Response to Reviewer # 1

We thank the reviewer for his review and valuable comments. The manuscript has been modified according to the suggestions proposed by the reviewer. The remainder is devoted to the specific response item-by-item of the reviewer's comments.

RC=Reviewer Comments
AR=Author response
TC=Text Changes

This paper develops simple functions to characterize the impacts of multiple scattering on lidar observations, based on simulations from a physics-based Monte Carlo multiple scattering code. The simulations are performed for one type of coarse aerosol, one water cloud case, and two cirrus cases, for typical configurations of ground-based and airborne lidars and for the CALIOP and ATLID spaceborne lidars.

I think this paper is a useful introduction to and overview of lidar multiple scattering effects. I disagree with the comment from RC2, who says "This aspect of Monte Carlo simulation is therefore not original in itself and many models exist in laboratories around the world. It is a basic design tool." Not every lidar group considers multiple scattering or applies corrections. Multiple scattering codes should be a basic design tool, but it is often not considered in lidar retrievals under an assumption that the lidar design ensures they are insignificant. The results presented in this paper are helpful to groups which haven't previously considered multiple scattering, and to users of lidar data who want to understand under what conditions the impacts should be considered and perhaps apply corrections to the data which is not already corrected.
We are grateful to the reviewer for providing his opinion, which we fully share. Among other things, the above arguments motivated this work.

The discussion of the method is sufficiently detailed but the discussion of the results is mostly a factual description of the simulations and fitting results. Some interpretation and synthesis of the results into general conclusions and guidance is needed. The major goal of the paper seems to be to identify conditions where multiple scattering are small enough they can be ignored. The paper identifies these conditions for the four particle types considered and two 'standard' FOVs. The authors should use their results to make more general statements. Only a few specific lidar viewing geometries and particle cases are considered.
In response to the pertinent questions of the reviewer, we have added to the revised manuscript Chapter 5.3 (page 21, line 455) (see below).

What are the limitations in using these fitting equations to estimate multiple scattering for other conditions (range, FOV, extinction, particle size).
We already underlined in the section "Conclusions and discussion" that the empirical model has demonstrated very good quality of MC-data fitting for all considered cases. We have not confronted any exception despite profound changes in the MS growth rate at high values of the extinction coefficient or wide RFOVs.
It seems that our empirical model has no limitations from point of view of the fitting quality of MS contribution to lidar signals provided that MC simulations were performed and the values of the coefficients $\boldsymbol{a}=\{a1,a2,a3\}$ were found. We also underlined in the section "Conclusions and discussion" that an approach has to be developed to predict $\boldsymbol{a}=\{a1,a2,a3\}$ values only on the base the lidar configuration and particles characteristics, and that the empirical model has to be generalized to the case of varying profiles of the extinction coefficient.

Are the aerosol, water cloud, and cirrus types defined in a way that they predict typical multiple scattering effects? Are the conclusions valid over expected variations in particle size? There is some variability in cirrus phase functions due to differences in particle habit. Would you expect variations in habit to change these conclusions?

In response to the pertinent questions of the reviewer, we have added to the revised manuscript Chapter 5.3 (page 21, line 455).

5.3 Estimation of MS magnitude in other cases

This work data are limited to a set of cases because MC simulations are time consuming. Some ideas about dependence of the MS relative-contribution R_{MSto1} on the lidar-configuration parameters and on the particles characteristics can be obtained from an analysis of Eq. (11) of the work by Eloranta (1998). That equation is very complex and numerical integration has to be done even when the extinction coefficient is constant. Thus, it is hardly probable that relatively simple estimations of the coefficients $\boldsymbol{a}=\{a1,a2,a3\}$ can be developed directly. In such a situation, it is reasonable to suggest a way to predict some useful characteristics.

The magnitude of MS contribution to lidar signals, i.e., the level of R_{MSto1} is of special interest because, for example, it indicates whether the single scattering approximation can be used in other cases under the usual operational conditions. Analysis of the literature (see, e.g., Eloranta, 1998) suggests that there exist key parameters governing MS contribution, namely, the receiver field-of-view RFOV, the distance to the cloud near-edge h_b, the in-cloud distance d, the particles extinction coefficient ε_p, and the angle θ_{max}. And, as it follows from Eq. (14) and seen in Figs. 3 and 5, $R_{MSto1} \sim d$ when the in-cloud distance d exceeds 0.5 km.

The first idea that comes is to search for approximate relationships between R_{MSto1} and the key parameters for the range $d > 0.5$. Thereupon, those approximate relationships can be used along with the data of Tables 2 – 4 to estimate the magnitude of MS contribution to lidar signals in cases of interest.

It follows from MC simulations of this work that $R_{MSto1} \sim (RFOV)^{k_F}$, $R_{MSto1} \sim \left(\varepsilon_p\right)^{k_\varepsilon}$, $R_{MSto1} \sim (\theta_{max})^{-k_\theta}$, $R_{MSto1} \sim (h_b)^{k_h}$, and $R_{MSto1} \sim d$. (We recall that the width θ_{max} or θ_d of the forward scattering peak depends on the wavelength and the effective size of particles.) The powers k_F, k_ε, k_θ, and k_h are approximately within the following ranges $k_F \in [0.9 \div 1.1]$, $k_\varepsilon \in [0.6 \div 1.3]$, $k_\theta \in [0.3 \div 1.1]$, and $k_h \in [0.5 \div 0.7]$. The fact that the powers are within some intervals means that there is strong nonlinear interdependence between effects of the key parameters. Therefore, an estimation of the magnitude of MS contribution will be rough even in the UOC.

The effective diameter d_{eff} of the fine-mode aerosols is lower than d_{eff} of the coarse mode (see, e.g., Dubovik et al., 2006), and the same is true for hydrated sea salt aerosol (see, e.g., Masonis et al., 2003). Consequently, forward scattering peak of those aerosols are larger. Therefore, it is safe to say that the coarse-aerosol data of Tables 2 – 4 can be used as the upper bounds for fine-mode aerosols and for hydrated sea salt aerosol. The mean values of the effective diameter of marine and continental low-level stratiform clouds are of 19.2 µm and 10.8 µm, respectively (Miles et al., 2000). Thus, the water-cloud data of Tables 2 – 4 can be useful when $\varepsilon_p \le 1.0$ km^{-1}. (The cases of high values of the particles extinction coefficient are addressed below.)

In support of the approach above we obtained the following results. Optical characteristics of sea salt aerosol were computed at the wavelength 0.532 µm. The size distribution of particles was assumed to be log-normal with the mean radius of 2 µm, the standard deviation of 0.6 µm, and d_{eff}=4.75 µm, that is, the same as for the coarse mode. We used the mixture of spheroids with the distribution of axis ratios within the range [0.9129, 1.0954] and the real and imaginary part of the refractive index were 1.40 and 0.0006, respectively (Masonis et al., 2003). The obtained phase function has θ_{max} = 2.37 degree, which is larger than θ_{max} of the coarse mode due to the changes in the refractive index and the shape of particles. Assuming that $R_{MSto1} \sim (\theta_{max})^{-1}$, we used Tables 2 and 4 to estimate the MS magnitude for the cases ε_p =1.0 km^{-1}, RFOV 1.0 mrad and the distances to the sea-salt aerosol layer 1 and 8 km. The estimations of the approach above lead to the values 3.8 % and 11.6 %, respectively, at the in-cloud distance 3 km. As the reference, MC simulations gave 3.7 % and 11.0 % for the same cases.

It is well known that the phase function of ice particles depends not only on the effective size but also on particle habit (see, e.g., Yang et al., 2013) and roughness of particle surface (see, e.g., Shcherbakov et al., 2006). The data library (Yang et al., 2013) provides reliable scattering, absorption, and polarization properties of ice particles in large spectral and size ranges, 11 ice crystal habits and three surface roughness conditions (i.e., smooth, moderately roughened, and severely roughened). The data library provides means to obtain the angle θ_{max} and estimate MS magnitude using Tables 2 – 4. Broadly speaking, large differences with the results of this work are hardly expected for other habits of ice particles provided that surface of the facets is severely roughened. When surface of the facets is smooth, that is, the halo features are present in a phase function, higher or much higher MS magnitude could be expected because much more energy is scattered within very small forward angles even in case of an ensemble of randomly oriented particles (Yang et al., 2013).

Specific comments

Line 23: The authors should quantify here what is meant by "acceptable"

We added to the revised manuscript (page 1 line 23) the following text.

…, i.e., multiple scattering contribution to lidar signal is lower than 5% …

Line 126: Is "coarse aerosol" meant to represent dust? More details should be provided on the model for coarse aerosol: index of refraction, shape (spheres, spheroids, aspect ratio), and size. Why was this particular model chosen, is it generally representative of coarse aerosol? Is multiple scattering different for desert dust or hydrated sea salt aerosol of similar size? How sensitive are the results to changes in aerosol optical properties?

We added to the revised manuscript (page 5 line 146) the following text.

The scattering matrix of the coarse-aerosol was simulated according to the work by Dubovik et al. (2006) as the "Mixture 1" of spheroids with the distribution of axis ratios within the range [0.3349, 2.986] (assuming, as the first-order approximation, that shape is independent of size). The size distribution of particles was assumed to be log-normal with the mean radius of 2 µm, the standard deviation of 0.6 µm, and d_{eff} = 4.75 µm. That value is in agreement with data of the work by Weinzierl et al., (2009), where it was found that the effective diameter of the Saharan dust showed two main ranges: around 5 µm and 8 µm. The real and imaginary part of the refractive index were 1.55 and 0.002, respectively (see, e.g., Petzold et al., 2009).

Line 321: Explain why 5% is selected as the threshold where the multiple scattering contribution must be considered. Because 5% is smaller than other sources of error typically found in lidar retrievals?

The threshold 5% was chosen from point of view of measurement errors. We agree that 5% is smaller than other sources of error that affect lidar retrievals. We added to the revised manuscript (page 14 line 344) the following text.

It follows from EARLINET (European Aerosol Research Lidar Network) instrument intercomparison campaigns (Fig. 4b, Wandinger et al., 2016) that the relative deviation of the lidar signals (λ = 0.532 µm) from the common reference is mostly within ±3%. In our opinion, MS contribution lower than 5 % could hardly be detected in such conditions. It should be underlined that the results of this work are presented so that an interested reader can use other threshold value to assess whether the single scattering approximation is acceptable in view of measurement errors of a specific lidar.

Technical corrections
We are grateful to the reviewer for providing the technical corrections.

Line 24 and 40: "of 1 km" does this mean 'equals 1 km', 'less than 1 km'?
Corrected in the revised manuscript.
Line 65: "techniques" should be "technique"?
Corrected in the revised manuscript.
Line 77: when "the" impact
Corrected in the revised manuscript.
Line 100: "The" other two ...
Corrected in the revised manuscript.
Line 265, 383, 409, and 452: "again" rather than "another time"
Corrected in the revised manuscript.
Line 632: "drown" should be "shown"?
Corrected in the revised manuscript.
Line 637: "the shown in Fig. A1b function" should be "the function shown in Fig. A1b", I think
Corrected in the revised manuscript.

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