not present the detailed derivation in the paper. We only shown Eq. (3) for the intensity of the lidar signal (with citation) and give the explanation of the terms (Eq.4 and text around). This takes about half of the page and helps the readers who are not well familiar with the topic. The final Eq. 5 is needed for understanding of images represented on Figures 3, 5, 6 and cannot be eliminated.

*“Page 8*

*- line 14: here you refer to aerosol backscatter but use subscripts M and MB for molecular.*

*Further, in particular for aerosol, there is not a “typical” value. Cf. Vrancken et al. 2016 Table 3 and in particular references therein, or Groß et al. ACP 2013 (DOI: 10.5194/acp-13-2487-2013), e.g.”*

Indeed the aerosol values discussed in (Ishimaru, 1978) correspond to weak water aerosol and can be considered as typical only for this case. The sentence was changed and citation on your paper was included:

*“This value typically corresponds to weak water aerosol in accordance with Fabelinskii (2012); Ishimaru (1978), which implies that the aerosol scattering does not significantly decrease the propagating laser pulse energy. The values for the other types of aerosol can be found, for example, in (Vrancken et al. 2016).”*

*“Page 9:*

*- lines 19ff: The discussion of the retrieved lidar signal (Fig. 3) is rather long, to obtain such “bars” (for lifespan >  $L_{max}/u_0$ ) is rather evident. Please try to clarify and shorten.”*

The importance of these bars is that they provide non-disturbed signals from the clusters with different time of living and sizes. This bar is needed for understanding the results presented in Fig. 5 though comparing distorted and undistorted signals. In order to make the discussion shorter the sentences contains the repeating information were merged. The following sentences were excluded:

*“Vertical cluster scale does not influence the lidar image under the assumed conditions.”*

*“This parameter is important for obtaining images of short-living clusters at large distances L, because the observer moves closer to the detected cluster.”*

*“4 The impact of measurement direction fluctuations on cluster lidar images*

*Page 10:*

*- line 2: Again misconception of the term “position”. You probably mean “attitude””*

The term was corrected.

*“- line 6: here is the first notion of a time constant of this pitch variation (as mentioned above):*

*Why do you choose 20s? Please explain/justify.”*

According your comment the following discussion is included in the paper:

*“Our choice of the  $T_\phi$  is based on one of the characteristic times of pitch angle fluctuations measured in the experiment. These times vary in the range from few to tens of seconds (Fig.6 (b) and (d)). The considered effect do not disappear for smaller/larger times; such changes would result in changing of thickness of the breaches.”*

*“- Eq. (7): I do not see any periodicity. Is there lacking a sin/cos?”*

The misprint was corrected.

*“- line 10: Why do you choose 3 and 6°?? On page 2, you talked about a tenth of these values. (apparently, this is a typo)”*

The misprint was corrected.

*“- line 11: instead of “position”, better use “altitude” (if this is what you mean)”*

The term was changed.

*“- Figure4: I do not see the utility of this figure – what does it show me? To what extent does it help the paper to arrive at its conclusion?”*

This figure visually represents the value of beam shift along the sensing distance. It helps understanding the difference of the pitch angle effect for different distances. This Figure helps understanding the behavior of lidar signal (which is shown in Fig.5).

*“5 Airborne lidar measurements in presence of pitch angle fluctuations*

*Page 13:*

*- line 24: A more comprehensive source is Vrancken et al. Appl. Opt. 2016”*

The reference to this paper was added.

*“- line 31: Please use the 24h format, p.m. and a.m. is not used in aviation nor science (as recommended by ISO 8601)”*

The time format was changed.

*“Page 14:*

*- line 1: The altitude is 9.46km (flown pressure altitude FL310), NOT the height which is defined differently!”*

The term was corrected.

*“- General: You are presenting here lidar data obtained with the DELICAT instrument. You infer that there is no pitch fluctuation in Fig. 6a. How do you arrive at this conclusion?”*

We meant that pitch angle fluctuations are in the range of [-1.0,1.0] degrees for the lidar backscattered signal presented in the Fig.6a, while they are about [-0.5,0.5] for the case presented in the Fig.6d, i.e. twice smaller. But they still can affect the lidar backscattered signal. Since the discussion of the experimental results was expanded following your other comments this information is now presented in the paper.

*“What is different to Fig.6b, 10min earlier? Why do you suppose a fluctuation here?”*

We have to note that, based on the flight map, area of the flight was almost behind the Alpes. For this flight, the changes of flight parameters can happen very fast.

*“There is no relation to any quantity (pitch fluctuation range, time constant, vertical extent of “cluster” etc.) responsible for these signal variations. Please discuss!”*

The discussion is added based on your previous comments.

*“- line 11: aerosol cluster backscatter (not reflection!)”*

The term was corrected.

*“Conclusions*

*Page 14:*

*- line 16: “are the most important factor for the discussed airborne lidar sensing scenario” – factor in what respect. Phrase is not complete.”*

The phrase is rewritten:

“It is shown that the pitch angle fluctuations are the important parameter for the airborne lidar sensing ahead the flight direction in the case when their uncompensated value result in the sensing beam shift about the vertical size of the aerosol clusters.”

“Page 15:

- line 2: “We also show that LIDAR sensing ahead along the flight direction can potentially provide information about aerosol temporal evolution characteristics.” – How did you show that? It appears to me, that you primarily showed that the pitch angle fluctuation (if there is such of a sufficient level, with an appropriate time constant/bandwidth) would impede obtaining such information. Between the lines one may also suspect that the “arbitrary” pitch scanning delivers information on the vertical extent of aerosol (cloud?) clusters. Under very rare circumstances (that you should describe), despite pitch fluctuations, one may retrieve information on the temporal evolution. But I understood that this was just the purpose of this paper to derive exactly the necessary conditions. But I do not see them described here.”

This conclusion is based on the results of our numerical analysis. We show that the In order to make this statement clear, the following discussion of the simulations’ results was added to the text around Fig.5:

“As shown in Fig.5, even the clusters with smallest evolution time corresponding to a living time below 30 sec still appeared twice for strongest fluctuations (0.6 degree) for the largest sensing distance. It means that we can observe evolution of the smallest considered cluster (0.5 km length) with the smallest considered evolution time at the any considered sensing distance. The evolution of the cluster is clearly seen in decreasing the signal in the periods between the breaches caused by pith angle fluctuations. Such decreasing can be seen for all considered clusters with and without pitch angle effects (Fig.5).”

This were summarized in the conclusion:

“We also show in numerical simulations that lidar sensing ahead the flight direction can potentially provide information about aerosol temporal evolution characteristics even in presence of pitch angle fluctuations for reasonable cluster size and evolution time at the considered sensing distance.”

“- line 5: The numerical simulations are based on somewhat arbitrary values (pitch values and time constant), so I do not see what to conclude from them.”

The answer to this comment was given above. Shortly, in order to clarify the choice of pitch angle fluctuations parameters the experimental measurements was included in the Fig.6. The other parameters are based on references which can be found in Introduction with the quantitative characteristics of experimentally observed cluster parameters. One of the conclusion statements is:

“Numerical simulations predict that uncontrolled fluctuations can result in signal noise including extreme fades and spikes. We show that the aerosol concentration variations on a scale of 100-300m have a significant impact on the backscattered signal, if the correction for the angular fluctuation has a residual rms error about of 0.1–0.2 degrees, which is typical for conventional gyro-platforms used in the civil aviation.”

“- lines 9-10: “We formulate criteria for distinguishing this impact from the temporal evolution of atmospheric aerosol clouds” – What criteria? I do not find them. If you mean page 13, lines 11-13 – this is rather obvious.”

We meant the lines 8-10:

“It may be expected that a natural process intensity, like aerosol evolution due to evaporation or condensation, varies for different clusters. A distortion due to flight direction fluctuations has the same impact on the images of all the clusters observed at the same distance.”

This idea is very simple, but taking into account formulated limitations for the cluster parameters and pitch angle fluctuations, it allows to easily distinguish the pitch angle fluctuations. It is not the main result of our paper, however it is important for the analysis of the backscattered signal and distinguishing areas of wandered beam which cannot be used for turbulence strength estimations.

# Impact of pitch angle fluctuations on airborne lidar sensing ahead along the flight direction

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**Abstract.** Airborne lidar sensing ahead along the flight direction can serve for notification of clear air turbulence (CAT) and help to prevent injuries or fatal air accidents. The validation of this concept was presented in the framework of the DELICAT (DEmonstration of LIdar based CAT detection) project. However, the ~~difficulties encountered during the processing of DELICAT data~~ strong variations of signal level sometimes, which were observed during the DELICAT measurements but not explained, indicated the need of a better understanding the observational errors due to geometrical factors. In this paper, we discuss possible error sources imminent to this technique, related to fluctuations of the flight parameters, which may lead to ~~an incorrect estimation of the turbulence intensity~~ strong signal variations caused by the random deviations of the sensing beam from the forward flight trajectory. We analyze the variations of backscattered lidar signal caused by fluctuations of the most important ahead sensing flight parameter, the pitch angle. The fluctuation values considered in the paper correspond to the error limits of the compensational gyro-platform used in the civil aviation. ~~Uncompensated~~ The part of pitch angle fluctuations ~~uncompensated by the beam steering device~~ in the presence of aerosol concentration variations can lead to noticeable signal variations that can be mistakenly attributed to wind shear, turbulence or fast evolution of aerosol layer. We formulate the criteria that allow the recognition of signal variations caused by pitch angle fluctuations. Influence of these fluctuations is shown to be stronger for aerosol variations on smaller vertical scales. An example of DELICAT observations indicating a noticeable pitch angle fluctuation impact is presented.

## 1 Introduction

Airborne lidar systems (Fukuchi and Shiina, 2012; Weitkamp, 2006) may play a significant role in alarming, preventing, and compensating problems caused by atmospheric turbulence. Such system were previously ~~developed~~ developed for short range sounding (Schmitt et al., 2007; Jentink and Bogue, 2005). Recently, a medium range ~~lidar was~~ lidars were developed, built and tested (Huffaker and Hardesty, 1996; Inokuchi et al., 2009; Veerman et al., 2014; Vrancken et al., 2016; Inokuchi et al., 2009b; Targ et al., 2010). One of these systems was developed in the framework of the DELICAT project (DEmonstration of LIdar based Clear Air Turbulence detection) (~~Huffaker and Hardesty, 1996; Inokuchi et al., 2009; Veerman et al., 2014; Gurvich and Kulikov, 2013; Inokuchi et al., 2010~~). Medium range systems are ~~focused on~~ designed to work up to 20-30 km sensing distance, which corresponds to ~~2-10~~ 2-10

minutes of warning time for typical flight speed of airplane and helicopter correspondingly. An earlier warning is preferable and airborne lidar with larger sensing distance could be developed in a future.

Sensing of turbulence can be based on backscattered signal from air density fluctuations (Veerman et al., 2014) (Veerman et al., 2014; Ferrell et al., 2014) allows detecting turbulence even in the absence of aerosol scatterers. At the same time, dust and smog, water vapor etc. contribute to the backscattered signal as well. The signal filtration is a good method to exclude undesirable contributions (Hair et al., 2008) but it is impossible to cut responses from all types of atmospheric aerosol. For example, Hair and co-authors used an extremely narrowband iodine vapor (I<sub>2</sub>) absorption filter to eliminate the aerosol returns and pass the wings of the molecular spectrum (Hair et al., 2008). At the same time, in the DELICAT system the depolarization was used (Vrancken et al. 2016). Backscattered signal measurements at different polarizations (Burton et al., 2015; Veerman et al., 2014) will only allow excluding the component produced by non-spherical aerosol particles. The measured signal is, however, composed of the responses of different atmospheric components. A signal at the background level which can include the spherical aerosol. The presence of atmospheric aerosol should not be a critical problem for turbulence detection even in presence of aerosol. The problem arises when the signal from aerosol layers is changing during the observation time. However, changes of a aerosol layer density during the observation time and the experimental noise which can affect signal in both polarizations simultaneously could be a problem for backscattered signal analysis.

There is another technique of CAT detection based on backscattering enhancement (BSE) effect which was initially found in the theoretical research (Vinogradov et al., 1973) and then experimentally confirmed (Gurvich and Kashkarov, 1977). In framework of DELICAT project the idea of possible turbulence strength estimation based on BSE was theoretically analyzed and reported (Gurvich, 2012; Gurvich and Kulikov, 2013). The two channel scheme based on backscattering enhancement (BSE) looks very promising for future airborne applications in light of both thorough theoretical analysis and experimental evidence of success reported in (Banakh and Smalikho, 2011; Banakh, 2011; Banakh and Razenkov, 2016a, b). This technique is also sensitive to the airborne specific noise caused by fluctuations of flight parameters.

The atmospheric effects can bend the sensing beam and prevent to lidar turbulence detection based on any principle. The turbulence anisotropy can noticeable bend the light propagated over such long distances (Gurvich and Chunchuzov, 2003; Sofieva et al., 2003). This impact should be almost negligible for short fifteen km optical path; possible laser beam trajectory deviation of about ten meters is small taking into account the thickness of cluster discussed in our paper (100 meters). At the same time, refractive layers can also significantly change the trajectory of optical wave propagation (Werf, 2003; Nunalee et al., 2015). The consideration of such effects can be performed in the framework of geometrical (Southwell, 1982; Werf, 2003; Nunalee et al., 2015) or wave optics (Vorontsov and Kulikov, 2015; Kulikov et al., 2017). Both turbulence anisotropy and possible impact of refractive layers should be considered in the case of extended sensing distances.

A series of atmospheric processes influence the aerosol concentration and turbulence strength on temporal and spatial scales of medium range sensing. The aerosol concentration can change due to wind shear and evaporation/condensation processes (Ivlev and Dovgalyuk, 1999). For example, small cloud with horizontal characteristic scales about one kilometer can be displaced completely out of originally occupied volume during 40–200 sec by the wind with a speed within the range of 5–25 m/s (Liu et al., 2002). Clouds, as well as significant concentration changes in the could split could

~~be split up~~ into numerous small clusters at the horizontal scale of one or several kilometers ~~were~~. ~~Such splitting was~~ observed for different types of aerosol (Chazette et al., 2012; Cadet et al., 2005; Reichardt et al., 2002). The concentrations of both submicron aerosol and gas may change by 2–3 times during the equilibration process at characteristic time scales of about 3 minutes (Meng and Seinfeld, 1996). Gravity waves (Nappo, 2013; Fritts and Alexander, 2003) ~~also impact clear~~  
5 ~~air turbulence (CAT) (Plougonven and Zhang, 2016; Lane et al., 2003), especially at scales~~ ~~are one of the reasons of CAT~~ ~~(Plougonven and Zhang, 2016; Lane et al., 2003) and new results suggest that turbulence was most strongly forced at the scale~~  
of about 700 m (Koch et al., 2005). The smallest spatial and temporal scales of gravity waves amount to about 1 km and 1-2 minutes, respectively (Lu and Koch, 2008; Koch et al., 2005; Plougonven and Zhang, 2016). Therefore, lidar sensing ahead along the flight direction does not only allow the operational detection of dangerous atmospheric conditions but can also pro-  
10 vide information on macrostructures in the aerosol spatiotemporal distribution. At the same time, the signal variations at this time scale may be caused by the variations of lidar sensing trajectory due to the fluctuations of the flight parameters.

Backscattered signal can also be influenced by changing laser pulse properties or atmospheric propagation effects. Laser instability leads to time variation of both power and shape of pulses, which results in the change of the backscattered signal. Multipath propagation effect is usually ignored in consideration of backscattered signal, which can significantly degrade the  
15 accuracy of the measurement analysis (Godbaz et al., 2012). ~~Strong laser pulses may indicate a non-linear interaction with the medium, resulting in the filamentation effect (??)~~. The detectors can be a source of noise, which depends on the input signal (Acharya et al., 2004). These factors also contribute to the complexity of the signal analysis.

In this paper, we discuss the source of errors, which is specific to the airborne measurements. Variations of aircraft flight height and direction angle are always present in airborne measurements and they influence the observed backscattered signal.  
20 Uncontrolled fluctuations of flight height are usually about several meters and lead to the same height shift along the sensing path. It is highly probable that atmospheric aerosol and turbulence properties do not change noticeably at the scale of a few meters. Variations of flight direction angle lead to variations of the sensing pulse trajectory. Variations of sensing angles for lidars mounted on gyro-platform should be within the error limits of these compensating systems. The accuracy of pitch angle measurements and fluctuation compensation is about 0.1–0.2 degree rms (SOMAG AG Jena, 2016; Temp-Avia, 2016). Thus  
25 the uncompensated angles lie in the range of 0.3–0.6 degrees, which corresponds to 150–300 m shift at the end of a 30 km path. Roll and yaw angle fluctuations do not influence the backscattered signal because this shift is small as compared to the horizontal size of the smallest atmospheric clouds, which is about one kilometer and more. At the same time pitch angle fluctuation can result in significant signal variations, if the trajectory shift caused by the angular deviation and the horizontal characteristic scale of aerosol concentration changes are comparable.

30 There are many experimental observations of variations of aerosol and water vapor concentration on small vertical (about one hundred m) and horizontal (several km) scales in the lower atmosphere. Small clouds with such characteristic scales are referred to as “clusters”, in order to avoid mixing them up with usual aerosol layers and clouds with the horizontal length of the order of hundred kilometers. Clusters can be produced, for example, at the final stage of the collapse of internal gravity waves (Barenblatt and Monin, 1979) or by turbulence (Klyatskin, 2005; Klyatskin and Koshel, 2000).

Observations of Eyjafjallajökull volcano eruption in 2010 showed small cluster structures as well as huge ash clouds. In the observation carried out by Chazette et al. by Ultra-Violet Rayleigh-Mie lidar, clusters with minimal horizontal size corresponding to about 50 seconds of aircraft flight time and 80 meters thickness were found (Chazette et al., 2012, Fig.3, Fig 4). At the same time clouds with sizes up to 1 km in the vertical direction and 100 km in the horizontal direction were also observed (Chazette et al., 2012). Layers with 1 and 2 km thickness and concentration changes about 7 times at this scale were found in (Dacre et al., 2013, Fig.3). The same thickness with a concentration jump, which is 2 time smaller, was also found in (Turnbull et al., 2012). Simulations predict clouds with thickness about of 0.5–2 km (Hervo et al., 2012, (Fig.1)) when real observations also show thin layers with thickness of about 100 meters (Hervo et al., 2012, Fig.2, Fig.10).

Cirrus cloud split into numerous clusters with a thickness of about 100 meters at the altitudes between 6 and 11 km ((Reichardt et al., 2002),Fig.1 or (Cadet et al., 2005),Fig.2b) and stable layers with 1 km thickness ((Cadet et al., 2005),Fig.2a) were observed. Based on possible wind speed, the horizontal size of these clusters can be estimated as 3–12 km. Their concentration is changing 2–5 times in both vertical and horizontal directions at cluster scales. Ice clouds containing cluster structures with horizontal characteristic scales about hundred meters were observed, for example in ((Haarig et al., 2016), Fig.2) at altitudes about 7–11 km. Aerosol clusters in the altitude range of 1–10 km with the thickness of about 100 m and the concentration variations by 2–5 times were reported in (Burton et al., 2015, Fig.3), (Burton et al., 2014, Fig.6 dust aerosol), (Burton et al., 2015, Fig.7, Fig.13), (Burton et al., 2014, smoke aerosol in Fig.9). Clusters with the 100 meter thickness and horizontal size of about few kilometers were also observed in (Hair et al., 2008). Urban plumes measured in (Kleinman et al., 2008) also contained clusters with horizontal sizes ~~corresponding~~ corresponding to about of 1-2 minutes of aircraft flight time with 4 times concentration changes.

Relatively thin and long water vapor layers observed at heights below 11 km indicate a thickness of about 100 meters and more (Whiteman et al., 1992; Kiemle et al., 2008; Leblanc and McDermid, 2008). An ice layer with 100 meters vertical size can have more than 10 times concentration changes (Johnson et al., 2012).

Aerosol and water vapor clusters can be routinely observed in the atmosphere in the civil aviation flight height range. The shear of cluster with horizontal characteristic scale of about 1 km at wind speed of 20 m/s could happen in about 30–60 seconds. The evaporation and condensation effects can also influence the time of aerosol cluster evolution. On the other hand, cluster could disappear from the field of view because of pitch angle fluctuation during the same time. This creates potential ambiguity in the interpretation of the lidar backscattering signal.

In this paper, we discuss the impact of pitch angle fluctuations on both simulated and measured lidar signal in the presence of aerosol clusters with different sizes monitored by an airborne lidar. We formulate the criteria for ~~distinguishing~~ distinguish of pitch angle fluctuation impact from the ~~natural changes caused by wind or time evolution~~ evolution of aerosol clusters. The paper is organized as follows: in Sections 2 and 3, we describe the observation model and its parameters, respectively. The simulation results are presented and discussed in Section 4. In Section 5, we make our conclusions.

## 2 Observation model and typical scales

Ground-based stationary lidar is the conventional technique for the study of the atmospheric composition, density, and aerosol properties (Zuev and Zuev, 1992). The sensing procedure is as follows: short radiation pulses are produced sequentially by a pulsed laser, each of them is transformed into a narrow beam by the optical system and sent into the atmosphere.

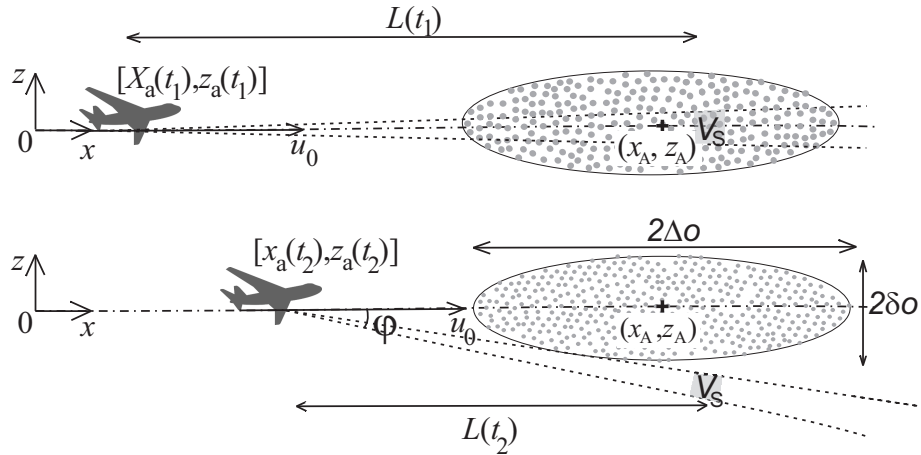
5 ~~Thermodynamic~~ The laser beam scatters on thermodynamic fluctuations of air density (Fabelinskii, 2012) and ~~particle concentration~~  
~~for particles of~~ solid or liquid aerosol (Bohren and Huffman, 2008) scatter the beam. Measured power profiles of the scattered  
radiation are a function of shot time  $t$  and distance  $L$  to the scattering volume, the latter being derived from measured backscatter  
delay time  $\delta t$ . For a ground-based lidar with an upwards-directed beam,  $L$  equals the altitude of the scattering volume and the  
power of the registered lidar response  $I$  bears information on the atmospheric properties along the line of sight (Hauchecorne  
10 et al., 2016; Keckhut et al., 2015). As the wind drift occurs, the altitudinal cross-section of long-living aerosol clusters can be  
inferred from  $I(L, t)$  relief images in the  $(L, t)$  plane as bars with width depending on both the wind speed and the 3D cluster  
structure (Haarig et al., 2016; Hoareau et al., 2012).

The wind drift poses a significant encumbrance to studies of aerosol cluster evolution, using ground-based platforms, because  
it is necessary to distinguish between the temporal evolution of a particular cluster and its drift in space with the wind. While  
15 thermodynamic fluctuations of atmospheric air density in time and space may be described under the assumption of their  
statistical homogeneity and stationarity, this assumption, in practice, often becomes invalid for the description of clustered  
aerosol.

For the enhancement of the civil aviation safety and flight comfort, it was suggested to use an ~~air-borne~~ airborne lidar with  
scanning the atmosphere ahead in the flight direction. The analysis of experimental results ~~presented in~~ (Veerman et al., 2014, Fig. 22),  
20 ~~suggests~~ demonstrated a rapid spatiotemporal evolution of aerosol clusters (Veerman et al., 2014, Fig. 22). A schematic dia-  
gram of lidar measurements that takes account of random pitch angle variations is shown in Fig.1. In field experiments, noise  
and distortions of the data are always present. One of the crucial factors is the noise related to uncontrolled fluctuations of  
the aircraft position and, as a result, of the airborne lidar position. In this work, we develop the results of a previous study  
(Gurvich and Kulikov, 2016), by the consideration of the spatiotemporal parameters of lidar images of aerosol clusters and by  
25 the assessment of the characteristic scales of clusters, at which noise caused by uncontrolled fluctuations of the aircraft position  
does not impede monitoring their evolution.

The ~~position of the aircraft is defined by~~ fluctuations of the sensing direction during the flight can be defined by fluctuations  
of three angles: roll, yaw and pitch. As the horizontal size of typical aerosol formations is usually large, the azimuthal shifts of  
the scattering volume due to rolling and yawing are not as significant as its vertical shift, which is characterized by the product  
30 of the observation distance  $L$  and pitch angle change. ~~Although the use of conventional gyro-stabilized platforms partially~~  
~~compensates for the fluctuations of the aircraft position, the residual angular deviation in the vertical angle still remains to be~~  
~~0.3 to 0.6 degrees for conventional civil aircraft gyro-platforms (SOMAG-AG Jena, 2016; Temp-Avia, 2016). At an observation~~  
~~distance of 16 kilometers, the shift of scattering volume due to such angle variations reaches about 83-168 meters in the vertical~~





**Figure 1.** A schematic diagram of lidar measurements of the flight direction from an aircraft. The  $x_a(t)$ ,  $z_a(t)$  represent the observer's coordinates at sequential time points  $t_1$  and  $t_2$ ; the center of the observed clusters is marked with +, and their coordinates are  $x_A, z_A$ .

~~direction.~~ For aerosol clusters with the thickness smaller or comparable to the shift of scattering volume, an incidental time modulation of the lidar response from monitored aerosol cluster may be mistaken for the cluster evolution.

Airborne lidar measurements in the flight direction, ~~conducted in the DELICAT project (Huffaker and Hardesty, 1996; Inokuchi et al., 20~~ that it may be possible to observe evolution of the aerosol clusters with evolution time smaller than ~~that of the measurement~~  
5 time interval the observation time. At the same time, ~~such~~ variations of the lidar response (Veerman et al., 2014, fig 22) could also be caused by variations of the airplane pitch. In this paper, we simulate and discuss the influence of airplane pitch angle variation variations on the lidar imaging of backscattered signal from the aerosol clusters.

It is evident that the backscattered signal coming from the aerosol, changes with pitch fluctuations. The scheme in Fig.1 shows that if the vertical shift of the scattering volume is ~~large~~  $L \sin(\varphi) > \delta o$ , where  $L$  is the distance between the plane and  
10 the scattering volume,  $\varphi$  is the angle deflection of the sensing beam from flight direction,  $\delta o$  is the characteristic vertical size of the aerosol cluster, then the signal from long-living cluster contains distortions caused by scattering volume shift. These distortions may be mistaken for a result of the cluster evolution. ~~The condition  $L \sin(\varphi) / \delta o < 1$  is, therefore, a technical requirement ensuring the compensation for the beam deflection in order to suppress the noise~~ In order to avoid the signal variations caused by the pitch angle variations fluctuations the condition  $L \sin(\varphi) / \delta o < 1$  on the maximal acceptable beam  
15 angle deviation  $\varphi$  should be fulfilled in presence of aerosol clusters with vertical size about  $\delta o$ .

If  $L \sin(\varphi) / \delta o \geq 1$ , then the aerosol cluster may occasionally disappear from the lidar's field of vision. Figure 1 is a schematic representation of the measurements with an airborne lidar that approaches a cluster (depicted by circlets) located on the flight path, with the airspeed  $u_0$ . The cluster thickness  $2\delta o$  is much smaller than its horizontal dimension,  $2\Delta o$ . The flight path is shown by the dash-and-dot line. The laser beam is shown by the long-dash line. The scattering volume  $V_S$ , which moves  
20 with the velocity of light  $c$  in measurement direction, is colored grey here. The scheme depicts two sequential time moments of

measurements. In the second time moment, the beam deflects from the flight direction by angle  $\varphi$  and the lidar only registers molecular scattering at the thermodynamic fluctuations of the air density.

The following typical scales of time and distance may be distinguished in the problem of lidar monitoring of the atmosphere from an aircraft in the flight direction. Assuming that the molecular scattering is negligibly weak and neglecting ~~the~~ molecular absorption, we may accept the length of molecular extinction ~~as  $L_{ext}$  to be~~ the maximum distance ~~scale  $L_{ext}$~~ . The intensity  $I$  of the observed backscatter response is decreases with the distance as  $L^{-2}$ . Together with the sensing pulse magnitude, the internal noises of the receiver, as well as the random nature of aerosol and turbulence determine the maximum sensing distance  $L_{max}$ . Distance  $L_{max}$  is defined as the maximal distance for which we are still able to register backscattered signal. Specifically, in our simulations we limited by signal registered with time delay corresponded to 16 km distance suppose, based on DELICAT lidar parameters, that the signal from longer distance cannot be registered due to the noise. We assume that  $L_{max} < L_{ext}$ . The minimum time scale is the sensing pulse duration  $\tau$ , which is about 10 nanoseconds for lasers used in lidars. The lengthwise dimension  $l_{\parallel}$  of the scattering volume  $V_S$  equals  $c\tau/2$ , where  $c$  is the light speed. ~~At  $\tau = 10$ , which is typical for modern lidars,~~ For considered pulse duration the lengthwise dimension is  $l_{\parallel} = 1.5$  m. The lateral dimension  $l_{\perp}$  is determined by the initial diameter  $D_0$  of the sensing beam and full divergence angle  $\gamma$ :  $l_{\perp} \simeq \gamma L + D_0$ . For the typical values of  $\gamma = 2 \cdot 10^{-4}$  rad,  $D_0 = 10$  cm, and  $L_{max} = 15$  km, the estimated value of  $l_{\perp}$  is about 3.1 m at the end of the sensing path. We define the sensing path as the path during which the experimental equipment registers the backscattered lidar signal. Signal record time is determined by the pass band of the photodetector and is usually slightly greater than  $\tau$ . Another characteristic time is the time interval  $t_{max} = 2L_{max}/c$  of backscatter return. It determines the maximum frequency of sensing pulses. For ~~distances of, e.g.,  $L_{max} = 15$ ,~~ the distance  $L_{max} = 15$  km. Such a time interval is negligible compared to the time scale of detectable variations in atmospheric aerosol systems (Ivlev and Dovgalyuk, 1999). For this reason, the properties of the scattering medium, including the aerosol density and backscattering cross-section, are considered to be invariant at time intervals  $t_{max}$  when analyzing the effects of cluster evolution upon lidar images.

Lidars, in most practical cases, send recurrent pulses. In Fig. 2 they are seen as a "comb". ~~Because the shot frequency is taken to be less than  $1/t_{max}$ ,~~ we may use the approximation of delta-pulses, assuming, therefore, the Based on the absence of coherent relation between pulses we assume the backscattered signals to be independent for each pulse. In the hierarchy of characteristic times, the value of  $t_{obs} = L_{max}/u_0$  is the time for the aircraft to approach the scatterer after the moment of its observation. The value of  $t_{obs}$  has been used in (Gurvich and Kulikov, 2016) to define long-living clusters. For observation distances from 10 to 20 km and modern aircraft velocities, this time may reach hundreds of seconds. The backscattering cross-section of aerosol particles may change significantly over the time interval of  $t_{obs}$ . This change is schematically depicted at Fig. 1 by the change in the number and size of scatterers.

### 3 Modeling of an aerosol cluster lidar image

For the lidar image model, we use a Cartesian coordinate system with its  $Ox$  axis coinciding with the flight direction of the aircraft moving straightforward at a constant altitude. We discuss relatively small distances,  $\ll \sqrt{a_E H_A}$  where  $a_E$  is Earth

radius,  $H_A$  is atmospheric scale height. Therefore, the Earth's curvature impact can be neglected. The coordinate system origin is placed somewhere on the flight path; the  $Oz$  axis is directed along the local vertical. Let's denote the aircraft position at time point  $t$  as  $x_a(t) = u_0 \cdot t, z_a(t)$ .

To investigate possible artifacts generated by uncontrolled wanderings of the line of sight, which may be caused, e.g., by the fluctuations of the aircraft position, errors in the beam stabilizing system, etc., we should consider the apparent movements of the scattering volume resulting from the above factors. If the distance between the aircraft and the center of the scattering volume at time  $t$  is  $L$ , then the coordinates  $x_S, z_S$  of the scattering volume center are:

$$x_S(t) = x_a(t) + L \cdot \cos(\varphi(t)) \cong x_a(t) + L, z_S(t) = z_a(t) + L \cdot \sin(\varphi(t)) \cong L \cdot \varphi(t) \quad (1)$$

Backscattered radiation is detected with the delay

$$\delta t = 2L/c \quad (2)$$

after time  $t_0$  when the sensing pulse was sent. Equation (2) allows the derivation of  $L$  from measured  $\delta t$ . Because the light velocity significantly exceeds the aircraft velocity, for the simulation purposes, it is convenient to treat  $L(t)$  and  $t$ , which can both be measured directly, as independent variables.

Below, we perform the analysis of the backscatter signal intensity  $I(L, t)$  in the receiving aperture superimposed on the lidar output aperture. We apply the approximation of the single-scattering on aerosol particles (Ishimaru, 1978). We use the following notations:  $\rho_A(x, y, z, t)$  is the number of scatterers per volume unit, or the scatterer density, and  $\sigma_{AB}(x, y, z, t)$  is the aerosol differential backscatter cross-section coefficient. For an arbitrary shaped sensing pulse with its complex envelope  $U(t, t_0)$ , where  $t_0$  is a time moment of pulse generation, the intensity registered by the receiver at an arbitrary time point is determined by the expression (Ishimaru, 1978, Eq. 5.35):

$$I(L, t) = C_s \int_{R_1}^{R_2} \frac{\rho(R', (t - t_0) - R'/c) \sigma_B(R', t - R'/c)}{R_2} |U_i(t - R'/c, t_0)|^2 e^{-2\Gamma(R', t)} dR' \quad (3)$$

Here  $R_1 = c(t - t_0)/2$  and  $R_2 = c(t - t_0 + \tau)/2$  are the corresponding positions of the scattering volume boundaries,  $t_0$  is the time of sensing pulse generation and  $L = (R_1 + R_2)/2$  is the position of the scattering volume center along the flight route. The integration is performed along the line of sight taking into account its direction fluctuations. The factor of  $\exp[-2\Gamma(R, t)]$  in (3) describes the extinction and is defined by equation

$$\Gamma(R, t) = Cd \int_{x_a(t)}^{R+x_a(t)} \rho(R', t - R'/c) \sigma_T(R', t - R'/c) dR' \quad (4)$$

Here,  $\sigma_T$  is total cross-section coefficient of scattering. The product of  $\rho(R', t - R'/c) \sigma_T(R', t - R'/c) dR'$  describes the total losses from molecular and aerosol scatters. Constant factors  $C_s$  and  $Cd$  in front of the integrals in Eqs. (3) and (4) account for the sensing pulse energy, beam geometry, receiver aperture, detector parameters etc. Equation (3) does not take into account the

contribution of weak molecular scattering, which, when the measured intensity  $I(L, t)$  is multiplied by  $L^2 \exp(2 \cdot \Gamma)$ , generates a constant background on the lidar image obtained.

Because ~~both the sensing pulse and detection time are very short as compared to typical times of atmospheric processes, the pulse may be approximated with a  $\delta$ -function~~ lidar pulse is short (10 ns) in comparison to the considered spatial scales, we

5 can use the Dirac function which significantly simplifies the analytical solution. Under this approximation, in the absence of measurement direction oscillations, signal  $I(L, t)$  in receiver aperture is determined by the equation:

$$\begin{aligned}
 I(L, t) &= I_M(L, t) + I_A(L, t) \\
 I_M(L, t) &= \frac{2C \cdot E_0}{c \cdot L^2} \rho_M(L, t - L/c) \sigma_{MB}(L, t - L/c) e^{-2\Gamma(L, t)} \\
 I_A(L, t) &= \frac{2C \cdot E_0}{c \cdot L^2} \rho_A(L, t - L/c) \sigma_{AB}(L, t - L/c) e^{-2\Gamma(L, t)}
 \end{aligned} \tag{5}$$

where the observed intensity  $I$  has two components,  $I_M$ , resulting from the molecular scattering, and  $I_A$  coming from the aerosol scattering. Here,  $E_0$  is the pulse total energy,  $C$  is the normalizing factor that accounts for the sensing pulse shape, the receiver aperture, detector features etc.,  $L$  is the distance between the lidar and the scattering volume. Equations (4) and (5) contain terms  $\rho_M(R', t) \sigma_{MB}(R', t)$  and  $\rho_A(R', t) \sigma_{AB}(R', t)$ , which are the products of scatterers density by the cross-sections of the molecular and aerosol backscattering, respectively. The term  $\exp(-2\Gamma(L, t))$  describes extinction,  $\rho(R', t - R'/c) \sigma_T(R', t - R'/c) dR'$  represents the total losses due to molecular and aerosol extinction. This relatively simple model appears to be a good approximation for a sensing laser pulse with the duration of several nanoseconds. ~~The typical value of  $\rho_M \sigma_{MB}$  for the weak aerosol (concentration  $10^8$  particles per  $\text{cm}^3$ , and density of water  $49 \text{ kg/m}^3$ ) is about  $\rho_M \sigma_{MB} = 2 \cdot 10^{-2}$  (Ishimaru, 1978).~~

15 ~~For the simulation purposes, we use the following normalized function for the atmospheric aerosol backscattering density:~~

$$P(x, z, t) = \rho_M \sigma_{MB}(x, y, z, t) / \rho_M \sigma_{MB}(max) = a \sum_q \exp\left[-\left(\frac{x-x_{0q}}{\Delta o_q}\right)^4 - \left(\frac{y}{\Delta y_q}\right)^4 - \left(\frac{z-z_{0q}}{\delta o_q}\right)^2 - \left(\frac{t-t_q}{\Delta t_q}\right)^2\right] \tag{6}$$

**Table 1.** Parameters of aerosol clusters

Cluster	$\Delta o_q$ , km	$\Delta t_q$ , sec	$x_{0q}$ , km	$t_q$ , sec	$u_0 t_{obs} / \Delta o_q$
A	2.0	60	11.0	34	5.1
B	1.0	40	16.3	70	6.8
C	1.0	40	20.0	40	6.8
D	1.0	16	24.0	80	2.7
E	0.5	10	28.0	95	3.4

In this expression,  $x$  is the axis collinear to the flight direction,  $y$  is the axis perpendicular to both the flight direction and vertical axis,  $z$  is the vertical axis, orthogonal to the Earth's surface below the aircraft position,  $t$  is the moment of measurement,

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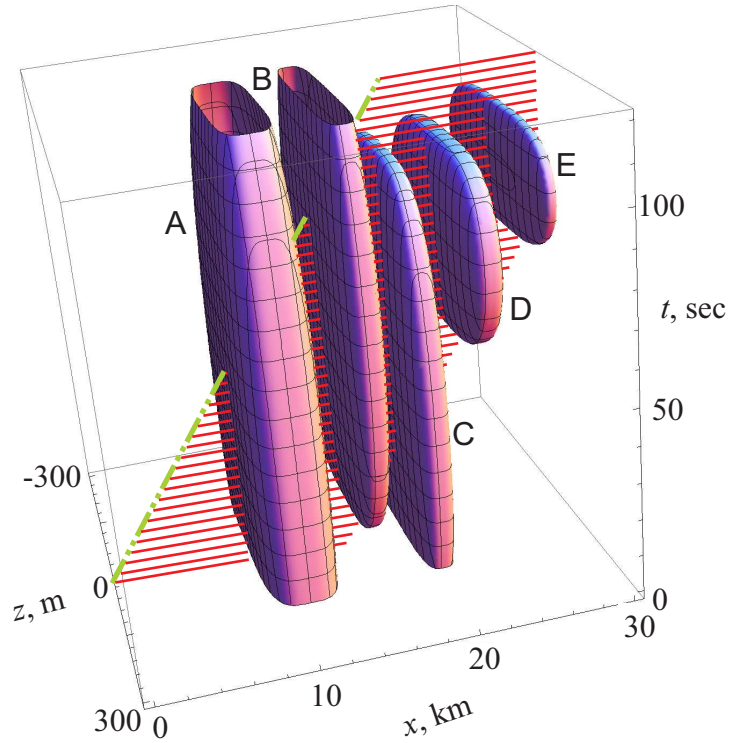
which we assume to coincide with the moment of pulse generation  $t_0$ , due to the aforementioned smallness of the ratio  $L_{max}/(c \cdot \Delta t_q) \ll 1$ ,  $x_{0q}$ ,  $y_{0q}$  and  $z_{0q}$  are coordinates of the clusters' centers,  $t_q$  is the time moment of the maximum cluster density,  $\Delta t_q$  is the typical cluster evolution time,  $\Delta o_q$  is the cluster scale in the flight direction,  $\delta o_q$  is the typical vertical dimension of cluster. The value of  $\Delta y_q$  is the transverse size of the cluster. The contribution of fluctuations of the flight direction along  $y$ -axis into the lidar image noise is negligible, because the changes of scatterers' density are smooth. The parameter  $\Delta y_q$  is chosen to equal  $\Delta o_q$  for all the simulated clusters. The sequence of five integers  $q$ , from 1 to 5, is the sequence order of clusters along the flight path. The model parameters are summarized in the Table 1. All the five clusters have the same thickness  $2\delta o_q = 2\delta o$ , which was equal to 100m; 300m; 900m in different simulations. Figure 2 presents the cluster sequence used in the model for  $\delta o = 150$ m. Aerosol cluster are represented as surfaces calculated at  $e^{-1}$  level of values. The distance from the initial position of the aircraft is laid off along the  $Ox$  axis, the flight altitude is laid off along the  $Oz$  axis and time along the  $t$  axis. The aircraft velocity is assumed to be 170 m/sec.

The last column of the table contains the unitless ratios  $u_0 \cdot t_{obs}/\Delta o_q$ . Because all of them are greater than 1, we can consider our modeled clusters as long-living ones (Gurvich and Kulikov, 2016). We consider "thin" clusters, whose ratios of vertical scales to lengthwise ones are  $\delta o/\Delta o \ll 1$ . If such clusters are detected in the vertical direction from a ground-based platform, they are registered as layers in the altitudinal distribution of the aerosol.

Since our work is aimed at the study of the most typical features of the cluster-image-changes-changes of the backscattered lidar signal, we only discuss their-clusters' shape and relative size, without focusing on the type of particles that produce the signal. Consequently, the value we need to monitor is the normalized backscatter intensity  $J_A(L, t) = [I_A(L, t)]/I_M(L, t)$ . As the constant background coming from the scattering on density inhomogeneities does not present any interest the lidar images, all the Figures present the value of  $J_A(L, t)$ .

Fig. 3 shows the lidar image of aerosol clusters, modeled according to model (6). This image is simulated under the assumption of the stable flight altitude and measurement direction. In terms of Eq. (1), this means that  $\varphi = 0$  and  $z_S = const$ , the latter value may be set to the flight altitude without restricting the generality. We focus on the problem of the impact of flight parameter fluctuations upon measured lidar backscattered signal. The experiment discussed in (Veerman et al., 2014, Introduction) was conducted under clear air conditions. For this reason, for our numerical simulation, we choose the product of scatterer cross-section and density  $\rho_M \sigma_{MB}$  to be equal to  $2 \cdot 10^{-2}$  dB/km at the cluster's center (concentration  $10^8$  particles per  $m^{-3}$ , and density of water  $49 \mu g/m^{-3}$  (Ishimaru, 1978)). This value typically corresponds to weak water aerosol clusters in accordance with Fabelinskii (2012); Ishimaru (1978), which implies that the aerosol scattering does not significantly decrease the propagating laser pulse energy. The values for the other types of aerosol can be found, for example, in (Vrancken et al., 2016).

The image  $J_A$  at Fig. 3 is shown in  $(L, u_0 t)$  coordinates, in which the cluster with a lifespan of  $\Delta t > L_{max}/u_0$  looks like a bar, whose slope with respect to the  $OL$  axis equals  $\pi/4$ . Longitudinal cluster scale  $\Delta o$  determines the image size along the  $L$  axis. ~~Vertical cluster scale does not influence the lidar image under the assumed conditions.~~ The image size at an angle of  $-\pi/4$  with respect to the  $L$  axis, is determined by  $u_0 \Delta t_q$  i.e. the product of aircraft speed by cluster's lifespan. Measurement of the image length  $J_A$  along this direction allows, therefore, the estimation of the cluster lifespan  $\Delta t_q$ . ~~This parameter is important for obtaining images of short-living clusters at large distances  $L$ , because the observer moves closer to the detected~~



**Figure 2.** 3D images of aerosol clusters  $P(x, z, t)$ , calculated at  $1/e$  level, for the model given by eq.(6). Dash-and-dot line is the flight trace, red "comb" represents sensing laser pulses,  $L_{max} = 16$  km,  $\varphi_0 = 0$ .

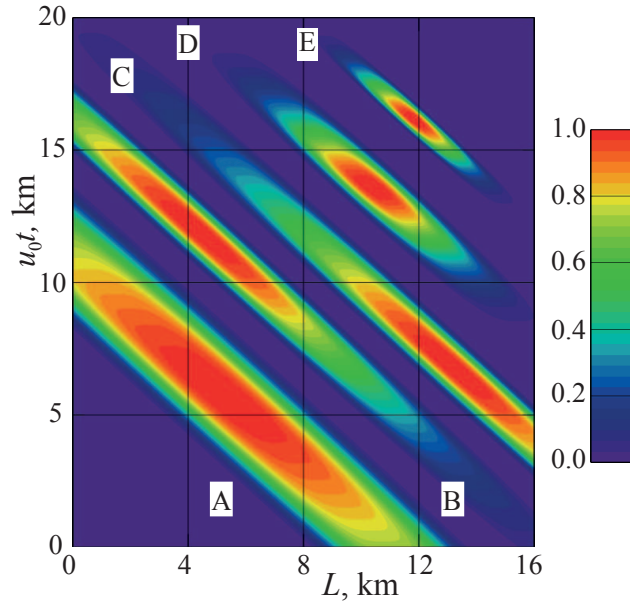
**cluster.** If the cluster has a long lifespan, such that  $u_0 \Delta t_q \gg L_{max}$ , then, for a constant measurement direction, its lidar image is a homogeneous bar.

#### 4 The impact of measurement direction fluctuations on cluster lidar images

Under the real-world conditions, the uncontrolled variations of measurement directions always exist due to both vibrations of the carrying platform and fluctuations of flying aircraft position altitude. If a cluster is strongly elongated in horizontal direction, then its lidar image is most sensitive to vertical variations of the measurement direction. For the simulation-illustration of the effects caused by sensing beam deviation from the flight direction, we assume that the measurement direction, which is determined in (1) by the angle  $\varphi$ , changes periodically with a period of  $T_\varphi = 20$  sec according to the equation

$$\varphi(t) = \varphi_0 \cdot [2\pi u_0 t / T_\varphi] \cdot [1 - \cos(\phi + 2\pi t / T_\varphi)] \quad (7)$$

10 where the normalization factor of  $\varphi_0$  determines the maximum deviation angle from the flight direction-,  $\phi$  is the correcting parameter. Our choice of the  $T_\varphi$  is based on one of the characteristic times of pitch angle fluctuations measured in the experiment. These times vary in the range from few to tens of seconds (Fig.6 (b) and (d)). The considered effects do not



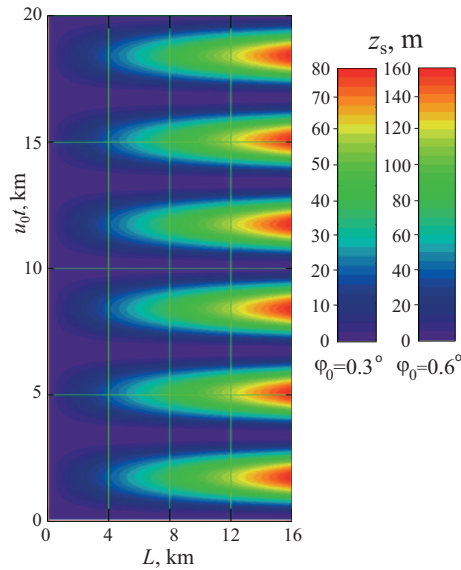
**Figure 3.** Lidar images  $J_A(L, t)$  of aerosol clusters simulated according to the model (eq. (6)) for a constant beam direction aligned with the flight trace. The scale of  $J_A$  is given in pseudo-color at the left. The vertical axis corresponds to the product of  $u_0 t_0$  where  $t_0$  is a sensing pulse generation point and  $u_0$  is the aircraft speed.

disappear for smaller/larger times; such changes would result only in changing of thickness of the breaches. Given the precision characteristics of modern gyro-stabilizing devices used in civil aviation (Temp-Avia, 2016; SOMAG AG Jena, 2016), we consider here two  $\varphi_0$  values:  $\varphi_0 = 3$  and  $\varphi_0 = 6$ ,  $\varphi_0 = 0.3$  and  $\varphi_0 = 0.6$  degrees. We consider here  $z_a(t) = 0$ .

~~The aircraft position fluctuations result in fluctuations of the center of scattering value  $z_S(t)$  at the same distance, without causing new type of effects compared to the angle fluctuations.~~ Fig. 4 shows the relation between the deviation of the scattering volume center coordinate  $z_S = L \cdot \varphi(t)$   $z_S = L \cdot \sin \varphi(t)$ , the measurement time  $u_0 t$  and the distance  $L$  between the observer and the scattering volume center. The distance  $u_0 t_0 = 20$  km corresponds to 2 minutes of airborne observation (for aircraft speed 170 m/sec). Beam displacement is changing from 0 to 160 m (from 0 to 80 m) for  $\varphi_0 = 0.3$  degree ( $\varphi_0 = 0.6$  degree) for about of 10 sec. The speed of movement was defined by period  $T_\varphi = 20$  sec. The correcting parameter  $\phi = 0$ .

Vertical movements of the scattering volume center  $z_S$  comparable to or greater than  $z_S$  should be visible in the lidar image. This qualitatively follows from the description of the measurement setup in Section 2. Lidar images computed in the presence of pitch angle fluctuations in the typical range of the laser-gyros (0.1-0.2 rms) are presented in Fig. 5.

The same 5 aerosol clusters described by Eq. (6) and shown in Fig.2 are taken for lidar image simulations, but their  $\delta\theta$  parameters that determine vertical dimensions are set to different values. Panes (a), (c) and (e) grouped in the upper row show the images simulated at lower oscillation amplitude  $\varphi_0 = 0.3$  degree, for  $\delta\theta$  values of 50, 150 and 450 m. The images at lower row panes: (b), (d) and (f), have a twice higher amplitude  $\varphi_0 = 0.6$  degrees and the same values, respectively. The measurement time is 120 sec for each pane and the maximum measurement distance  $L_{max} = 16$  km. Since the maximum vertical deviations



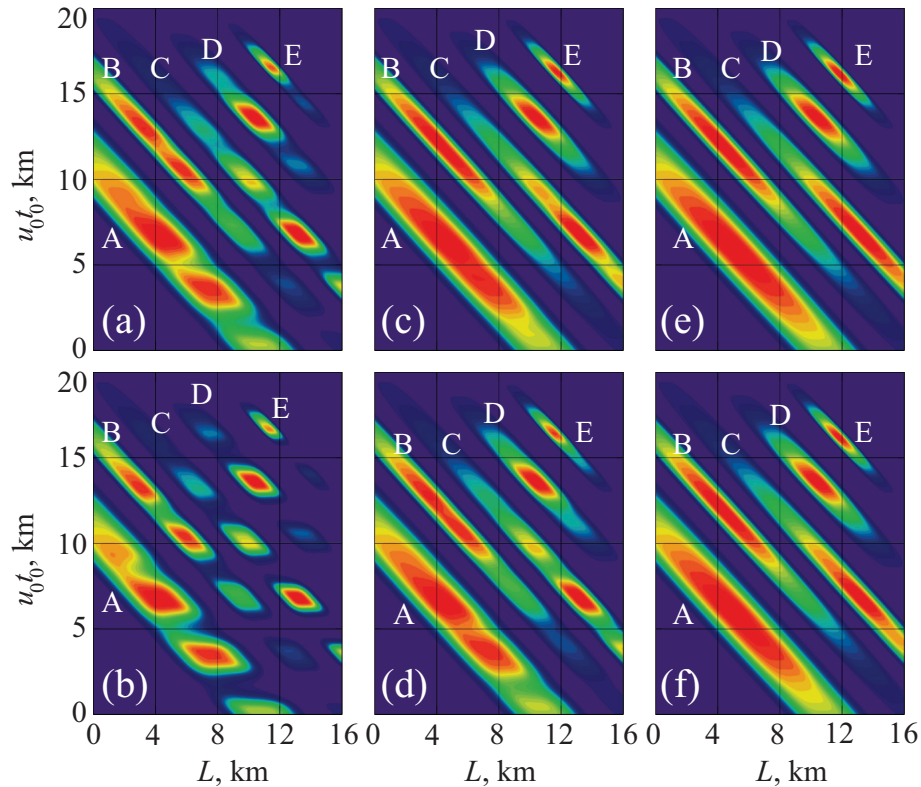
**Figure 4.** Deviation  $z_S$  of the scattering volume center from the flight direction as a function of the pulse generation time  $t$  and of the distance  $L$ .

of the scattering volume center coordinate  $z_S$  from the flight path reach 83 m and 168 m, respectively, it is possible to consider cases with  $z_S > \delta o$  and  $z_S < \delta o$ .

The comparison of the Fig. 3 and Fig. 5 reveals that sensing direction oscillations cause breaches in the clusters lidar images at large distances  $L$  when the deviations of  $z_S$  reach the maximum values. These signal fades appear due to the scattering volume shift outside cluster boundaries; the maximal shift equals  $\varphi_0 L \cdot \sin \varphi_0$ . For this reason the images are more distorted at the right side of each pane of Fig. 5. Image distortions are more intense for thin clusters with low values of  $\delta o$ .

For example, the backscattered signal at the sensing distance  $L=6$  km at the time corresponding to aircraft trajectory coordinate  $u_0 t_0 = 5$  km in presence of aerosol clusters with thickness  $2\delta o = 100$  m (Fig.5ab) decreased by about 20% and 60% from the level without the pitch angle fluctuations (see Fig.3) for  $\varphi_0 = 0.3$  degree and  $\varphi_0 = 0.6$  degree respectively. The signal decreased by about 10% in the presence of aerosol clusters with thickness 300 m for the  $\varphi_0 = 0.6$  degree and it had no noticeable changes for larger vertical sizes of cluster or smaller angles (Fig.5c,d). The backscattered signal from the aerosol layer at the sensing distance  $L=15$  km at the time corresponded to aircraft trajectory coordinate  $u_0 t_0 = 5$  km with thickness 100 m decreased by about 85% for the  $\varphi_0 = 0.3$  degree and absent (only background level) for the  $\varphi_0 = 0.6$  degree. The signal decrease about 35% and 45% in presence of aerosol clusters with thickness 300 m for the  $\varphi_0 = 0.3$  degree and  $\varphi_0 = 0.6$  degree correspondingly, while for the thickness of the cluster about 900 m the only noticeable change (about 12%) can be found for the  $\varphi_0 = 0.6$  degree. Similar effects can be found in Fig.5 for each other moment of time (corresponding to flight trajectory coordinate  $u_0 t_0$ ).





**Figure 5.** The impact of measurement direction fluctuations on the lidar image  $J_A$  of aerosol clusters. The pseudo-colored scale of  $J_A$  values is the same as in Fig. 3. Panes: (a), (c), (e) - oscillations amplitude  $\varphi_0 = 0.3$ degrees, panes: - (b), (d), (f) -  $\varphi_0 = 0.6$ degrees; panes: (a), (b) vertical dimension  $\delta o = 50$  m, panes: (c), (d) -  $\delta o = 150$  m, panes: (e), (f) -  $\delta o = 450$  m.

Fig.5 (a), (b) shows that the breaches appear at the same aircraft position  $u_0 t_0$  for all clusters. The lines could be drawn at 2 km, 5 km (as well as at 8, 12, 15, and 18 km) in accordance with the beam direction variations. The value of  $\varphi_0 \pm L \cdot \sin \varphi_0$  is smaller for smaller distance  $L$ , consequently, the breaches "depth" is smaller for a close distance. Thus the angle  $\varphi_0$  could be estimated from the intensity measurements. It may be expected that a natural process intensity, like aerosol evolution due to evaporation or condensation, varies for different clusters. A distortion due to flight direction fluctuations has the same impact on the images of all the clusters observed at the same distance.

The vertical beam deviation caused by pitch angle fluctuations is about 30 m and 60 m at 6 km distance for maximal amplitude of angle fluctuations  $\varphi_0 = 0.3$  degree and 0.6 degree, respectively (Fig.4). It increases up to 75 and 150 meters for the 15 km distance. The sensing beam can easily move outside the aerosol cluster with a thickness less than the doubled shift size. Even for a movement with a smaller amplitude the backscattered signal will decrease due to decreasing of the cluster density nearby its edge.

As shown in Fig.5, the clusters with smallest evolution time corresponding to a living time below 30 sec still appeared twice for strongest fluctuations (0.6 degree) for the largest sensing distance. It means that we can observe evolution of the

smallest considered cluster (0.5 km length) with the smallest considered evolution time at the considered sensing distance. The evolution of the cluster is clearly seen in decreasing the signal in the periods between the breaches caused by pitch angle fluctuations. Such decreasing can be seen for all considered clusters with and without pitch angle effects (Fig.5).

For thickness values large enough, like in panes (e) and (f), the images almost do not differ from the images in Fig. 3  
5 computed with zero  $\varphi_0$  value, i.e. in the absence of measurement direction oscillations. ~~Therefore, if the condition  $z_S \ll \delta\sigma$  is fulfilled, the cluster layers can be reconstructed by lidar measurements.~~

The data presented in Fig. 5 also suggest the possibility of obtaining actual information about the vertical structure of the aerosol cluster from measurements of  $\varphi(t)$  in flight.

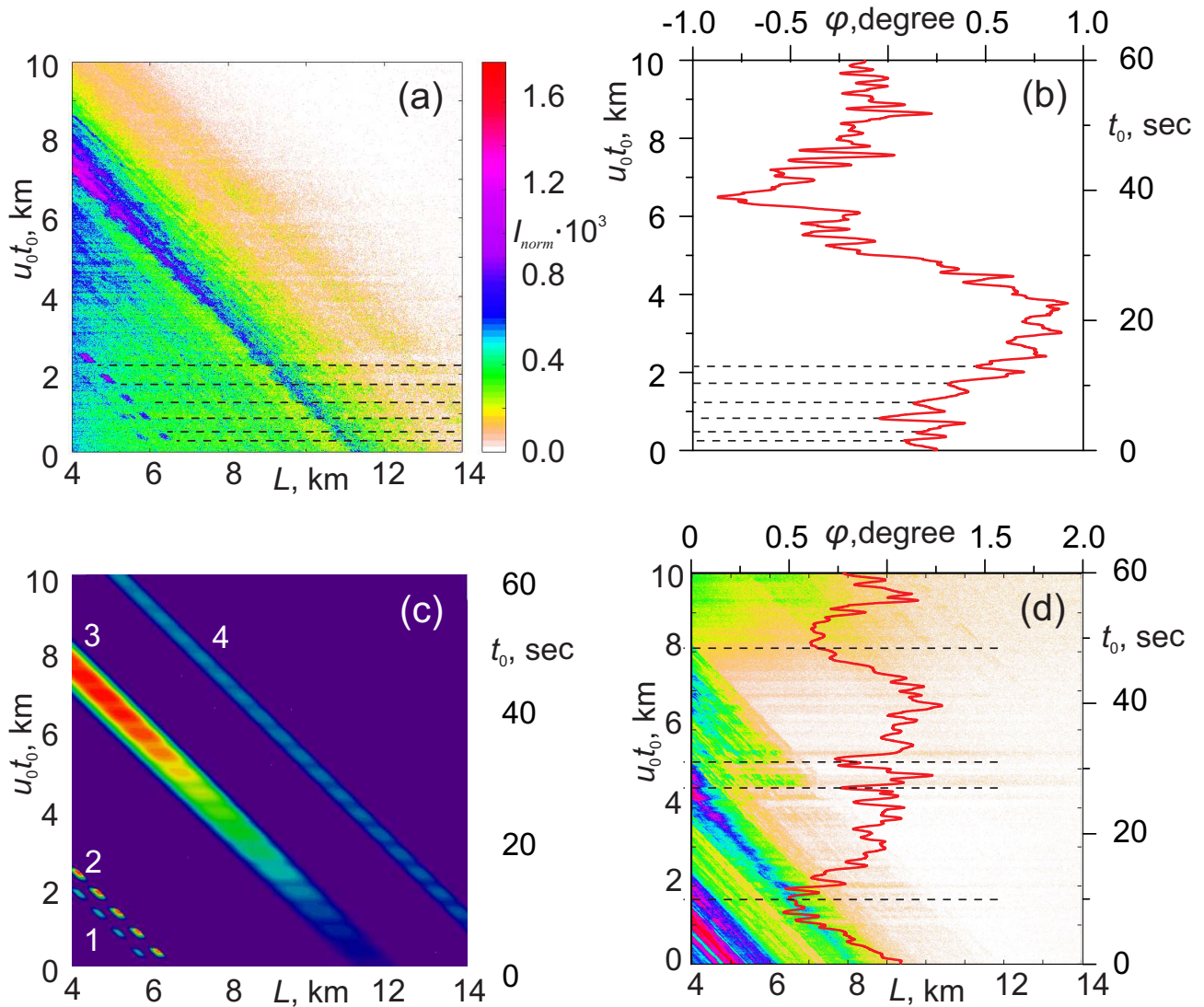
## 5 Airborne lidar measurements in presence of pitch angle fluctuations

10 Laboratory of Turbulence and Wave Propagation at Obukhov Institute of Atmospheric Physics was one of the participants of the DELICAT project. We consider the results of the airborne measurements carried out in the framework of DELICAT project (Veerman et al., 2014, flight map Fig.15). ~~Laboratory of Turbulence and Wave Propagation at Obukhov Institute of Atmospheric Physics was one of the participants of the DELICAT project.~~ The thorough analysis of CAT detection was performed in (Vrancken et al., 2016; Veerman et al., 2014; Hauchecorne et al., 2016). Here we discuss the examples of strong  
15 backscattered signal variations caused by pitch angle fluctuations which were sometimes observed during the experiments. A high-power UV Rayleigh lidar system was installed on an aircraft in a forward-looking configuration as described in detail in (Vrancken et al., 2016). The DELICAT airborne lidar is based on a high-power Nd:YAG laser, which generates 7.7 ns length pulses at wavelength 1064 nm. The lidar was developed by DLR (German Aerospace Center) while the beam steering system was developed by THALES AVIONICS. The third garmonic ( $\lambda = 355$  nm) with energy about 80 mJ was used for ahead  
20 sensing. The angular beam divergence was about of  $200 \mu\text{rad}$ . Lidar receiver contained several subsystems such as telescope with 140 mm diameter, and optical components for filtering, beam forming, stabilization, and detection. The receiver had two channels: for co- and cross-polarization. Lidar range resolution was about 5 m. Further details of the experimental setup can be found in ~~(Veerman et al., 2014)~~(Veerman et al., 2014; Vrancken et al., 2016).

~~In this paper, we only consider the~~ The turbulence area detection was based on the lidar measurements of the fluctuation  
25 in density of air associated with the turbulent wind (Feneyrou, 2009; Vrancken et al., 2016; Hauchecorne et al., 2016). This idea was tested at first with using of the ground-based lidar (Hauchecorne et al., 2016). Detail discussion of the  $C_n^2$  evaluation method and experimental examples of turbulence lidar signal responses with estimated values of  $C_n^2$  can be found, for example, in the Chapter 4b of the Ref. (Hauchecorne et al., 2016) or in (Vrancken et al., 2016).

In the Fig.6 only co-polarized component is shown. For the case that we discuss below, it only differs from the cross-polarized  
30 component by the amplitude coefficient. The measured intensity is normalized in order to compensate the signal decay with the distance  $I(L,t)_{norm} = I(L,t) * (R/R_{2km})^2$  and presented in Fig.6. Though the flight routes for the DELICAT experiments were chosen in order to avoid large amount of aerosol. ~~Usual civil aircraft flight can include much,~~ the signal variations caused by aerosol backscattering was significant (Fig.6 (b) and (d)). The civil aviation routes can include more aerosol clouds. The

measured intensity is normalized in order to compensate the signal decay with the distance  $I(L,t)_{norm} = I(L,t) * (R/R_{2km})^2$  and presented in Fig.6-



**Figure 6.** The experimental data and numerical simulations: (a) the normalized intensity  $I_{norm}$  measured during 1 minute at airborne experiments (a20.22-20.23) without noticeable fluctuations of flight parameters; (b) in presence of measured pitch angle fluctuations correspond to (a); (c) simulations of the experiment presented in (a), the clusters are marked by their numbers; (d) the normalized intensity  $I_{norm}$  measured during 1 minute at airborne experiments (20.32-20.33).

We only present a few minutes of flight N9 measured in France, August 8, 2013. The measurements presented in Fig.6a were acquired during the time interval from 8.32 pm to 8.33 pm 20.22 to 20.23 UTC time, between the geographical latitude/longitude positions (47.200352,6.488001) positions (46.26,6.38) and (47.307705,6.485252) at a height of 10km 46.33,6.48) at the altitude

of 9.46 km. The measurements presented in Fig.6b-d were acquired during the time interval from 8.22 pm to 8.23-20.32 pm to 20.33 pm UTC time, between the geographical positions (46.262356,6.375160) latitude/longitude positions (47.20,6.49) and (46.327354,6.483657) latitude/longitude positions (47.31,6.49) at a height of 9.46 km altitude of 10 km. The aircraft speed was about of 170m/s in both cases. The backscattered signal contains noise caused by different sources. Since this paper is mostly devoted to pitch angle fluctuations, we consider experimental data in the areas of the observation distance from 4 to 14 km, which are almost free from the other noise factors. The lidar signal correction from molecular attenuation is presented in (Veerman et al., 2014, Fig.17). It is mentioned there that the lidar signal is exploitable from 3 km to 15 km due to saturation effect. In order to avoid this problem completely and be sure that noises due to equipment instability do not impact on our research results we chose 4 to 14 km as minimal distance for signal analysis.

The experiment shows that the yaw as well as roll angle fluctuations did not exceed the pitch angles ones (excluding few moments of significant elevations/descent moments during the flight). The altitude changes during the flight, excluding few areas of the significant elevations/descent did not exceed a value of about ten meters. In accordance with the sensing geometry under discussion and possible sizes of the aerosol clusters, only pitch angle fluctuations can result in noticeable signal changes. The pitch angle fluctuations presented in Fig.6b corresponded to the lidar backscattered signal presented in Fig.6a. In this case, there is no; both backscattered signal and pitch angle fluctuations for the other observation interval are shown in Fig.6d. One can see that backscattered signal breaches appeared simultaneously with the pitch angle fluctuations and the aerosol cluster appears as a bar in the left bottom corner.

The experimental observations shown in Fig.6 (b) and (d) demonstrate that there are fast and slow pitch angle fluctuations, with the characteristic time scales of 3-4 sec and about 10-20 sec, respectively. The dotted lines in panels (a), (b) and (d) highlight period of these fluctuations. For the visual convenience only periods of few fast fluctuations in Fig.6 (b) and only few slow fluctuations in Fig.6d are highlighted. The pitch angle fluctuations lead to breaches in the lidar signal. At least three aerosol clusters can be found at the result in significant changes of backscattered signal. This impact can be seen, for example, in Fig.6b. The first a where each signal breach is a result of corresponded pitch angle fluctuations. Two significant signal changes due to slow pitch angle fluctuations can be seen in Fig.6d. The two clusters, first at the  $u_0 t_0 = 5$  km (30 sec) and second at  $u_0 t_0 = 8$  km (50 sec), are suddenly appeared in the field of view due to significant change of the pitch angle presented in the figure by the red curve. In order to resolve the features of backscattered signal caused by the slow pitch angle fluctuations, this type of fluctuations was chosen for the numerical simulation section.

Consider the first and second clusters in Fig.6a which firstly detected at distances 6 and 6.5, respectively, are weak. The third cluster, firstly detected at 11.5 km and 14 km, respectively. It can be seen that there are breaches in the signal which appeared simultaneously in both responds. The value of observed signal was decreased by 3 times from the undisturbed value in the breaches. The breaches demonstrate the same behavior as simulated (see Fig.6c) which is typical for the case of presence both uncompensated pitch angle fluctuations and aerosol clusters.

In order to simulate observed in Fig.6a effect, we chose four clusters with parameters presented in Table 2. The results of simulations are presented in Fig.6c. The density of the first and last cluster was chosen to be twice less than for the second and third cluster. The first and the second clusters have vertical thickness  $2\delta_0$  about 100 meters, while the third and fourth

**Table 2.** Parameters of aerosol clusters: the simulation of the experiment

Cluster	$\Delta \varrho_{g_1}$ , m	$\Delta t_{g_1}$ , sec	$x_{0g_1}$ , km	distance, has a larger scale size along the flight direction. It must also have a larger vertical scale, because it r
1	100	120		5.7
2	100	120		6.2
3	600	26		11.1
4	300	120		20.0

one have thickness about 1000 meters. For this reason, the other clusters. The breaches appear in all the clusters at the same time, which means that they may result from the pitch angle variations effect on the variations of the backscattered signal from the last clusters is weak. The period of pitch angle fluctuations was chosen  $T_\varphi = 2.85$  sec in accordance with observed fast fluctuations (Fig.6a). The correcting parameter  $\phi = 0.5\pi$ . The maximal amplitude  $\varphi_0$  of the pitch angle fluctuations in the simulation was 0.6 degree (corresponds to 0.2 degree rms). This parameters of the clusters and pitch angle fluctuations allows to fit the experimentally observed decreasing of the signal level and time interval between the signal reappearance (sizes of the breaches). Based on our numerical analysis we can conclude that the characteristic vertical size of the aerosol clusters provide a noticeable impact on the backscattered signal is about 50-100 meters. The decreasing of vertical size of the aerosol clusters would increase of this estimation. The normalized intensity of aerosol cluster reflections decreases with the distance. It may result from the scattering on aerosol particles. It also clear that such decreasing is only observed for large aerosol clusters-

If we assume that  $\varphi_0 = 0.15$  degree (corresponds to 0.05 degree rms), the experimental results can be approximated with the cluster thickness 25-30 m.

## 6 Conclusions

In this paper the influence of fluctuations of the flight parameters upon images acquired by an airborne lidar system sensing ahead of the aircraft along the flight direction have been discussed in regard to the dependence on characteristic sizes of aerosol layers. It is shown that the pitch angle fluctuations are the most important factor for the discussed important parameter for the airborne lidar sensing scenario ahead the flight direction in the case when their uncompensated value result in the sensing beam shift about the vertical size of the aerosol clusters. We performed numerical simulations, which demonstrate the pitch angle fluctuation impact upon lidar images signal. The simulations cover the thicknesses of atmospheric aerosol clusters in the range of tens and hundreds thousand of meters accounting for realistic values of pitch angle fluctuations. We also show that LIDAR sensing ahead along the flight direction can potentially provide information about aerosol temporal evolution characteristics - even in presence of pitch angle fluctuations for reasonable cluster size and evolution time at the considered sensing distance.

We demonstrate that pitch angle fluctuations can have a noticeable impact upon measurements of the backscattered signal, even for a lidar system mounted on a stabilizing gyro-platform with the system of compensation of the angle fluctuations.



Numerical simulations predict that uncontrolled fluctuations can result in signal noise including extreme fades and spikes. We show that the aerosol concentration variations on a scale of 100-300 m have a significant impact on the backscattered signal, if the correction for the angular fluctuation has a residual rms error about of 0.1–0.2 degrees, which is typical for ~~conventional gyro-platforms beam steering systems~~ used in the civil aviation. Fluctuation influence is shown to depend on the characteristic vertical size of atmospheric aerosol clusters and to introduce ~~harder-larger~~ errors for aerosol density variations on smaller vertical scales. We formulate criteria for distinguishing this impact from the temporal evolution of atmospheric aerosol clouds.

The lidar backscattered signal from 15 km sensing distance can disappear (or decrease by about 85%) for compensation of pitch angle fluctuations with 0.2 degree rms (0.1 degree rms) in presence of aerosol clusters with characteristic vertical scale about 100 meters. Aerosol clusters with thickness about 300 meters lead to 45% (35%) signal decreasing for the same sensing distance and pitch angle fluctuations. The signal level fluctuations about 60% (20%) can be caused by pitch angle fluctuations with 0.2 degree rms (0.1 degree rms) at the 5 km sensing distance. Pitch angle fluctuations in presence of aerosol clusters with thickness about [100-300] m with angular correction about [0.1-0.2] degree rms lead to noticeable breaches in the backscattered signal. Presence of two or more aerosol clusters allows to easily distinguish the areas of significant beam wander due to signal decreasing caused by pitch angle fluctuations.

We presented and discussed an example of airborne lidar experimental observations from the DELICAT project that shows signal variations simultaneously appearing from different aerosol clusters consistent with the signal fades caused by the impact of pitch angle fluctuations in accordance with ~~our simulations~~ measurements of the pitch angle fluctuations. Simulations of the experiment are performed with assuming the aerosol clusters thickness about 100 meters (1000 m for the large cluster) for the case of pitch angle compensation with 0.2 degree rms. For compensation with 0.05 degree rms noise the corresponded value of the aerosol clusters' thickness 25-30 meters (about 250 meters for the large cluster).

The signal from the areas with significant pitch angle fluctuations can be used only with additional assumptions due to the fact that the sensing beam deviates from the flight trajectory. We need to assume that turbulence strength does not significantly change at the scale of this deviation which is fulfilled only for the short distances and small angle fluctuations. Otherwise this deviation would lead to the turbulence strength estimation changes which cannot be corrected due to absence of backscattered signal from the actual aircraft trajectory. At the same time, generally speaking, the aerosol clusters' evolution in absence of significant uncompensated fluctuations of the pitch angle should not prevent to the turbulence strength estimation. The numerical simulations shown that, for reasonable parameter range, these cases can be distinguished.

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## References

- Acharya, Y.B., Sharma, S. and Chandra, H.: Signal induced noise in PMT detection of lidar signals, *Measurement*, 35(3), 269-276, 2004.
- [Banakh, V. A. and Smalikho, I. N.: Determination of optical turbulence intensity by atmospheric backscattering of laser radiation, \*Atmospheric and Oceanic Optics\*, 24 \(5\), 457–465, 2011.](#)
- 5 [Banakh V.A., Rازenkov I.A., Smalikho I.N.: Laser echo signal amplification in a turbulent atmosphere, \*Applied Optics\*, 54 \(7\), 7301-7307, 2015.](#)
- [Banakh V.A., A.; Rازenkov I. A.: Lidar measurements of atmospheric backscattering amplification, \*Optics and Spectroscopy\*, 120 \(2\), 326-334, 2016.](#)
- [Banakh V.A., Rازenkov I.A.: Refractive turbulence strength estimation based on the laser echo signal amplification effect, \*Optics Letters\*, 41 \(19\), 4429-4432, 2016.](#)
- 10 Barenblatt, G. I., and Monin, A. S.: Similarity laws for turbulent stratified shear flows, *Archive for Rational Mechanics and Analysis*, 70, 307 - 317, 1979.
- Bohren, C. F., and Huffman, D. R.: Absorption and scattering of light by small particles, John Wiley & Sons, 530 p., 2008.
- Burton, S.P., Hair, J.W., Kahnert, M., Ferrare, R.A., Hostetler, C.A., Cook, A.L., Harper, D.B., Berkoff, T.A., Seaman, S.T., Collins, J.E. and Fenn, M.A.: Observations of the spectral dependence of linear particle depolarization ratio of aerosols using NASA Langley airborne High Spectral Resolution Lidar, *Atmospheric Chemistry and Physics*, 15(23), 13453-13473, 2015.
- 15 Burton, S.P., Vaughan, M.A., Ferrare, R.A. and Hostetler, C.A.: Separating mixtures of aerosol types in airborne High Spectral Resolution Lidar data, *Atmospheric Measurement Techniques*, 7(2), 419-436, 2014.
- Cadet, B., Giraud, V., Haefelin, M., Keckhut, P., Rechou, A. and Baldy, S.: Improved retrievals of the optical properties of cirrus clouds by a combination of lidar methods. *Applied optics*, 44(9),1726-1734, 2005.
- 20 Chazette, P., Dabas, A., Sanak, J., Lardier, M. and Royer, P.: French airborne lidar measurements for Eyjafjallajökull ash plume survey, *Atmospheric Chemistry and Physics*, 12(15), 7059-7072, 2012.
- Dacre, H.F., Grant, A.L. and Johnson, B.T.: Aircraft observations and model simulations of concentration and particle size distribution in the Eyjafjallajökull volcanic ash cloud, *Atmospheric Chemistry and Physics*, 13(3), 1277-1291, 2013.
- 25 Fabelinskii, I. L.: Molecular scattering of light, Springer Science & Business Media, 622 p., 2012.
- [Fenevrou, P., Lehureau J.-C., and Barny H.: Performance evaluation for long-range turbulence-detection using ultraviolet lidar, \*Applied Optics\*, 48, 3750–3759, 2009.](#)
- [Fritts, D.C. and Alexander, M.J.: Gravity wave dynamics and effects in the middle atmosphere, \*Reviews of geophysics\*, 41\(1\), 2003.](#)
- [Fukuchi, T. and Shiina, T.: Industrial applications of laser remote sensing, Bentham Science Publishers, 2012.](#)
- 30 Godbaz, J.P., Cree, M.J. and Dorrington, A.A.: Closed-form inverses for the mixed pixel/multipath interference problem in amcw lidar, In *IS&T/SPIE Electronic Imaging*, 829618-829618, 2012.
- [Gurvich, A. S.: Lidar sounding of turbulence based on the backscatter enhancement effect, \*Atmospheric and Oceanic Physics\*, 48 \(6\), 585–594, 2012.](#)
- [Gurvich, A. S., and Chunchuzov I. P.: Parameters of the fine density structure in the stratosphere obtained from spacecraft observations of stellar scintillations, \*Journal of Geophysical Research: Atmospheres\*, 108.D5, 2003.](#)
- 35 [Gurvich, A. S. and Kashkarov, S. S.: On the issue of scattering enhancement in a turbulent medium, \*Izv. Vyssh. Uchebn. Zaved., Radiofizika\* 20 \(5\), 794–800, 1977.](#)

- Gurvich, A. S., and Kulikov V. A.: Lidar sensing of the turbulence based on the backscattering enhancement effect, SPIE LASE, Free-Space Laser Communication and Atmospheric Propagation XXV, pp. 86100U-86100U, International Society for Optics and Photonics, 2013.
- Gurvich, A. S., and Kulikov, V. A.: Airborne Lidar sounding of short-lived aerosol clusters, *Atmospheric and Oceanic Optics*, 29, 410 - 414, doi:10.1134/S1024856016050079, 2016.
- 5 Haarig, M., Engelmann, R., Ansmann, A., Veselovskii, I., Whiteman, D. N., and Althausen, D.: 1064 nm rotational Raman lidar for particle extinction and lidar-ratio profiling: cirrus case study, *Atmospheric Measurement Techniques*, 9, 4269 - 4278, doi:10.5194/amt-9-4269-2016, 2016.
- Hair, J.W., Hostetler, C.A., Cook, A.L., Harper, D.B., Ferrare, R.A., Mack, T.L., Welch, W., Izquierdo, L.R. and Hovis, F.E.: Airborne high spectral resolution lidar for profiling aerosol optical properties, *Applied optics*, 47(36), 6734-6752, 2008.
- 10 Hauchecorne, A., Cot, C., Dalaudier, F., Porteneuve, J., Gaudo, T., Wilson, R., Cenac, C., Laqui, C., Keckhut, P., Perrin, J. M., and Dolfi, A.: Tentative detection of clear-air turbulence using a ground-based Rayleigh lidar, *Applied Optics*, 55, 3420 - 3428, doi:10.1364/AO.55.003420, 2016.
- Hervo, M., Quennehen, B., Kristiansen, N.I., Boulon, J., Stohl, A., Fréville, P., Pichon, J.M., Picard, D., Labazuy, P., Gouhier, M. and Roger, J.C.: Physical and optical properties of 2010 Eyjafjallajökull volcanic eruption aerosol: ground-based, Lidar and airborne measurements  
15 in France. *Atmospheric Chemistry and Physics*, 12(4), 1721-1736, 2012.
- Hoareau, C., Keckhut, P., Baray, J. L., Robert, L., Courcoux Y., Porteneuve J., Vomel H., and Morel, B.: A Raman lidar at La Reunion (20.8 S, 55.5 E) for monitoring water vapor and cirrus distributions in the subtropical upper troposphere: preliminary analyses and description of a future system, *Atmospheric Measurement Techniques*, 5, 1333 - 1348, doi:10.5194/amt-5-1333-2012, 2012.
- Huffaker, R. M., and Hardesty, R. M.: Remote sensing of atmospheric wind velocities using solid-state and CO2 coherent laser systems,  
20 *Proceedings of the IEEE*, 84, 181-204, doi:10.1109/5.482228, 1996.
- Inokuchi, H., Endo, E., Ando, T., Asaka, K., Tanaka, H., and Hirano, Y.: Development of an airborne wind measurement system, *International Symposium on Photoelectronic Detection and Imaging 2009: Laser Sensing and Imaging*, edited by Farzin Amzajerdian, Chun-qing Gao, Tian-yu Xie, Proc. of SPIE Vol. 7382, 738205 doi: 10.1117/12.836606, 2009.
- Inokuchi, H., Tanaka, H. and Ando, T.: Development of an onboard doppler lidar for flight safety, *Journal of aircraft*, 46(4), 1411-1415, 2009.
- 25 Ivlev, L. S., and Dovgalyuk, Y. A.: *Physics of atmospheric aerosol systems*, Saint-Petersburg State University, 188 p., 1999.
- Ishimaru A.: *Wave propagation and scattering in random media*, Academic press NY, 572 p, 1978.
- Jentink, H.W. and Bogue, R.K., Optical air flow measurements for flight tests and flight testing optical air flow meters, In *Flight Test – Sharing Knowledge and Experience*, Meeting Proceedings RTO-MP-SCI-162, Paper 11, France, 2005.
- Johnson, B., Turnbull, K., Brown, P., Burgess, R., Dorsey, J., Baran, A.J., Webster, H., Haywood, J., Cotton, R., Ulanowski, Z. and Hesse, E.:  
30 In situ observations of volcanic ash clouds from the FAAM aircraft during the eruption of Eyjafjallajökull in 2010, *Journal of Geophysical Research: Atmospheres*, 117(D20), DOI: 10.1029/2011JD016760, 2012.
- ~~Kandidov, V.P., Shlenov, S.A. and Kosareva, O.G.G.E.: Filamentation of high-power femtosecond laser radiation. *Quantum Electronics*, 39(3), p.205-228 2009.~~
- Keckhut, P., Courcoux, Y., Baray, J. L., Porteneuve, J., Veremes, H., Hauchecorne, A., Dionisi, D., Posny, F., Cammas, J. P., Payen G,  
35 Gabarrot F.: Introduction to the Mado Lidar Calibration dedicated to the validation of upper air meteorological parameters, *Journal of Applied Remote Sensing*, 9, 094099, doi:10.1117/1.JRS.9.094099, 2015.



- Kiemle, C., Wirth, M., Fix, A., Ehret, G., Schumann, U., Gardiner, T., Schiller, C., Sitnikov, N. and Stiller, G.: First airborne water vapor lidar measurements in the tropical upper troposphere and mid-latitudes lower stratosphere: accuracy evaluation and intercomparisons with other instruments. *Atmospheric chemistry and physics*, 8(17), 5245-5261, 2008.
- 5 Kleinman, L.I., Springston, S.R., Daum, P.H., Lee, Y.N., Nunnermacker, L.J., Senum, G.I., Wang, J., Weinstein-Lloyd, J., Alexander, M.L., Hubbe, J. and Ortega, J.: The time evolution of aerosol composition over the Mexico City plateau. *Atmospheric Chemistry and Physics*, 8(6), 1559-1575, 2008.
- Klyatskin, V. I.: Diffuse and clusterization of passive admixture in random hydrodynamic flows, Moscow Fizmatlit, 149 p., 2005.
- Klyatskin, V. I., and Koshel, K. V.: Simple example of the development of cluster structure of a passive tracer field in random flows, *Physics-Uspokhi* 43, 717 - 723, doi:10.1070/PU2000v043n07ABEH000743, 2000.
- 10 Koch, S.E., Jamison, B.D., Lu, C., Smith, T.L., Tollerud, E.I., Girz, C., Wang, N., Lane, T.P., Shapiro, M.A., Parrish, D.D. and Cooper, O.R.: Turbulence and gravity waves within an upper-level front, *Journal of the atmospheric sciences*, 62(11), 3885-3908, 2005.
- ~~Kosareva, O. G., Murtazin, I.N., Panov, N~~
- ~~Kulikov, V. A., Basu, S., and Vorontsov, M. A., Savelev, A.B., Kandidov, V.P. and Chin, S.L.: Pulse shortening due to filamentation in transparent medium, *Laser Physics Letters*, 4(2), 126-132, 2006.-: [Simulation of laser beam propagation based on mesoscale modeling of optical turbulence and refractivity, OSA conference: Propagation Through and Characterization of Atmospheric and Oceanic Phenomena, PTh3D-3, 2017](#)~~
- 15 Lane, T.P., Sharman, R.D., Clark, T.L. and Hsu, H.M.: An investigation of turbulence generation mechanisms above deep convection, *Journal of the atmospheric sciences*, 60(10), 1297-1321, 2003.
- Leblanc, T. and McDermid, I.S.: Accuracy of Raman lidar water vapor calibration and its applicability to long-term measurements. *Applied optics*, 47(30), 5592-5603, 2008.
- 20 Liu, Z.S., Wu, D., Liu, J.T., Zhang, K.L., Chen, W.B., Song, X.Q., Hair, J.W. and She, C.Y.: Low-altitude atmospheric wind measurement from the combined Mie and Rayleigh backscattering by Doppler lidar with an iodine filter, *Applied optics*, 41(33), 7079-7086, 2002.
- Lu, C. and Koch, S.E.: Interaction of upper-tropospheric turbulence and gravity waves as obtained from spectral and structure function analyses, *Journal of the Atmospheric Sciences*, 65(8), 2676-2690, 2008.
- 25 Meng, Z. and Seinfeld, J.H.: Time scales to achieve atmospheric gas-aerosol equilibrium for volatile species, *Atmospheric Environment*, 30(16), 2889-2900, 1996.
- Nappo, C.J.: An introduction to atmospheric gravity waves, Academic Press, 365 p., 2013.
- ~~Nunalee C. G., He P., Basu, S., Minet J., and Vorontsov M. A.: [Mapping optical ray trajectories through island wake vortices, \*Meteorology and Atmospheric Physics\*, 127\(3\), 355-368, 2015.](#)~~
- 30 Plougonven, R. and Zhang, F.: Gravity waves generated by jets and fronts and their relevance for clear-air turbulence, In *Aviation Turbulence* (pp. 385-406). Springer International Publishing, 2016.
- Veerman, H. P. J., Vrancken, P., Lombard, L.: Flight testing delicat - a promise for medium-range clear air turbulence protection, European 46th SETP and 25th SFTE Symposium 2014, Lulea, Sweden, 2014.
- Veselovskii, I., Whiteman, D. N., Korenskiy, M., Suvorina, A., and Perez-Ramirez, D.: Use of rotational Raman measurements in multi-wavelength aerosol lidar for evaluation of particle backscattering and extinction, *Atmospheric Measurement Techhniques*, 8, 4111 - 4122, doi:10.5194/amt-8-4111-2015, 2015.
- ~~Vinogradov, A. G., Kravtsov, Y. A. and Tatarskii, V. I.: [Backscattering enhancement effect on bodies placed in a medium with random inhomogeneities, \*Izv. Vyssh. Uchebn. Zaved., Radiofizika\* 16 \(7\), 1064-1070, 1973.](#)~~

- [Vorontsov, M. A., and Kulikov, V. A.: Framework for analysis of joint impact of atmospheric turbulence and refractivity on laser beam propagation, OSA conference: Propagation through and Characterization of Distributed Volume Turbulence and Atmospheric Phenomena pp. PM4C-1, 2015.](#)
- 5 [Vrancken, P., Wirth, M., Ehret, G., Barny, H., Rondeau, P., and Veerman, H.: Airborne forward-pointing UV Rayleigh lidar for remote clear air turbulence detection: system design and performance, Applied optics, 55 \(32\), 9314-9328, 2016.](#)
- Reichardt, J., Reichardt, S., Behrendt, A. and McGee, T.J.: Correlations among the optical properties of cirrus-cloud particles: Implications for spaceborne remote sensing, Geophysical research letters, 29(14), 2002.
- Schmitt, N.P., Rehm, W., Pistner, T., Zeller, P., Diehl, H. and Nave, P.: The AWIATOR airborne LIDAR turbulence sensor, Aerospace Science and Technology, 11(7-8), 546-552, 2007.
- 10 [Sofieva, V. F., Gurvich A. S., and Dalaudier F.: Mapping gravity waves and turbulence in the stratosphere using satellite measurements of stellar scintillation, Physica Scripta, T142, 014043, 2010.](#)
- Company SOMAG AG Jena, product GSM 3000 <http://www.somag-ag.de/gsm-3000/>
- [Southwell W. H., Ray tracing in gradient-index media, J. Opt. Soc. Am. 72, 908-911, 1982.](#)
- Targ, R., Steakley, B.C., Hawley, J.G., Ames, L.L., Forney, P., Swanson, D., Stone, R., Otto, R.G., Zarifis, V., Brockman, P. and Calloway, R.S.: Coherent lidar airborne wind sensor II: flight-test results at 2 and 10  $\mu\text{m}$ . Applied optics, 35(36), 7117-7127, 1996.
- 15 Temp-Avia, product MGV-4V <http://www.temp-avia.ru/index-13.htm>
- Thales Avionics and ONERA: A 1.5  $\mu\text{m}$  LIDAR demonstrator of low airspeed measurement for civil helicopter, Proceedings of the 30th European Rotorcraft Forum, (2004).
- Turnbull, K., Johnson, B., Marengo, F., Haywood, J., Minikin, A., Weinzierl, B., Schlager, H., Schumann, U., Leadbetter, S. and Woolley, A.: A case study of observations of volcanic ash from the Eyjafjallajökull eruption: 1. In situ airborne observations, Journal of Geophysical Research: Atmospheres, 117(D20), 2012.
- ~~Fritts, D.C. and Alexander, M.J.: Gravity wave dynamics and effects in the middle atmosphere, Reviews of geophysics, 41(1), 2003.~~
- ~~Fukuchi, T. and Shiina, T.: Industrial applications of laser remote sensing, Bentham Science Publishers, 2012.~~
- Weitkamp, C.: Lidar: range-resolved optical remote sensing of the atmosphere, Springer Science & Business, 2006.
- 25 [der Werf S. Y., Ray tracing and refraction in the modified US1976 atmosphere, Appl. Opt. 42, 354-366, 2003.](#)
- Whiteman, D.N., Melfi, S.H. and Ferrare, R.A.: Raman lidar system for the measurement of water vapor and aerosols in the Earth's atmosphere. Applied Optics, 31(16), 3068-3082, 1992.
- Zuev, V. E., and Zuev, V. V.: Remote optical sensing of the atmosphere, Gidrometeoizdat, Moscow, 232 p., 1992.