Statement on the Revision of ⟨AMT 2017-182⟩ Based on the Referees' Report

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This statement concerns our revision of the ⟨AMT 2017-182⟩ paper, entitled "⟨*Impact of Varying Lidar Measurement and Data Processing Techniques...*⟩", based on the referees' report.

Comments by Reviewer #1

> `The revised version is not ready for publication. The quality is rather low, and if this would be the first round of review, I would vote for rejection. I am a bit disappointed about the answers of the first author (I speculate the co-authors were never involved in the review). I have the feeling after reading the responses, the first author is not willing to invest more work, needed to become a good science article. This is disappointing.`

We would like to thank the reviewer for revising the paper again, and for the helpful suggestions for improving the quality of the paper. In the following specific answers to all the points raised by the reviewer are addressed.

As general remark we want to reassure the reviewer that all the revisions have been carefully discussed among all the co-authors.

> Zenith pointing of the laser beam (this is obviously the case for the Italian lidar, rather than the required off-zenith pointing) and multiple scattering can introduce severe uncertainties in cirrus extinction profiling with lidar so that all the subsequent radiative transfer computations are useless when the multiple scattering effect is not considered and, independent of that, very questionable when the lidar is pointing to the zenith. As a consequence, the cirrus studies in this paper are practically useless. More details are given below. The paper is clearly not state-of the-art from the basic and fundamental lidar point of view. At least, major revisions are required.

Those two main issues are now fixed (see discussion below). Again, the previous version was a first study with the goal of showing discrepancies of lidar technique and data processing that can be performed also on synthetic lidar signals.

> L27: ... with respect to cirrus... must be added because in the case of liquid-water clouds the single-scattering lidar ratio is 18 sr, and when considering multiple scattering the apparent one is around 8-12 sr.

Added, as suggested by the reviewer.

> L45-47: strange argumentation.... to link geometrical properties of aerosols and clouds with passive remote sensing.... which have practically no profiling capability (only the model behind all the column integrated measurements may allow the retrieval of geometrical properties, but then with large error bars).

The sentence has been modified to avoid any possible misunderstanding

> L68-70: I would remove these lines and Madonna references. Almost all experts in this field do not believe that the measurements and conclusions are ok.

The authors don't agree with the reviewer. The cited paper went through a regular and independent review process on a top level journal in geosciences (i.e. JGR). The authors believe that it is not fair to open in this context a discussion on the reliability of Madonna's paper results. This is in hand of the scientific community and it is appropriate anyhow to cite it. The authors also would like to remind to the the reviewer and the editor that this is not the only paper dealing with aerosol observations using radar and that the papers results have been cited by other independent papers in literature also demonstrating the reliability of the Madonna's paper observations.

> L90: I do not know why we have equations in the introduction, I would move them to section 2 (2a: lidar methods). And why do we need the simple lidar equation? And why is there the overlap term missing (O(r))? The overlap profile affects MPL observations up to 4-5 km height. That should be mentioned. In such a Section 2a, I would present the Fernald equation and the Raman lidar equation. They are used later on, and in this new Section 2a, all problems and differences could be explained in detail..., which is not possible (or should not be given) in the introduction.

The equation, enriched with overlap term and relative description has been moved to the new section 2.1. MPL overlap is mentioned too.

> L99: There are meanwhile so many lidar ratio papers (real measurements!).... Please provide some references, e.g. Muller 2007, Gross, Tellus 2009, ACP 2013, 2015? , Ferrare, JGR..., Sakai, JGR... Veselovskii 2016 and many many others . Ackermann (1998) is just a very simple simulation study.

We take into account the reviewer suggestions and we added the references.

> L105: Raman roto-vibrational ... bad wording...

The sentence was rephrased

> L133: The impact of these differences on end-user applications have never been evaluated...Please be more precise, what do you mean with end-user applications?

The paragraph was rephrased to avoid ambiguity

> L195: Now the RFOV is mentioned. The RFOV is 1.5 mrad. This means the multiple scattering effect is rather large in case of clouds. The measured apparent cirrus extinction coefficient is roughly a factor of 2 lower than the desired single-scattering extinction coefficient (throughout the cirrus layer). The single-scattering extinction coefficient is the basic input in radiative transfer equations. Multiple scattering depends on cirrus crystal microphysics (size, shape, amount...). And such a huge multiple scattering effect is not considered in the paper? ... the authors tell us: they ignore it! This is not acceptable! These effects must be considered. There is no way to circumvent this problem.

We corrected Raman extinction profiles using Eloranta MS code. We used a monodisperse averaged value for the cirrus cloud size diameter obtained from Heymsfield et al., 2014 parameterization. For the two cirrus clouds we obtained a MS corrected value of 24sr and 26sr respectively for 10 June 2010 and 17 Feb 2014. The elastic channel MS correction is restricted to the values of the Lidar Ratio that multiply the retrieved backscattering coefficient (that is barely influenced by MS). In this case, the LR values employed in the analysis are a good estimate from the MS corrected Raman profiles.

> L202: I complained last time with good reasons: There is no information on the laser beam pointing (zenith or off zenith). Even in the revised version there is no hint on beam pointing. I speculate the laser beams were pointed to the zenith. This in turn means that the cirrus backscatter profiles are probably strongly affected by specular reflection. In case of zenith pointing, the backscatter coefficients (from which the extinction coefficients are estimated when using the Fernald method) are an order of magnitude larger in the case of aligned, falling crystals than the true backscatter values (obtained at off zenith pointing, 3-5 degrees off the zenith is sufficient). The alignment effect depends on particle size (only >100 mikrometer particles are able to be horizontally oriented), thus the effect can vary from height to height. So, cirrus backscatter and extinction profiles from zenith pointing elastic backscatter lidars are highly corrupt and uncertain, and to my opinion these Fernald extinction profiles are useless for further use in radiative transfer computations.

MUSA lidar is not tilted due to some technical constraints. However, MS corrected Raman channel retrieval show lidar ratio values higher than 20sr.

Those high values support the hypothesis that strong specular reflection is extremely unlikely. In support to this hypothesis, Heymsfield parameterization shows average diameter values ¡ 100 micrometer. Hogan and Illigworth Moreover, Hogan et Illingworth (2003), found that specular reflection tends to be much stronger and more common when temperatures are between 250 K and 264 K (a temperature range found at much lower altitude with respect to the examined cirrus cloud cases), where plate crystals, which give the greatest specular signal, grow in this temperature range. For this reason we believe that specular reflection doesn't provide a significant contribution to the backscattering profile.

> `Figure 1: The aerosol measurements are ok. Multiple scattering effects can be neglected, as well as beam pointing effects.Why are there different descriptions (1b, left: Iterative, Iterative, Raman, 1b, right: Raman, Elastic, Elastic) ? X-axis and y-axis text and numbers of Fig 1a are much too small! Figure 2b, left: extinction values of 0.1, 0.2 ...., 0.4 m-1 are wrong... Figure 3: All plot frames should have the same size (and should be well arranged above each other), all x-axis and y-axis text should use the same letter font, and PT The caption should briefly explain what Raman, Full Res., and Iterative means. Full Res is obviously Iterative (60 m), and Iterative denotes Iterative (360 m)? Please harmonize this with the other figures... Figure 4: The same concerning plot frames, and explanations of Raman, Full. Res. and Iterative. X-axis and y-axis text and numbers need to be harmonized. To repeat: The cirrus results in Figure 4 are highly questionable. To my opinion, they are useless because of the lidar-related problems with zenith pointing and multiple scattering.`
>
> `All plot frames should have exactly the same size (at least for 1a and for 1b)`

All the figures have been accordingly modified and corrected, harmonized as the caption and legends.

Comments by Reviewer #2

> The main objective of this revised paper, novelty entitled \Impact of varying lidar measurement and data processing techniques in evaluating cloud and aerosol direct radiative effects" is still to quantify inconsistencies in aerosol (two case this time in the revised paper : dust aerosol and biomass burning event) and cirrus cloud (two cases in the revised paper : a thin and an opaque cirrus) radiative forcing at Top Of the Atmosphere and at surface due to two different ground lidar techniques (elastic and Raman lidar, i.e. the Multi-wavelengh System for Aerosols (MUSA) Lidar (Madonna et al., 2011)) and/or data processing (i.e. effect lidar measurement with different vertical resolution together with smoothing techniques). The revised paper is based on the same approach and analysis technics as the initial paper, that is a good point. Quality of references of the revised paper are now better and the title is now appropriate. This revised paper still address relevant scientific topics within the scope of AMT. Nevertheless, the revised paper shows dramatic drawback and inconsistency with the study based on cirrus cloud. Figures a not all clear. For a revised paper, it is quite annoying. This revised paper needs major revision. Major remarks: 1) Line 689 (i.e. figure 2) Right panels show the opaque cirrus. On the right top panel, the base and top altitude are between 6 km and 8 km, respectively, whereas the retrieved extinction coefficient profile is between 11 and 13.5 km. Where is the problem?

Thank you for pointing this out. We put by error the old picture. We substitute it and now we have the correct picture for cirrus cloud on 10 June 2010.

> 2) Line 689((i.e. figure 2) Optical depth is defined as extinction times distance. Bases on this simple formula and on information provided by the figure 2, optical depth tau of thin cirrus, is, roughly, tau=0.1(m-1)*100(m) = 10 and the optical depth of the opaque cirrus, is, tau=5e-5(m-1)*2000 (m)= 0.1 ! How can we qualify a thin cirrus with an optical depth of 10 and an opaque cirrus with an optical depth of 0.1 ?

Thanks, nice catch. We changed the figure as there was an error in the measurement unit scale. We added also the new profiles corrected for the multiple scattering. All the pictures are now at high resolution.

> 3) Line 689((i.e. figure 2) The comparison of the direct radiaitve effect of theses both cirrus is not suitable. Indeed, direct radiative effect is function of optical depth, effective radius (or asymmetric parameter and single scattering albedo) and of temperature (i.e. of the mean altitude of the cirrus but also of the cirrus cloud base and top altitude). In order to interpret differences of direct radiaitve effect between an optically thin and opaque cirrus, geometrical thickness must be the same, as well as the cloud base and cloud top altitude. Moreover, why two different vertical resolution (420 m for the thin cirrus and 780 m for the opaque cirrus? Based on my major comments, it is impossible to evaluate the conclusions of this revised work. This paper need major revision.

The main goal of the manuscript is not to compare the differences in terms of direct radiative effects of the two cirrus clouds, but to assess how much different techniques/data processing affect directly the direct radiadive effects computed on the same cirrus cloud. We performed the analysis on two separate cirrus clouds to show if it is possible to detect any variability with cirrus thickness. We changed the narrative in the manuscript to make it more clear.

> Specific comments line 31-32 : This sentence is not clear. Please rephrase line 48-52 : acronyms are missing line 122 : please define lamba 0 line 144 : I think \...computed using..." is better than \... retrieved using..." line 166 : the FLG model needs the phase function ? How is computed the phase function? line 192 : please define a.s.l. Figure 1 : - please define Tito(PZ) - All the \no-information" (above 7 km, the blue color) is useless. Please rescale the figures. - Please use the same color for the legends on right and left (b) - What is the difference between iterative and elastic (on the legend of figure 1b)? - Why the range corrected signal is at 1065 nm whereas the retrieved extinction is at Figure 2 : same global remarks as figure 1 but also : - Why the Raman vertical profile is so different compared to the Klett profile for the opaque cirrus whereas it doesn't for the thin cirrus ? Figure 3 and 4 : please define Raman, Full Res. and iterative and put coherency with elastic and Klett

We took into consideration all the reviewer suggestions. FLG uses aerosol scattering properties from OPAC catalog and cirrus clouds properties from embedded routines. For more information please refer to the provided bibliography. All the figures have been changed as required and now are at high resolution. Thanks for pointing out the discrepancies. Also legend and caption clarity has been improved.

Comments by Reviewer #3

> The authors have addressed most of the concerns I had before recommending the article for its publication in Atmospheric Measurement Techniques. Personally, I think that the new title proposed is appropriate and that the new study cases for aerosol and cirrus clouds show more convincing results. But I have some minor concern I would like authors address before recommending the final publication: - Although the authors responded well to my concern about the effects of aerosol microphysical properties in aersol radiative forcing computations, I miss such a paragraph in the revised manuscript. - Authors refer in the abstract and in the text to aerosol and clouds optical and geometrical properties. Please, replace by 'aerosol and clouds optical and microphysical properties'. - Although HSRL technique is not used in operational lidar networks such as EARLINET, their potential can not be ignored. Please refer this in the text and add appropriate references. - The statement about the upcoming NASA Aerosol-Clouds-Ecosystems mission is not in the correct place. It is very important to reference such mission, and I recommend to move the sentence at the end of line 141. Also, please update reference to Whiteman et al., 2018: Whiteman, D.N., Pérez-Ramírez, D., Veselovskii, I., Colarco, P., Buchard, V. (2018) Simulations of spaceborne multiwavelength lidar measurements and retrievals of aerosol microphysics. Journal of Quantitative Spectroscopy and Radiative Transfer, 205, 27-39 - Please, define each term of equation 4. - Axis of Figure 1 and Figure 2 are difficult to read

We thank the reviewer for the positive comments. We addressed all the remaining reviewer concerns.

Impact of Varying Lidar Measurement and Data Processing Techniques in evaluating Cirrus Cloud and Aerosol Direct Radiative Effects.

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ABSTRACT

In the past two decades, ground-based lidar networks have drastically increased in scope and relevance, thanks primarily to the advent of lidar observations from space and their need for validation. Lidar observations of aerosol and cloud geometrical, optical and microphysical atmospheric properties are subsequently used to evaluate their direct radiative effects on climate. However, the retrievals are strongly dependent on the lidar instrument measurement technique and subsequent data processing methodologies. In this paper, we evaluate the discrepancies between the use of Raman and elastic lidar measurement techniques and corresponding data processing methods for two aerosol layers in the free troposphere and for two cirrus clouds with different optical depths. Results show that the different lidar techniques are responsible for discrepancies in the model-derived direct radiative effects for biomass burning (0.05 W/m^2 at surface and 0.007 W/m^2 at top of the atmosphere) and dust aerosol layers (0.7 W/m^2 at surface and 0.85 W/m^2 at top of the atmosphere).

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Data processing is further responsible for discrepancies in both thin (0.55 W/m^2 at surface and 2.7 W/m^2 at top of the atmosphere) and opaque (7.7 W/m^2 at surface and 11.8 W/m^2 at top of the atmosphere) cirrus clouds. Direct radiative effect discrepancies can be attributed to the larger variability of the lidar ratio for aerosols (20-150 sr) with respect to cirrus clouds (20-35 sr). For this reason, the influence of the applied lidar technique plays a more fundamental role in aerosol monitoring because the lidar ratio must be retrieved with relatively high accuracy. On the contrary, for cirrus clouds, being the lidar ratio much less variable, the data processing is critical because smoothing it modifies the aerosol and cloud vertically resolved extinction profile that is used as input to compute direct radiative effect calculations.

1. Introduction

According to the International Panel for Climate Change (IPCC, 2014), the major sources of uncertainty relating to current climate studies include direct and indirect radiative effects caused by anthropogenic and natural aerosols. Further, current estimates of the global aerosol direct radiative effect remain subject to large relative uncertainties affecting even the actual sign (indicating either net cooling or heating of the earth-atmosphere system), which may change from positive to negative diurnally (e.g., Campbell et al., 2016, Lolli et al., 2017a, Tosca et al., 2017). This depends on the so-called albedo effect (or the capability of aerosols for reflecting incoming solar light) and whether or not it is outweighing the greenhouse effect (or the capability of trapping/absorbing outgoing longwave radiation; Campbell et al., 2016)

Studies on cloud and aerosol optical, geometrical and microphysical properties largely increased in the last two decades through the abundance of passive ground-based measurements (i.e., AErosol RObotic NETwork Network; AERONET Holben et al., 1998, Dubovik et al., 2000, Smirnov et al., 2005, Eck et al., 2014; the Atmospheric Radiation Measurement program; ARM; Campbell et al., 2002, Ferrare et al., 2006, Perez-Ramirez et al., 2012, McComiskey et al., 2016; Aerosols, Clouds and Trace gases Research Infrastructure; ACTRIS Asmi et al., 2013, Pappalardo et al., 2014) or using satellite sensors (i. e. MODerate resolution Infrared Spectroradiometer; MODIS, Tanré et al., 1997, King et al., 2003, Remer et al., 2005; i. e. Multi-angle Imaging Spectro-Radiometer; MISR, Diner et al., 1998, Di Girolamo et al., 2004, Kahn et al., 2009; i.e. Polarization and Anisotropy of Reflectances for Atmospheric science coupled with Observations from a Lidar; PARASOL, Tanré et al., 2011; NASA Aerosol-Cloud Ecosystem, ACE, Whiteman et al., 2018). Nevertheless, these measurements provide only an estimate of the columnar aerosol (or cirrus cloud) properties.

On the other hand, the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP; Winker et al., 2007), on board of the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite launched by the National Aeronautics and Space Administration (NASA) in 2006, is capable of estimating range-resolved aerosol and cloud physical properties. However, the sun-synchronous orbit limits spatial and temporal coverage (orbital revisit time period of 16 days) that make the datasets difficult to apply and interpret for specific forms of process study. The vertical structure of cloud and aerosol properties can also be retrieved through combined lidar and radar ground-based measurements as proposed in the frame of the CloudNet European Project (Illingworth et al., 2015). Still, the radar technique proves capable of characterizing only the relatively extreme fraction of the aerosol size distribution (Madonna et al., 2010, Madonna et al., 2013).

Based on the progress in optical technologies in the late 1990's and the beginning of 2000's, federated ground networks of lidars were established [NASA Micro Pulse Lidar NETwork(MPLNET), Campbell et al., 2002, Welton et al., 2002, Lolli et al., 2013; European Aerosol Research LIdar NETwork, (EARLINET) Pappalardo et al., 2014, Asian Dust NETwork (ADNET), Sugimoto et al., 2010, Latin American Lidar NETwork

(LALINET), Antuña-Marrero et al., 2015, Lolli et al., 2015], the bulk of which are based on single or dual-channel elastic and Raman lidar instruments. The Eulerian viewpoint of ground-based lidars is providing important contextual measurements relative to satellite profiling, like from CALIOP (Winker et al., 2007).

The emerging prominence of ground-based lidar, however, strengthens the necessity for further studies of optical, geometrical and microphysical aerosols and clouds properties resolved from multi-spectral lidar techniques, as claimed by several papers (Pappalardo et al., 2004, Mona et al., 2006, Wang et al., 2012, Pani et al., 2016, Lolli et al., 2013, Campbell et al., 2016, Lolli et al., 2017). Multi-spectral and Raman lidars can retrieve aerosol and cloud properties with much better accuracy than elastic lidars, without many fundamental assumptions, (e.g. Ansmann et al., 1992; Goldsmith et al. 1998, Mona et al., 2012, Pappalardo et al., 2014), thought with greater operational expenses. The High Spectral Resolution Lidar (HSRL - Shipley et al., 1983; Grund and Eloranta, 1991) technique allows for the separation of molecular and aerosol signals, and thus affords an independent retrieval of aerosols extinction and backscattering coefficients. However, the technology remains relatively complex and expensive, making them an unattractive choice for operational networks (e.g. Hair et al., 2008).

The Raman technique (section 2.2) permits retrieval of aerosol and cloud vertically-resolved extinction coefficient without any binding assumptions, which are the cornerstone of elastic-based retrieval techniques (section 2.1). Certain instabilities exist, however (Ansmann et al., 1992, Wandinger et al, 1995). In order to reduce the random uncertainty affecting the retrieval, a smoothing of the range-resolved profile is required at expense of the effective vertical resolution (Pappalardo et al., 2004, Iarlori et al., 2015) of the extinction coefficient profile.

Ultimately, different lidar techniques and/or processing algorithms lead to differences of the retrieved vertically-resolved particulate optical properties, affecting the apparent significance, position and the geometry of observed aerosol and cloud layers. The impact of these differences has never been extensively evaluated. Since lidar-derived optical properties obtained from different instrument techniques are more and more frequently used to assess the direct radiative effects of clouds and aerosols (e.g., Campbell et al., 2016, Lolli et al., 2017a, Tosca et al., 2017), corresponding uncertainties in determining direct radiative effects, which may help reconcile inconsistencies in studies carried out at the global scale based on different lidar techniques, are compulsory, especially now that several new space missions with lidar on board have been launched (Cloud-Aerosol Transport System; CATS, McGill et al., 2015) or are scheduled (European Space Agency Earth Care mission; Illingworth et al., 2015).

The primary goal of this paper is to evaluate the relative differences between the aerosol/cloud direct radiative effects both at surface (SFC) and at the top-of the-atmosphere (TOA) computed using the aerosol/cloud optical properties estimated from more sophisticated versus basic lidar techniques (i.e., Raman vs. elastic lidar). To reach this goal, we use the Fu-Liou-Gu (FLG; Fu and Liou, 1992, Fu and Liou, 1993, Gu et al., 2003, Gu et al., 2011, Lolli et al, 2017b) radiative transfer model to calculate the difference in net direct radiative effect for aerosols and clouds at TOA and SFC for profiles derived from both elastic and combined Raman/elastic lidar techniques.

2. Method

2.1 Elastic and Raman Lidar techniques

Elastic-scattering lidar instruments require assumptions and careful consideration of measurement strategies to constrain the single-scattering lidar equation (Eq. 1), defined as

$$P_r(r) = O(r)K\frac{\beta(r)}{r^2}exp^{-2\int_0^r \alpha(r')dr'} \quad , \qquad (1)$$

where $P_r(r)$ is the received power at a range r *and* $O(r)$ is the overlap function, which depends on intersection between the respective telescope and laser field of view. $O(r)$ equals to unity for a distance r_0 depending on the specific lidar system, spanning from few hundred meters to 4-5 km for Micro Pulse Lidar systems (MPL; Campbell et al., 2002). K is the so-called lidar constant (instrument dependent, function of detector quantum and optical efficiencies, telescope diameter, etc.), followed by the two unknown variables, $\beta(r)$ the total backscattering coefficient and $\alpha(r)$ the total extinction coefficient.

A classical method to solving Eq. (1) for single-channel elastic-backscatter lidars (Fernald, 1984) is based on the assumption of the columnar-averaged value of the ratio between the two unknown coefficients, typically indicated by S and called “lidar ratio”. The method, due to the large variability of S (i.e., 20-150 sr for aerosols; Ackermann, 1998; Ferrare et al., 2001, Sakai et al., 2003, Müller et al., 2007, Groβ et al., 2011, 2013 and 2015, Veselovskii et al., 2015) translates into large uncertainties associated with the retrieval of α and β (Lolli et al., 2013).

Through greater spectral complexity, it is possible to retrieve α and β with multi-spectral lidars without relying too heavily on fundamental assumptions. For instance, the combined detection of the elastic-backscattered and inelastic backscattered radiation due to the Raman effect by nitrogen (or oxygen) molecules excited to a different vibrational or rotational energy level is possible. Using the Raman lidar technique, we can constrain and rewrite Eq. (1) as

$$\alpha_{\lambda_L}^{par}(r) = \frac{d/dr\left\{\ln\left[n_R(r)/P_r(r)r^2\right]\right\} - \alpha_{\lambda_L}^{mol}(r) - \alpha_{\lambda_R}^{mol}(r)}{1+\left(\lambda_L/\lambda_R\right)^{\mathring{a}}} \tag{2}$$

where λ_L is the elastic wavelength while λ_R is the wavelength of the Raman scattering, $\alpha_{\lambda_L}^{par}(r)$ represents the particle (aerosols or clouds) extinction coefficient at elastic wavelength at range r while $\alpha_{\lambda_L}^{mol}(r)$ and $\alpha_{\lambda_R}^{mol}(r)$ are the molecular extinction coefficients at wavelengths λ_L and λ_R respectively, $P_r(r)r^2$ is the detected range corrected Raman signal from range *r,* while $n_R(r)$ represents the number density of range-resolved scatters. The wavelength dependence of the particle extinction coefficient is described by the Ångström coefficient, å, defined from the relation

$$\frac{\alpha_{\lambda_L}^{par}(r)}{\alpha_{\lambda_R}^{par}(r)} = \left(\frac{\lambda_R}{\lambda_L}\right)^{å} \tag{3}$$

Eq. (2) allows for independently retrieving vertically-resolved optical coefficients with only very limited *a-priori* assumptions (the Ångström coefficient should be estimated or assumed, but this estimate or assumption, involving a ratio, typically amounts to less than 5% of total error; Ansmann and Müller, 2005). The particle backscattering coefficient, $\beta_{\lambda_R}^{par}(r)$ and $\beta_{\lambda_L}^{par}(r)$, can be derived directly from the ratio of the Raman signal at λ_R and the elastic signal at λ_L.

2.2 Fu-Liou-Gu Radiative Transfer Model

To calculate aerosol and cloud direct radiative effects, we use the one-dimensional FLG radiative transfer model, developed in the early 1990's. The original code has been adapted to retrieve cloud and aerosol direct radiative effects using the aerosol and cloud vertical profile of lidar extinction as input. There exist several parameterizations that provide the vertical profile of cloud microphysics using lidar-retrieved cloud extinction profile, each one with pros and cons, as showed in Comstock et al. (2007). For the purpose of this study and also considering authors past experience (Campbell et al., 2016, Lolli et al., 2017a), we parameterize cirrus clouds through the Heymsfield et al., (2014) empirical relationship conceived expressly for lidar measurements. Here, the cirrus cloud ice crystal average diameter is directly proportional to the absolute atmospheric temperature (obtained through a radiosonde, regularly launched at measurement site, or numerical reanalysis dataset). Cirrus cloud optical depth and crystal size profiles are used to calculate the single scattering albedo (SSA), phase function and asymmetry factor (AF) at each level.

Similarly, FLG calculates the direct radiative effect of aerosols as a function of the partial contribution of each aerosol species to the total optical depth at each altitude level. FLG uses a lookup table (LUT) with single scattering properties for eighteen different types of aerosols coming from the OPAC (Optical Properties of Aerosol and Clouds) database (d'Almeida et al., 1991; Tegen and Lacis, 1996; Hess et al., 1998). Among all aerosol species, for the initial cases introduced in Section 2.2 we assume that the dust layer is constituted by pure dust advected from Saharan region (aerosol type 17 in FLG), while in the second case we assume pure biomass burning aerosol (aerosol type 11 in FLG). Nevertheless, if the measured aerosol atmospheric profiles do not match exactly the two-selected aerosol types this does not affect the results because we are interested in evaluating the relative discrepancies among the different lidar techniques/data processing. Therefore, what is most relevant in the approach is the application of the same parameterization to each of the different techniques/data processing.

The aerosol/cloud direct radiative effect is calculated subtracting from the FLG total sky run (where aerosols or clouds are present) the FLG run with a pristine atmosphere (control), expressed as

$$DRE = FLG^{TotalSky} - FLG^{Pristine} \quad , \qquad (4)$$

where *DRE* is the direct radiative effect (from aerosols or clouds), while the superscript *TotalSky* means that FLG is computed taking into account the aerosol/cloud profile and *Pristine* represents a hypothetical "clear-sky" atmosphere with no aerosols or clouds.

Direct measurements of aerosol microphysical properties require multi-wavelength lidar (e.g. Veselovskii et al., 2002, 2013), which are not common in many networks and also are sensitive to systematic and random errors in the optical data (Perez-Ramirez et al., 2013). We focus here on lidar systems that can operate continuously in different networks, and our direct radiative effect calculations do not vary much when changing effective radius and single scattering albedo.

2.3 Direct radiative effect computation

For the analysis in this study, we analyzed lidar data collected with the MUlti-wavelength System for Aerosols (MUSA) Lidar (Madonna et al., 2011), deployed at Consiglio Nazionale delle Ricerche (CNR), Istituto di Metodologie per l'Analisi Ambientale (IMAA) Atmospheric Observatory (CIAO) in Potenza, Italy (40.60N, 15.72E, 760m above sea level; a.s.l). MUSA is a mobile multi-wavelength lidar system based on a Nd:YAG laser source equipped with second and third harmonic generators and on a Cassegrain telescope with a primary mirror of 300mm diameter.

MUSA full angle field-of-view (FOV) and laser beam divergence are large enough (1.0 mrad and 0.6 mrad, respectively) to add important multiple scattering (MS) contributions to the retrieved cirrus extinction coefficient profiles. The Raman extinction coefficient profiles have been corrected for MS as described in Wandinger (1998), taking into account MS contributions by introducing in the respective lidar equation the multiple scattering parameters. These parameters have been calculated, by applying Eloranta's model (Eloranta, 1998) to estimate the contributions of individual orders of multiple scattering. In the model simulations, MUSA specifications (FOV and laser beam divergence) have been used, and a mono-disperse size distribution profile of cirrus cloud ice crystals has been assumed with effective diameters derived from the same parameterization used in FLG model (Heymsfield et al., 2014). The first five scattering orders have been summed.

MUSA lidar system is not tilted due to technical constraints. However, the averaged cirrus cloud retrieved lidar ratios from the combination of Raman and elastic lidar techniques (corrected for MS effects) are 24sr and 26sr, for cirrus cloud cases highlighted here from 10 June 2010 and 17 February 2014, respectively. Those values are consistent with a very low probability of significant specular reflection. The previous statement is supported by the fact that crystal size diameter computed with Heymsfield et al. (2014) parameterization is below 100μm, a threshold value above which the specular reflection can arise. Moreover, in Hogan and Illingworth (2003) work, it is founded that specular reflection tends to be much stronger and more common for temperatures between 250 K and 264 K (that corresponds to much lower altitudes with respect to the examined cirrus cloud cases), where plate crystals, which induce the greatest specular signal, are most common.

The three laser beams at 1064, 532 and 355nm are simultaneously and coaxially transmitted into the atmosphere in a biaxial configuration. The receiving system has three channels for the detection of the radiation elastically backscattered from the atmosphere and two channels for the detection of the Raman radiation backscattered by the atmospheric N_2 molecules at 607 and 387 nm. The elastic channel at 532 nm is split into parallel and perpendicular polarization components by means of a polarizer beamsplitter cube. The backscattered radiation at all the wavelengths is acquired both in analog and photon counting mode. The typical vertical resolution of the raw profiles is 3.75 m with a temporal resolution of 1 min. The system is compact and transportable. It has operated since 2009, and it is one of the reference systems used for the intercomparison of lidar systems within the EARLINET (Pappalardo et al., 2014; Wandinger et al., 2016) Quality Assurance program. In this paper, the data analysis has been carried out considering four observation scenarios at night, as the Raman channel signal shows a much higher signal-to-noise ratio during nighttime:

1) **Dense Dust Aerosol and Biomass Burning Events**. The aerosol extinction profiles are retrieved using the UV (355nm) channel. For each case, the extinction profile is retrieved both with the Raman technique (Ansmann et al., 1990, Whiteman et al., 1992, Veselovskii et al., 2015) and estimated using the sole elastic channel, applying an iterative algorithm (Di Girolamo et al., 1999) with an assigned lidar ratio (S=57 sr for dust case, Mona et al., 2006 and S=63 sr for biomass burning, retrieved averaging the lidar ratio from MUSA Raman channel). Both the Raman and elastic lidar signals have been smoothed by performing a binning of 16 range gates, resulting in a vertical resolution of 60 m. For the Raman channel retrieval, the extinction profile has been calculated using the sliding linear fit technique, with a bin number resulting in an effective vertical resolution of 360 m (Pappalardo et al., 2004). For the elastic channel retrieval, the estimated extinction profile has been first calculated with the signal full vertical resolution of 60 m and then smoothed to the same effective vertical resolution as the Raman extinction profile (360m), using a 2nd order Savitzky-Golay smoothing filter (Press et al., 1992; Iarlori et al., 2015).

2) **Thin and Opaque Cirrus Clouds**. Like aerosols, cirrus cloud extinction profiles are retrieved using the UV (355nm) channel with the Raman technique. The elastic channel retrieval for thin cirrus cloud is obtained applying the same iterative algorithm followed for dust and biomass burning. Although, for the opaque cirrus cloud, due to convergence problems of the iterative method for higher cloud optical depths, we used the MPLNET Level 1.5 cloud product algorithm (Lewis et al., 2016) based on a Klett inversion (Klett, 1985). For both cases (iterative and MPLNET), we assumed a fixed lidar ratio value obtained from Raman and elastic measurements corrected by MS effects of 24sr for thick and 26sr for thin cirrus cloud.

The Raman extinction profile has been calculated with an effective vertical resolution of 420 m (thin cirrus cloud) and 780 m (opaque cirrus cloud), respectively. The iterative (thin cirrus) and MPLNET Level 1.5 cloud algorithm (opaque cirrus; Lewis et al., 2016) extinction profiles are calculated with the original signal vertical resolution of 60 m and smoothed at a resolution of 420 m (thin cirrus) and 780 m (opaque cirrus), respectively, using the Savitzky-Golay filter to match Raman channel spatial resolution.

3) The thermodynamic profile of the atmosphere, needed to calculate the direct radiative effect, is estimated using a standard thermodynamic profile (USS976) mid-latitude model. Emissivity and albedo values are taken from the MODIS Bidirectional Reflectance Distribution Function (BRDF)/Albedo algorithm product (Strahler et al., 1999), with a spatial resolution of 0.1 degrees averaged over a 16-day temporal window (Campbell et al., 2016). As each measured cloud and aerosol extinction profile comes with a relative uncertainty per range bin, the sensitivity of FLG to the input parameters is evaluated applying a Monte Carlo technique. Each extinction profile is replicated 30 times (i.e. a number statistically meaningful), running the MonteCarlo code on the original profile random uncertainty. Likewise, for each replicated extinction profile, the Monte Carlo technique gives a value of surface albedo and profile temperature, based on their respective uncertainties. The direct radiative effect parameters derived for each profile are then represented with a boxplot. It is possible then to quantify the effect of the smoothing calculating the uncertainty from the mean and the standard deviation of the values of net forcing.

3. Results

3.1 Dust and Biomass Burning Event

The analyzed dust event is retrieved from measurements taken on 03 July 2014 at CIAO. Figure 1 shows both the range-corrected composite signal at 1064 nm (Fig. 1a, left panel), and the lidar aerosol extinction profiles at 355 nm (Fig. 1b, left panel) obtained using the Raman technique with an effective resolution of 360 m and estimated using the elastic lidar technique at two different resolutions (60 m and 360 m) and a fixed *S* value obtained analyzing climatological data (S=57sr; Mona et al., 2006). The Raman extinction profile is noisier with respect to those obtained with the iterative method. All profiles, calculated with an integration time of 121 minutes, in the time window from 19:34 UT to 21:40 UT show no significant aerosol loading above 5.5 km.

Figure 3a shows the difference between the estimation of the direct radiative effect using the two considered lidar techniques and data processing at the top-of-the-atmosphere (TOA; Fig 3a, left panel) and surface (SFC; Fig. 3a right panel). The most important contribution to this difference in FLG calculations for this case is related to the adopted lidar technique (red arrows in Fig. 3a, left and right panels) and not to the effective vertical resolution determined by the smoothing (blue arrows in Fig. 3a, left and right panels). This characteristic is invariant switching from TOA (Fig. 3a right panel) to SFC (Fig. 3a left panel) and is mainly the result of the assumption of a fixed lidar ratio to estimate the aerosol extinction profile using the elastic technique.

For the dust case, the net direct radiative effect determined with the two different lidar techniques differs by 0.7 W/m^2 (5%) at SFC and 0.85 W/m^2 (6%) at TOA. In absolute magnitudes, these net total forcing values are larger than the uncertainty, on average, estimated direct effect by IPCC (mean -0.5 W/m^2, range -0.9 to -0.1). The contribution due to smoothing is negligible in comparison.

The analyzed biomass burning case study is retrieved from measurements taken on 19 June 2013 at CIAO integrating the signal temporally from 19:27 UT to 20:48 UT. The extinction profiles used as input into the FLG radiative transfer model were retrieved in the same way as for the dust case. Instead of a climatological lidar ratio value at 355nm, however, we used S=63 sr, obtained by averaging the lidar ratio profile retrieved with combined Raman-elastic techniques in the biomass burning layer. In Figure 1b (right panel) are the extinction profiles obtained from both the Raman and iterative methods (full resolution and smoothed over 360m window). Figure 3b shows the difference in biomass burning direct radiative effects with respect to the different lidar and data processing techniques. Similar to the dust case event, the bigger differences are found to be related to the different lidar techniques both at SFC (0.05 W/m^2 or 5%; red arrows, Fig. 3b right panel) and at TOA (0.007 W/m^2 or 5%; Fig. 3b left panel).

The analysis shows how the mixing of different lidar techniques in a specific study or in the routine operations of an aerosol network at regional or global scale must take into account of the uncertainties related to the assumptions that are behind the retrieval of the optical properties. This is important not only to provide a complete assessment of the total uncertainty budget for each lidar product, but also to enable a physically consistent use of the lidar data in the estimation of the direct radiative effect and, likely, for many other user-oriented applications based on lidar data.

3.2 Cirrus cloud

Similar to Fig.1, Figs. 2a and 2b shows the composite range-corrected signal and three extinction profiles retrieved from Raman lidar measurements of cirrus clouds with a vertical resolution of 420 m (thin cirrus, Fig 2a,b left panel) and 780 m (opaque cirrus, Fig 2a,b right panel), and with the elastic channel at two vertical resolutions (60m and 420m iterative method for thin cirrus cloud; 60m and 780 m MPLNET Level 1.5 cloud product algorithm for opaque cirrus cloud) using a MS corrected lidar ratio of 24sr (opaque cirrus) and 26sr (thin cirrus) . The obtained cloud extinction profiles from the different lidar and data processing techniques are averaged over 42 minutes, in the time window from 01:29

UT to 02:13 UT on 17 February 2014 (thin cirrus) and from 19:40 UT to 20:44 UT on 10 June 2010 (opaque cirrus), respectively.

Figure 4a depicts the results obtained for cirrus cloud measurements taken on 17 February 2014. Here we have a completely different situation with respect to the aerosol cases. That is, the discrepancies between the Raman and elastic lidar techniques (red arrows in Fig. 4a, left and right panels) are much smaller than the discrepancies due to the effective vertical resolution of the extinction coefficient profile both at TOA and SFC (blue arrows in Fig. 4a, left and right panels). This is related to what is typically a much stronger extinction coefficient for clouds than for aerosols. In this cirrus cloud case, the direct radiative effect determined with the two different lidar techniques differs by about 1.2 W/m^2 (16%) at TOA and 0.04 W/m^2 (4%) at SFC, while the effect of smoothing within a window of 420 m provides an additional difference of 2.7 W/m^2 (47%) at TOA and about 0.55 W/m^2 (53%) at SFC.

Results from the opaque cirrus cloud (Fig. 4b, left and right panels) exhibit a similar behavior to the thin cirrus cloud, with signal smoothing outweighing the impact of the lidar technique (blue arrow). The order of magnitude is similar to the thin cirrus cloud, with a difference at TOA between techniques of 4.6 W/m^2 (14%) and 1.6 W/m^2 (11%) at SFC. In contrast, the difference in data processing is of 11.8 W/m^2 (39%) at TOA and 7.7 W/m^2 (64%) at SFC. The results are evidence of the critical need to study cirrus clouds using high-resolution profiles of the optical properties to provide an accurate estimation of the cloud direct radiative effect.

4. Conclusions and future perspectives

We applied the adapted Fu-Liou-Gu (FLG) radiative transfer model to quantitatively evaluate how much the lidar and/or data processing technique applied influence the net direct radiative effect exerted by two different upper atmospheric aerosol layers (dust and biomass burning) and a thin versus opaque cirrus cloud layer, both at top-of-the-atmosphere (TOA) and surface (SFC). The evaluation has been made using aerosol/cloud extinction atmospheric profiles as inputs into FLG radiative transfer model retrieved using the Raman/elastic technique and as estimated by lidar elastic measurements only (iterative method for aerosol layers and thin cirrus cloud; NASA Micro-Pulse Lidar Network Level 1.5 cloud algorithm for opaque cirrus cloud). Because the Raman measurement retrieval is unstable due to the derivative of the signal at the numerator (see Eq. 2), a smoothing of the range-corrected signal is necessary to reduce the associated random uncertainty. The same processing treatment has been applied also to the elastic measurement signals.

The results show that the difference in direct radiative effect between the lidar and data processing/smoothing techniques applied is mostly unvaried at TOA and SFC. For the dust and biomass burning episodes, the data processing/smoothing does not play a major role, but instead the lidar measurement technique is more important with respect to the final result. This can be explained by the large variability of the lidar ratio (i.e., the unknown extinction-to-backscatter ratio used to constrain the single-solution lidar equation) compared to the assumed value. The opposite is true for cirrus clouds, where the applied data processing/smoothing play a fundamental role in determining sensitivities in the final results. This is due to the smoothing effect on the observed sharp structures that strongly alters the vertical structure and the extinction of the cloud.

Summarizing, we found that for the aerosol cases, the main difference both at TOA and SFC is driven by the respective lidar technique and not the data processing, with a difference on dust direct radiative effect of 0.7 W/m^2 (5%) at SFC and 0.85 W/m^2 (6%) at TOA. Similarly, for biomass burning we found a discrepancy 0.05 W/m^2 (5%) at SFC and 0.007 W/m^2 (5%) at TOA. For the cirrus clouds, the data smoothing is producing larger differences with respect to the lidar technique. On the contrary, using a different data processing/smoothing implies a larger difference in cirrus cloud direct radiative effect. A discrepancy of 0.55 W/m^2 (53%) is found at SFC while about 2.7 W/m^2 (47%) at TOA for the thin cirrus cloud. Similarly for the opaque cirrus, the discrepancies produced by data processing/smoothing are larger with respect to the different lidar technique. At SFC we find a difference of 7.7 W/m^2 (64%) and 11.8 W/m^2 at TOA (39%).

A possible explanation of this different behavior is that the FLG radiative transfer model calculations are strongly dependent on the optical depth of the examined atmospheric layer. At coarse resolution (cloud) the smoothing is producing changes in the extinction profile that translates into creation/suppression of ice crystals that have a strong influence on direct radiative effect. At finer resolution, as in the case of aerosol case studies, the smoothing is just producing fluctuations that do not influence the total radiative effect. In this case, the lidar technique is making a big difference, as an assumed wrong value for lidar ratio (*S*) that has a much larger variability with respect to the clouds, will amplify or suppress the aerosol peak that will translate into a higher/lower radiative effect.

With this study, we wish to draw attention in speculating how much the derived aerosol and cloud radiative effect is dependent on the lidar measurement and retrieval techniques, as well as on the data processing constraints/assumptions. This dependence looks increasingly relevant for existing and future space missions involving lidar instrument, as well as for the GAW Atmospheric LIdar Observation Network (GALION; Hoff et al., 2008) project, which features then main objective of federating all existing ground-based lidar networks to provide atmospheric measurement profiles of the aerosol and cloud optical and microphysical properties with sufficient coverage, accuracy and resolution. For future work, it is imperative on the community to continue understanding and refining what are the limits of the each lidar technique along with the related retrieval algorithms adopted in each ground-based network. FLG or any other well-established radiative transfer model then can be used as diagnostic tool to assure data quality through continued intercomparisons with real observation both at ground (using flux measurements), in situ (aircraft measurements) and at TOA (using satellite-based measurements).

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Figures

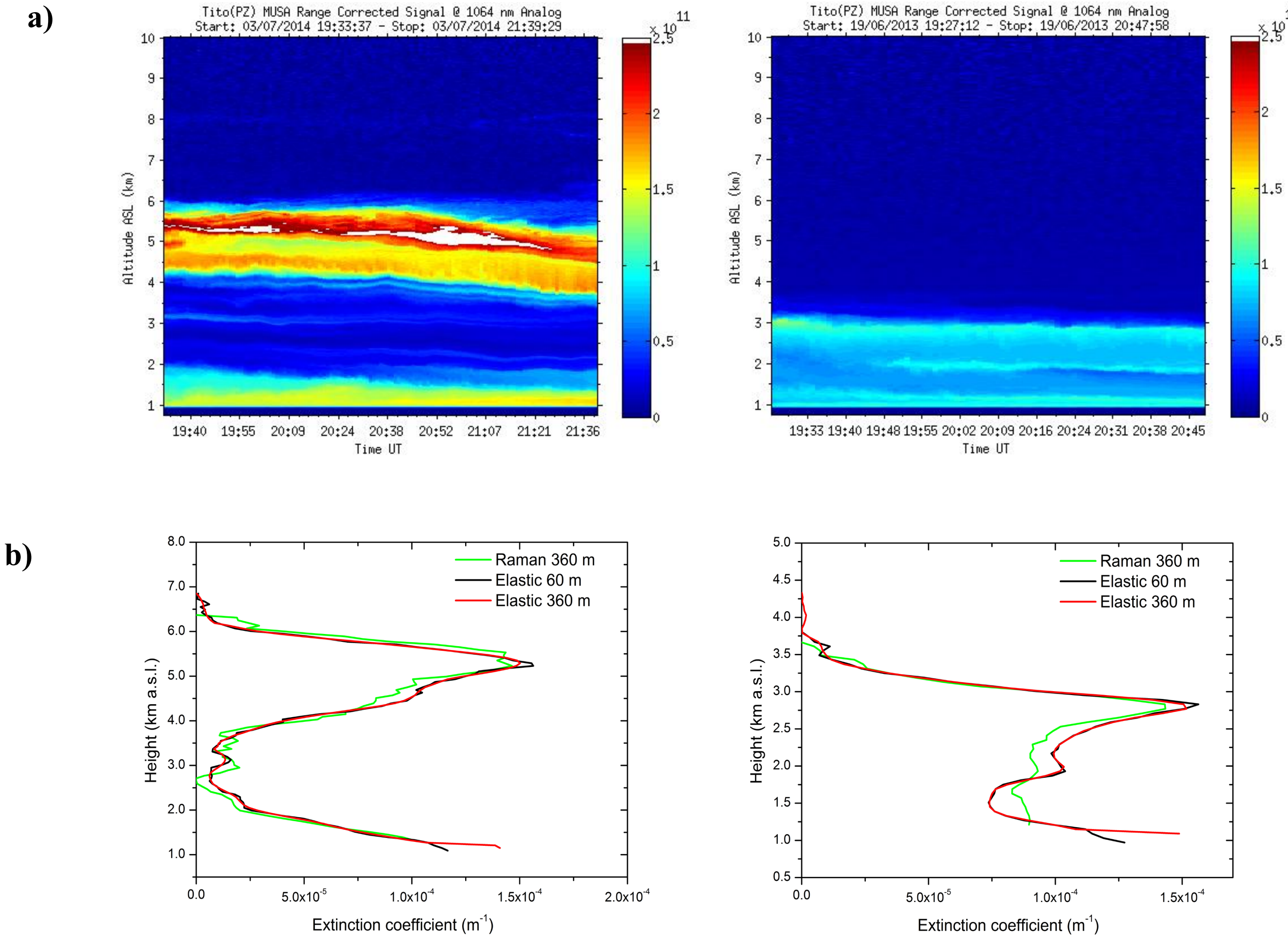

Figure 1 a): composite plot of the range corrected signal at 1064nm showing a well-defined dust layer at about 5 km a.s.l. (left panel) and for a biomass burning aerosol layer at about 2 km (right panel). b): aerosol lidar extinction profiles at 355nm retrieved with the Raman and the elastic lidar techniques with different spatial resolutions (60m and 360m) for dust (signal temporally integrated from 19:34UT to 21:40UT) outbreak on 3 July 2014 (left panel) and for biomass burning (signal temporally integrated from 19:27UT to 20:48UT) on 19 June 2013 (right panel). The iterative method used a fixed lidar ratio value of S=45sr, determined by climatological measurements (Mona et al., 2006) for the dust aerosol layer. For the biomass burning we used the averaged value of S=63sr obtained from MUSA Raman lidar.

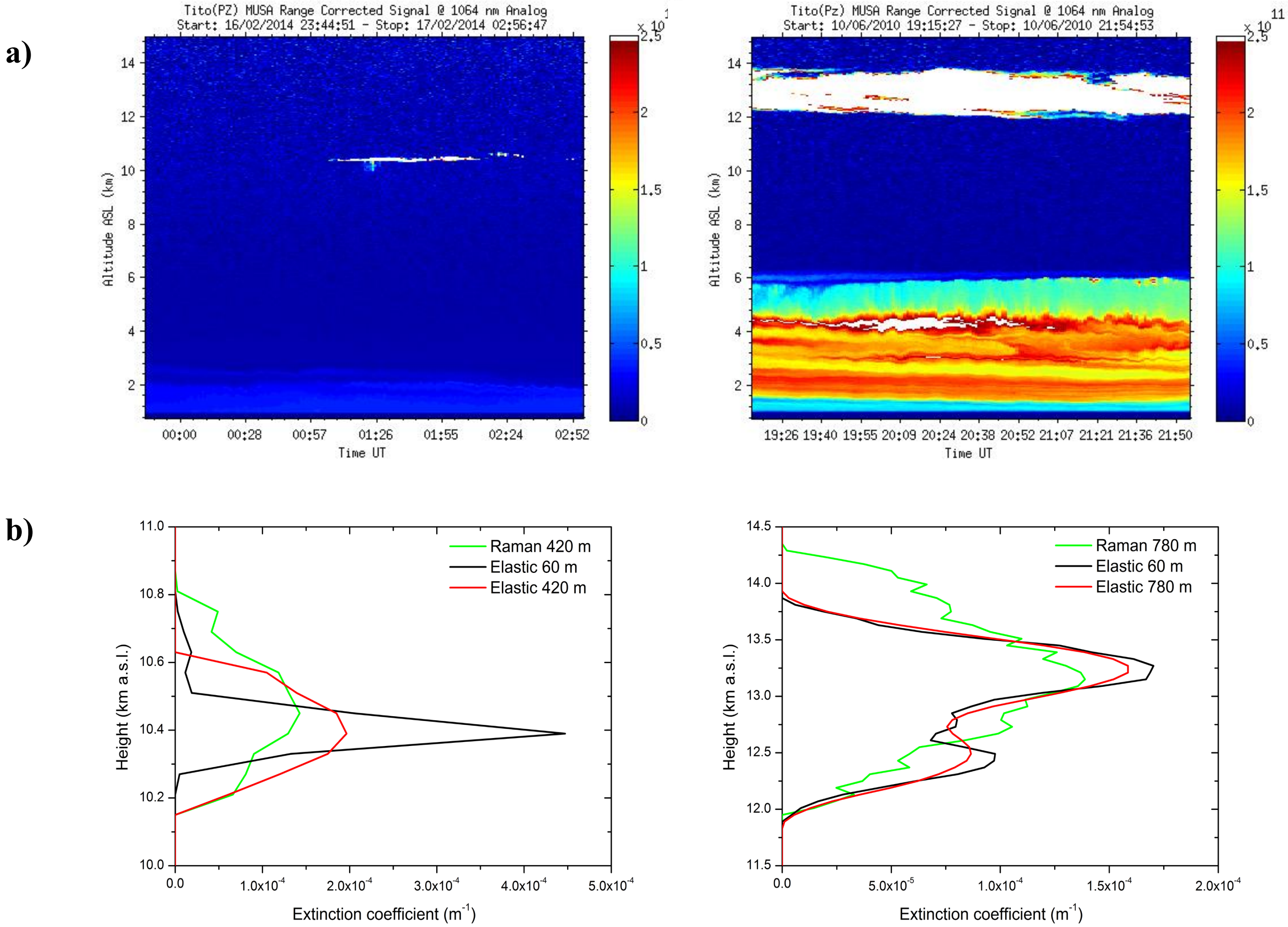

Figure 2: a) composite plot of the range corrected signal at 1064nm showing a thin cirrus cloud at about 10km (right panel) and an opaque cirrus cloud at about 12.5 km. b) left panel: lidar extinction profiles at 355nm from Raman and elastic channel respectively a cirrus cloud on 17 February 2014 (signal temporally integrated from 01:29UT to 02:13UT). The iterative method at the two different resolutions (60m and 420m) used a fixed S value (*25sr*), determined by climatological measurement. Figure 2a, b) right panels: same as Figure 2a, b) left panels but for a cirrus cloud detected on 10 June 2016 (signal temporally integrated from 19:42UT to 20:44UT). The Raman lidar channel is smoothed over a 420m and 780m spatial window. On 10 June 2016, the elastic channel is retrieved using MPLNET algorithm (Lewis et al., 2016) with *S=25sr* at 60m and 780m respectively.

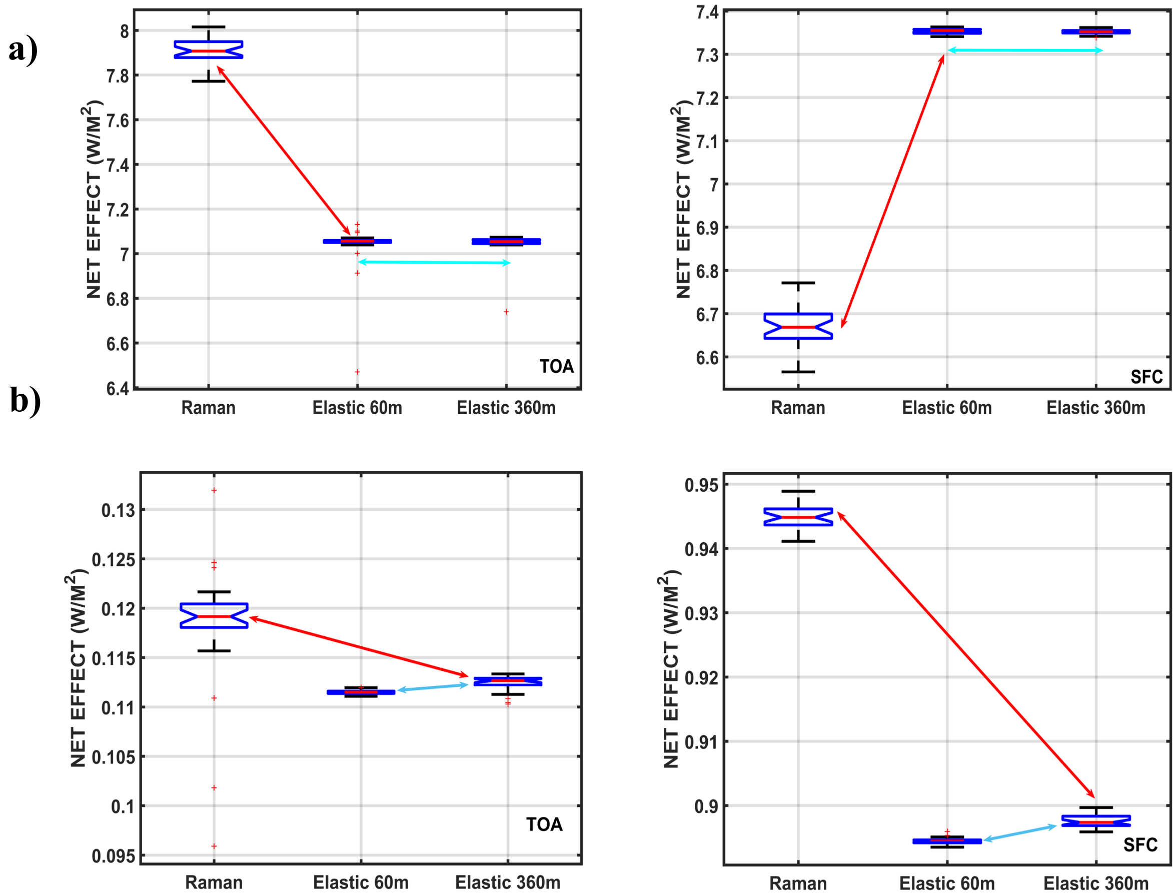

Figure 3. The direct radiative effect, for the dust aerosol case study (Figure 3a) on 03 July 2014 and biomass burning case on 19 June 2013 (Figure 3b) computed for retrievals obtained with Raman lidar channel smoothed over a window of 360m, elastic channel at full resolution (60m) and elastic channel smoothed over a 360m window to be compared with Raman channel . The results are represented as a distribution of values obtained with the MonteCarlo simulations by the boxplots, is calculated at TOA (left panel) and SFC (right panel) respectively. As it is clearly visible, the larger discrepancy in forcing is related mostly to the lidar measurements technique (red arrows), not on the data processing constraints/assumptions (blue arrows).

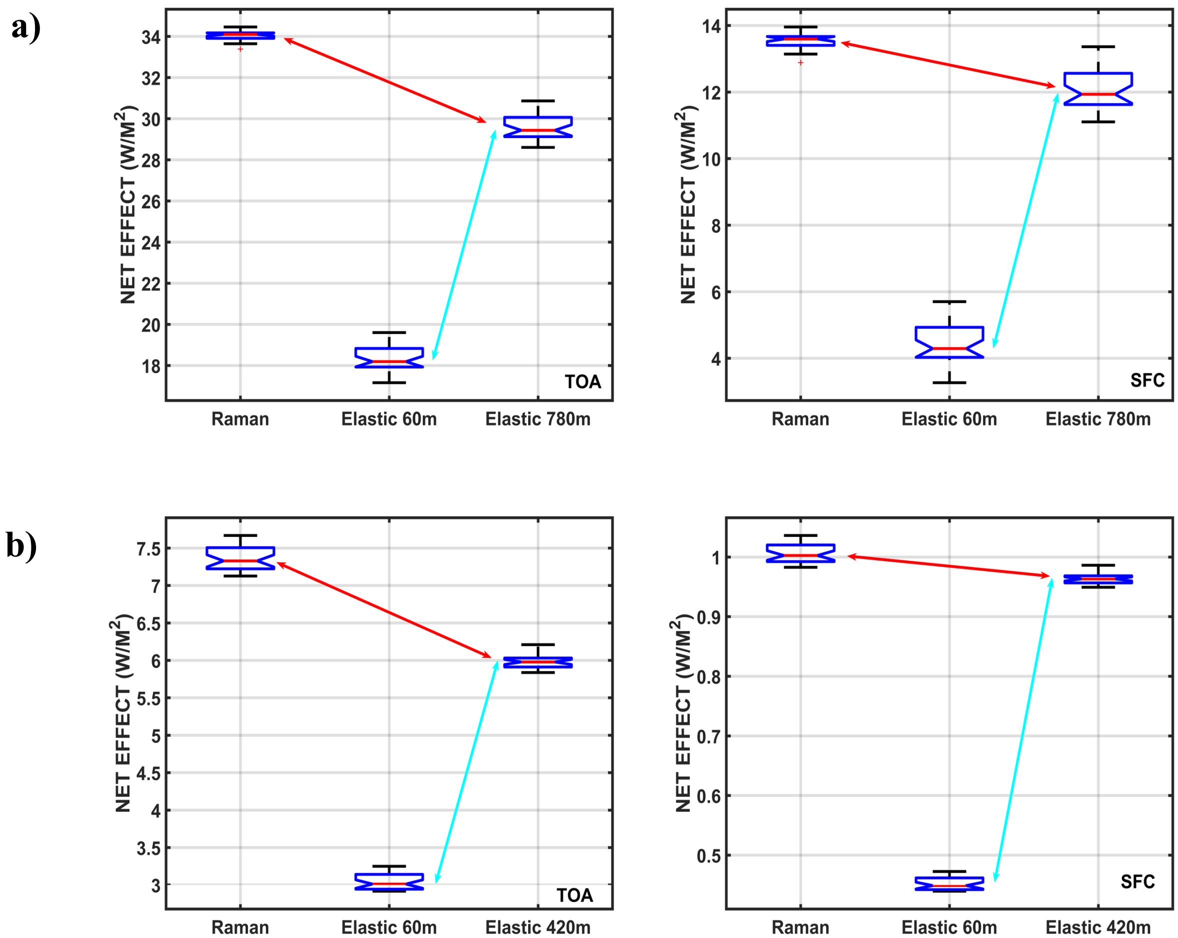

Figure 4 Same as Figure 3 but for two cirrus cloud cases (Fig. 4a, 17 Feb 2014, Fig 4b, 10 June 2016). The Raman lidar channel is smoothed over 420m window for cirrus on 17 Feb. 2014 and 780m window for cirrus on 10 June 2010. The net radiative effect is calculated at TOA (left panel) and SFC (right panel) respectively. As it is clearly visible, in both cases the larger discrepancy in radiative effect is related mostly to the data processing (blue arrows), not on lidar technique (red arrows).