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Atmospheric Measurement Techniques Discussions

# *Interactive comment on* "Impact of pitch angle fluctuations on airborne lidar sensing ahead along the flight direction" *by* Alexander Sergeevich Gurvich and Victor Alexeevich Kulikov

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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."

The thorough analysis of CAT detection by DELICAT lidar is given in References (Vranchken et al., 2016; Veerman et al., 2014; Hauchecorne at el., 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 (Vranchken 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; Vranchken et al., 2016; Hauchecorne at el., 2016). This idea was tested at first with using of the ground-based lidar (Hauchecorne at el., 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 at el., 2016).

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 both turbulence and aerosol signals. When the sensing beam strays 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. The aerosol lidar signal observed in the experiment was comparable with turbulence strength $C_n^2 = 2.5 \cdot 10^{-16} m^{-2/3}$. Estimations of expected turbulence signal respond based on the assumptions of the value of the structure characteristic $C_n^2 = 2.5 \cdot 10^{-16} m^{-2/3}$ 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 the level of response of the turbulence/aerosol which is present in the area sensed by the strayed beam.

References 1

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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."

The two channel scheme based on backscattering enhancement (BSE) looks promising for future airborne applications in light of both thorough theoretical analysis and experimental evidence of success reported in (Banakh and Smalikho, 2011; Banakh et al., 2015; Banakh and Razenkov, 2016a; Banakh and Razenkov, 2016b).



The BSE effect for the optical waves which encounter an obstacle in turbulent medium 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).

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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 inhomigeneities 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."

The papers devoted to theoretical and experimental research of the atmospheric anisotropy (Gurvich, 1984; Gurvich, 1997; Gurvich and Brekhovskikh, 2001; Gurvich and Kan, 2003a,b; Gurvich and Chunchuzov, 2003; Sofieva at el 2010) contains consideration of long paths about few hundreds of kilometers. In these research papers the signal transmittance from satellite to satellite or observations of star scintillations from the satellite-borne sensor through the atmosphere were considered. The turbulence anisotropy can noticeable bend the light propagated over such long distances, but this impact is 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 (der Werf, 2003; Nunalee 2015). The consideration of such effects can be performed in the framework of geometrical (Southwell, 1982; Werf, 2003; Nunalee, 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

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

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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."

That is true that non-liner effects should not occur during propagation of the laser pulses emitted by the DELICAT lidar. The discussion of non-linear effects is included in Introduction because of the possible future implementations which may demand more accuracy or longer propagation distance, and therefore demand shorter pulses with higher energy.

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