

## ***Interactive comment on “Synergy between CALIOP and MODIS instruments for aerosol monitoring: application to the Po Valley” by P. Royer et al.***

**P. Royer et al.**

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**The authors appreciated the comments of reviewers that help to improve our manuscript. Please find a point-by-point discussion and answer of the issues raised by the reviewer.**

### **Anonymous Referee #1**

The paper is on the determination of aerosol extinction coefficient ( $\alpha_p$ ) profiles and aerosol optical depth  $\tau_p$  derived from (typically) 200-shot averages of CALIOP data over the Po valley being constrained by the aerosol optical depth derived from MODIS Aqua and Terra data. From this constraint the authors derive a height-independent

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lidar ratio  $Sp$  and found out that in some/many cases it differs from the lidar ratios used in the operational algorithm of CALIPSO, and as a consequence, the extinction coefficient profiles differ as well. In summary, they state that the agreement between both  $Sp$ , however, is still acceptable.

*This agreement only concerns average values over the three years, but not individual profiles or seasonal trends.*

The main weakness of the paper is, that it is not really clear what the purpose and the benefit of this study is. Shall the retrieval of  $\tau_p$  be improved, better than MODIS alone by means of CALIPSO data?

*The structure of the paper has been deeply changed in order to clarify the purposes and the benefits of this paper. The abstract has been also changed in this way. This study has been led after observing the large discrepancy in Aerosol Optical Depth (AOD) values over the Po Valley derived from MODIS and CALIOP instruments. A dichotomous algorithm constrained by MODIS AOD has thus been developed to determine the suitable LR. Data from MODIS and CALIOP have been averaged over large areas to reduce uncertainties on the retrieval of LR. The main benefit of this study is that this synergistic approach is in most of cases applicable whereas no solution is found by CALIOP operational algorithm (70 LR values among 102 cases for CALIOP level-2 against 86 among 102 cases for the synergy CALIOP/MODIS). It is also a complementary approach to retrieve LR from CALIOP enabling a comparison with LR values from the look-up table used in CALIOP operational algorithm.*

Shall a climatology of  $Sp$  be established?

*The synergistic approach involving MODIS and CALIOP spaceborne instruments has been here applied for the first time over land in the Po Valley where mainly pollution aerosols are present. It would be interesting to apply the same approach over other geographical areas where other aerosol type are encountered (dusts, biomass burning, sea salt. . .) in order to establish a climatology of LR. It is not the topic of the paper.*

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Shall the CALIPSO-retrieval be improved by providing more realistic  $S_p$  (by means of lidar ratios independent of height and averaged over 70km and no clearly attributable to aerosol types!)? It is certainly true that  $\alpha_p$  from CALIPSO is sometimes questionable because of wrong lidar ratios. However, the synergistic approach has also "question marks": temporal difference between Terra and CALIPSO, nighttime interpolation, spatial variability, height-dependent  $S_p$ , uncertainties in  $\tau_p$  from MODIS, and more (as the authors state by themselves). So, both retrievals (operational CALIPSO vs. MODIS-synergy) are subject to errors, and the authors present two solutions but it remains open, which is closer to the truth. So, what do we learn from the paper? What is the future benefit, what might be a future strategy? Here, clear statements must be added.

*This purpose of this study does not consist in choosing between retrievals from operational CALIPSO and MODIS-synergy which one is better, but to propose an alternative method when AOD derived from MODIS and CALIOP operational algorithm significantly diverge. It is right that the synergistic approach has also lots of sources of uncertainties which are discussed in the paper. The uncertainties from relative humidity, MODIS AOD constraint and CALIOP SNR have been assessed with Monte Carlo simulations and have led to a mean uncertainty on LR of  $\sim 12$  sr. We can notice that the agreement with CALIOP LR is better considering Aqua than Terra. This can be linked to the temporal difference between Terra and CALIPSO and to the highest bias observed between Terra-MODIS radiometer and AERONET sun-photometer at Ispra. The highest LR values observed (higher than 100 sr) are due to nighttime CALIOP profiles inverted with daytime MODIS AOD. In these cases the temporal difference between the lidar and radiometers (more than 11h40min) can lead to significant difference of AOD under CALIOP track and may explain the large LR observed. The spatial variability does not clearly influence the results here as CALIOP and MODIS measurements are averaged over the same portions. These different remarks have been added or clarified in the text.*

Furthermore, it becomes not clear, how the synergistic approach really works; it is

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never clearly described, one can only read between the lines, what the authors might have done. Probably, addition of a small paragraph will suffice.

*Additional informations have been added in the text to describe the synergistic approach: 'Here we consider the coupling between the passive instrument MODIS and the spaceborne lidar CALIOP. After the removal of CALIOP cloudy profiles, CALIOP and MODIS AOD ( $\tau_{MO}$ ) data are averaged along the red portions of CALIOP track in the Po Valley (Fig. 1). The mean CALIOP profile is then inverted with a classical Klett algorithm (Klett, 1985) and requires a dichotomous approach on LR values converging when the difference between CALIOP and MODIS AOD along CALIOP track ( $\tau_{MO}$ ) is lower than 0.01. Such a value has been established for a relative residual error on LR lower than 3%. A similar approach has been developed using LITE and Meteosat by Berthier et al. (2006).'*

Another weakness of the paper is the imbalance between relevant and irrelevant parts, at least it is not convincing that some sections contribute to the overall purpose of the paper:

1. parts are apparently of marginal importance (e.g. most parts of 4.2).

(b) significant parts cover a lot of details with respect to  $\tau_p$ -intercomparisons (ISPRA radiometer [wavelength-interpolation required!])

*This wavelength interpolation between 500 and 550 nm has been realized. 'The sunphotometer-derived AOD  $\tau_{MO}$  at 550 nm have been calculated using the Angström exponent between 500 and 675 nm.'*

MODIS-Aqua and MODIS-Terra, AERONET) but it is not clear what this is good for as the authors use all (btw: last paragraph in 3.2 is hard to understand from the figure; maybe the regression lines help; from visual inspection one would expect just the opposite conclusion),

*For sake of clarity, the structure of the paper has been deeply changed. The instruments used in this study are presented in Sect. 2. In Sect. 3, the aerosol optical depth from MODIS radiometers over the Po Valley is analyzed and compared with AOD derived from AERONET sun-photometer stations and CALIOP level-2 data. The synergistic approach using CALIOP and MODIS spaceborne instruments as well as the error analysis are described in Sect. 4. Finally LR and aerosol extinction coefficients retrieved over the Po Valley are described and discussed in Sect. 5.*

*The discussion in section 4.2 has been shortened and clarified. A new Table (Table 3) has been added to summarize the different LR found in other studies for pollution and dusts aerosols. The authors apologize for the mistake occurring in Fig. 5 caption where blue and red colors had been inverted. This mistake has been corrected.*

(c) several parts are not precise

1337/7: what means "more important"?

*the sentence has been removed in the new manuscript*

1339/10: depolarization data from which instrument?

*We have mentioned the instrument (CALIOP lidar) has been added in the text.*

1340/18: polarization again.

*The correction has been done in the manuscript*

1334/27: given SNR-range not found in Table.

*The correction has been made in the manuscript*

(d) whereas relevant topics are not covered in detail:

description of the synergistic method as already mentioned:

*the description of the synergistic method has been clarified (see answer above)*

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comments/explanations to the figures [examples see below]:

*see answers below*

strategies for validation:

*comparisons with Raman lidar observations in central Europe have been added in Table 3 (Müller et al. (2007) and Mattis et al. (2004)) They found LR values for pollution continental aerosols of 50-55 sr and 53 sr respectively. These values are lower than the one retrieved with the synergy between CALIOP and MODIS (~70 sr) and also lower than other values found in the literature (60-70 sr for Doherty et al. (1999); 50-70 sr for Ansmann et al. (2001);  $71 \pm 10$ sr for Catrall et al. (2005)).*

A few comments to the figures:

Fig. 7: what do the blocks mean, e.g. Fig. 7a, second from left: 15 cases of BER from 0.01 to 0.014, with nighttime BER larger than daytime BER?

*This figures have been plotted again to avoid any confusion.*

What about lidar ratios larger than 100 sr or even larger than 200 sr (Fig. 7b). What kind of aerosol is this (never seen before)? Such a finding needs comments in the text.

*These values correspond to nighttime CALIOP measurements inverted with daytime AOD from MODIS. This suggests that the synergetic approach is not convincing when nighttime interpolation is performed. This point has been explained within the text.*

Fig. 8: I don't see an annual cycle. There are almost no measurements in winter (only one per year)! This is certainly over-interpreted.

*The sentence 'a seasonal cycle with lower LR values during spring, summer and fall and higher values in winter' has been changed into 'The lowest LR values (under 60 sr) are mainly observed in spring and summer and can be associated to desert dust transport over the Po Valley, which may occur during those seasons.'*

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Finally, the authors should avoid BER. Everybody uses the lidar ratio, and it makes no sense to use a more or less private nomenclature. It seems that the authors are aware of this problem, as they include Sp in addition to BER in the last part of the paper. So, they can directly omit BER.

*All BER occurrences have been replaced by LR (lidar ratio) in the text and in the figures.*

By the way: "BER"-inclusion in Eq. 1 causes pain.

*BER has been removed from this equation*

References:

*Klett, J. D.: Lidar inversion with variable backscatter/extinction ratios, Appl. Opt., 24, 1638–1643, 1985.*

*Mattis, I., Ansmann, A., Müller, D., Wandinger, U., and Althausen, D.: Multiyear aerosol observations with dualwavelength Raman lidar in the framework of EARLINET, J. Geophys. Res., 109, doi:10.1029/2004JD004600, 2004.*

*Müller, D., Ansmann, A., Mattis, I., Tesche, M., Wandinger, U., Althausen, D. and Pisani, G.: Aerosol-type-dependent lidar ratios observed with Raman lidar, J. Geophys. Res., 112, D16202, doi:10.1029/2006JD008292, 2007.*

### **Anonymous Referee #2**

Overall quality evaluation:

The paper is on the determination of aerosol extinction coefficient profiles and aerosol optical depth derived from CALIOP data over the Po valley being constrained by the aerosol optical depth derived from MODIS Aqua and Terra data.

The overall quality of the paper is quite poor, as the paper is based on a wrong concept: the derivation of the aerosol extinction profile based on lidar backscattered CALIOP data, assuming a priori "guessed" 1/lidar ratios. The correct concept to derive the

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aerosol extinction profile is to use ONLY specific techniques, such as multi-wavelength Raman, multi-angle or High Spectral Resolution lidar systems. Therefore, it is not acceptable, scientifically speaking, to present aerosol extinction profiles of CALIOP, based only on backscatter data and AOD data derived from MODIS or AERONET measurements. The only acceptable aerosol extinction profile from CALIOP is derivable from CALIOP backscatter data, CALIBRATED using as input LR profiles derived from one of the above-mentioned techniques. This has already been done in the frame of groundbased lidars, as appeared in several papers validating the CALIOP profiles (i.e papers appearing in AMT and JGR) in 2009 and 2010. Therefore, the authors should re-orient and re-perform their research using, for example, lidar data from multi-angle measurements they are able to perform over the studied area. This proposed approach will help them to reduce the uncertainty in the derived LR values and increase the correlation coefficients between the inter-compared aerosol data.

*Most of the specific techniques proposed by the reviewer are well-known by the authors and have already been used to retrieve aerosol extinction profiles (see for example Raut and Chazette, 2009 and Sicard et al., 2002 for multiangle and Royer et al., 2009 for Raman lidar measurements). All these different techniques, similarly as Klett methodology, can also introduce a lot of errors in the retrieval of aerosol extinction coefficient, for instance due to the weak Raman backscattered signal limiting the retrieval of extinction profile to the lowest part of the atmosphere during daytime and the hypothesis of horizontal homogeneity of the atmosphere for multi-angle measurements which is not always verified, mainly close to the aerosol sources.*

*The aim of this paper is to characterize aerosol optical properties over the Po valley from spaceborne instruments (CALIOP lidar and MODIS radiometers) and not from ground-based instrumentation (Raman lidar, HSRL, multiangular measurements), which would be difficult to perform over such a large area without a great number of lidar systems spread out during several years in different representative sites over the Po Valley.*

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*At this time the only lidar system which enables to cover such a vast area is the spaceborne Rayleigh-Mie backscatter lidar CALIOP (which is thus not one of the specific technique previously mentioned). One has to notice that LR values provided by CALIOP Level 2 data in each layer detected are not determined by one of the specific techniques mentioned by the reviewer but have been selected between 6 different aerosol types (polluted continental, biomass burning, desert dust, polluted dust, clean continental and marine) with a model-matching scheme (Omar, 2009) considering optical (attenuated backscattered coefficient at 532 nm, depolarization ratio), temporal and geophysical characteristics (surface type).*

*This study has been driven after noticing the large discrepancy between CALIOP and MODIS derived AOD. A dichotomous algorithm has been developed to invert CALIOP backscatter data using MODIS AOD over the same portion of orbit. The different sources of uncertainties have been analyzed in the manuscript and, although uncertainties can be larger in using Klett inversion technique ( $\sim 12\text{sr}$ ), there is still much that can be learned. The authors are well-aware that the synergy between lidar and passive instrument only gives access to the mean aerosol LR in the column, which prevents from distinguishing different types of aerosols in the vertical column. The authors have therefore compared in this study integrated LR values from CALIOP level-2 and the synergistic approach. The BER ( $1/\text{LR}$ ) retrieved from the synergy between lidar and radiometer is the real vertical profile of BER ( $1/\text{LR}$ ) weighted by the aerosol extinction coefficient. Such point has been specified within the text.*

Open scientific questions/issues:

I would like to express my full agreement with the comments and issues raised by Referee 1 (posted on April 16, 2010). These comments corroborate most of my arguments expressed, in the previous paragraph, in the quality evaluation of the paper. Therefore, I would not like to add more comments on these scientific issues.

*All remarks of referee #1 have been taken into account and modified in the manuscript.*

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Suggestions for corrections:

BER values (used only by some members of the French lidar community) should not be used any more and should be replaced by the Lidar Ratio (LR). It makes no sense to use the term BER, which is greatly confusing within the lidar community, which has long ago, adopted the LR values expressed in (sr).

*All BER occurrences have been replaced by LR in the text and in the figures.*

References:

*Raut, J.-C. and Chazette, P.: Assessment of vertically-resolved PM<sub>10</sub> from mobile lidar observations, Atmos. Chem. Phys., 9, 8617-8638, 2009.*

*Sicard, M., Chazette, P., Pelon, J., Won, J. G., and Yoon, S.-C.: Variational method for the retrieval of the optical thickness and the backscatter coefficient from multiangle lidar profiles, Appl. Opt., 41, 493-502, 2002.*

*Royer, P., Chazette, P., Lardier, M., Raut, J.-C., Sauvage, L.: A new generation of mobile Raman lidar: Application to MEGAPOLI project, International Symposium on Tropospheric Profiling, Delft, 2009.*

*Omar, A., D. Winker, C. Kittaka, M. Vaughan, Z. Liu, Y. Hu, C. Trepte, R. Rogers, R. Ferrare, R. Kuehn, C. Hostetler, 2009: "The CALIPSO Automated Aerosol Classification and Lidar Ratio Selection Algorithm", J. Atmos. Oceanic Technol., 26, 1994–2014, doi:10.1175/2009JTECHA1231.1.*

### **Anonymous Referee #3**

General

The paper presents original material. A CALIPSO/MODIS method already applied to the Saharan air layer over the tropical Atlantic Ocean (Liu et al., JGR, 2008, CALIPSO/MODIS synergy) is now applied to the highly polluted Po Valley in northern Italy. So, the method used is not new, but now applied over land.

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*This paper (Liu et al., JGR, 2008) has been cited with a previous paper showing the advantage of the coupling between LITE and Meteosat (Berthier et al., JGR, 2006).*

The goal of the paper remains a bit unclear. The goal (as stated) is to present the results of a multiannual study of Po Valley aerosol conditions . . . involving a synergy between MODIS and CALIPSO spaceborne instruments. . . Most of the paper is dealing with the retrieval method itself.

*The structure of the paper has been deeply changed in order to clarify the purposes and the benefits of this paper. This study has been led after observing the large discrepancy in Aerosol Optical Depth (AOD) values over the Po Valley derived from MODIS and CALIOP instruments. A dichotomous algorithm constrained by MODIS AOD has thus been developed to determine the suitable LR. Data from MODIS and CALIOP have been averaged over large areas to reduce uncertainties on the retrieval of LR. The main benefit of this study is that this synergistic approach is in most of cases applicable in most cases whereas no solution is found by CALIOP operational algorithm (70 LR values among 102 cases for CALIOP level-2 against 86 among 102 cases for the synergy CALIOP/MODIS). It is also a complementary approach to retrieve LR from CALIOP enabling comparison with LR from the look-up table used in CALIOP operational algorithm. This point has been added in the introduction.*

The retrieval of lidar ratios ( $1/\text{BER}$ ) is one of the main points of the paper. The authors should switch to LIDAR RATIO (extinction-to-backscatter ratio), a well-established quantity, that is used by 98% of the aerosol lidar specialists around the world (including the CALIPSO science team). BER (backscatter-to-extinction ratio) was introduced to quantify the 180deg scattering phase function in cirrus (Eloranta in the 1980ies). But the aerosol can be highly absorbing so that BER parameter no longer describes the scattering properties alone, and thus the authors should use the main street notation (lidar ratio).

*All BER occurrences have been replaced by LR in the text and in the figures.*

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## Details

Page 1324, line 13: avoid the word: homemade, scientific work is always more or less homemade.

*The correction has been done in the paper.*

Page 1324, line 18: the lidar ratio is NOT a product of the CALIPSO measurements, it is just a look-up-table value!

*This sentence has been replaced by : 'LR determined from a look-up table through a selection algorithm in CALIOP level 2 operational products ( $\sim 63 \pm 8$  sr)'.*

Page 1325, line 5, megalopolis, better use ... megacities ...

*Correction done in the paper.*

Page 1325, line 20 to page 1326, line 6: many French references, no other work to be mentioned (e.g., Liu et al. JGR, 2008, and may be references in that paper)?

*This reference to Liu et al. (2008) has been added in the text.*

All the references in the manuscript here are dealing with the synergy of a standard backscatter lidar with satellite remote sensing or Sun photometer. But there are probably better alternatives? Raman lidars/HSRL combined with passive remote sensing! When inhomogeneous layering (may be boundary layer haze and lofted Saharan plume on top) is present, the synergy of standard backscatter lidar and passive remote sensing may be poor. At the moment, the introduction gives the impression that the synergy of simple backscatter lidar with passive remote sensing is the optimum.

*A reference for Raman lidar combined with passive remote sensing giving access to microphysical aerosol properties over Thessaloniki has been added in the text (Balis et al., 2010).*

Page 1327, line 21, ... level-2 data... there is a new releases of level-2 data a few

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weeks ago? *This level-2 data were not available when the paper study has been realized. The extraction of data and removal of clouds in CALIOP profiles would need a lot of time and work. Moreover, the new calibration will not impact the results present in our paper.*

Page 1327, line 24, as mentioned, switch to lidar ratio, please, : : :.throughout the paper.

*All BER occurrences have been replaced by LR in the text and in the figures.*

Page 1330, line 23, give the explicit reference, on which your algorithm is based, Klett (1981) is not appropriate, holds for particles (no Rayleigh) only.

*The reference to Klett (1981) has been replaced by Klett (1985)*

Page 1330, line 25, . . . from CALIPSO/MODIS you retrieve a height independent lidar ratio only, but the lidar ratio can be highly variable so that the column value poorly reflects the reality.

*To clarify our conclusions, we have added 'It is importance to note that this approach only give access to a height independent LR. In presence of several aerosol layers, this column value can be significantly different from the LR in each layer (case of dust aerosols above the PBL for example).'*

Page 1331, line 8, please explain tau-MO already here.

*Tau-MO has already been defined page 1328 line 25.*

Page 1333, line 17, results based on nighttime CALIPSO and daytime MODIS data (>9 h time difference) should be generally removed. They are at all not trustworthy.

*We have voluntarily kept the results based on nighttime CALIPSO and daytime MODIS data in the figure to show that in some cases nighttime interpolation was not convincing and led to unrealistic LR values (higher than 100 sr). This has been also been discussed in the new version of the manuscript.*

Page 1336, line 4, What does it mean . . . does not converge. . . Does it mean that the solutions become unstable? Klett forward retrieval problem?

*“Does not converge” means that the retrieved value of LR is not comprised between 20 and 200 sr. The following sentence has been added in text to precise the reasons of divergence : ‘Among the 16 cases where the algorithm did not converge (i.e. not comprised between 20 and 200 sr), 2 were night-time tracks constrained with MODIS daytime AOD and 12 had an AOD lower than 0.1 with uncertainties on  $\tau_{MO}$  higher than 30% corresponding to uncertainties on LR higher than 15 sr.’*

Page 1336, line 14, . . . the vertical profile of the lidar ratio (CALIOP). . . is taken from look-up tables. Such values cannot be interpreted as products (they are input to obtain the other products).

*This sentence has been removed.*

Page 1336, line 21, Again: Please avoid the impression that CALIPSO measures the lidar ratio. This standard lidar CALIOP may measure color ratios, depolarization ratio, and so on, . . . : to come up with the most appropriate look-up-table lidar ratio value for the analyzed scene, but it is by far not a lidar ratio measurement. That must be clearly said!

*The sentence has been replace by: ‘In order to compare LR retrieved from the space-borne instrumental synergy CALIOP/MODIS with that determined from CALIOP operational algorithm,’*

In this context, I miss comparisons with real-world lidar ratios from Raman lidars (see Muller et al., JGR, 2007?, aerosol type dependent lidar ratio from Raman lidar) and other EARLINET lidar ratio observations. There must be a lot.

*References to lidar measurements in central Europe have been added in the manuscript (Müller et al. (2007) and Mattis et al. (2004)). They found LR values for pollution continental aerosols of 50-55 sr and 53 sr respectively. These values are*

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lower than the one retrieved with the synergy between CALIOP and MODIS ( $\sim 70$  sr) and also lower than other values found in the literature (60–70 sr for Doherty et al. (1999); 50–70 sr for Ansmann et al. (2001);  $71 \pm 10$  sr for Catrall et al. (2005)).

Page 1337, line 14, avoid ... homemade. ... ,

*This word has been removed in the sentence*

shorten the lengthy discussion,

*The lengthy discussion has been shortened by adding a table (Tab. 3) to summarize the different LR found in the literature for pollution and dust aerosols.*

omit data of combined daytime MODIS and nighttime CALIPSO observations,

*see answer above.*

one should however more frequently mention how sensitive the CALIPSO approach (Klett method, forward mode) is to small errors in the applied lidar ratios so that backscatter uncertainties are in general not just low.

*Uncertainties in the determination of  $\alpha_a$  can be related to five main causes: (1) the uncertainty on the a priori knowledge of the vertical profile of the molecular backscatter coefficient as determined from ancillary measurements, (2) the uncertainty on the lidar signal in the altitude range used for the normalization, (3) the uncertainty on LR and on its altitude dependence, (4) the statistical fluctuations in the measured signal, associated with random detection processes, and (5) the overall uncertainty resulting from the value of  $\tau_{MO}$ . We considered here uncertainties on LR from SNR,  $\tau_{MO}$  and RH effects which have been supposed to be independent. A sensitivity study has been carried out in Sect. 4.2 and the overall uncertainty has been assessed to be  $\sim 12$  sr. These points have been clarified in the text.*

Page 1338, line 27, the only pure-dust lidar ratios were obviously measured during this SAMUM campaign: : please check the special issue in Tellus (2009?). All the EAR-

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LINET results on dust lidar ratios (at least at lower heights, <4 km) may be influenced by marine particles (lidar ratio of 25sr) or urban haze (mixing with pollution at the northern African coast). Catrall et al. used photometer observations (photometers do not measure 180 backscatter) and estimated the lidar ratio from phase function extrapolation to 180 deg.(based on some assumptions on particle shape that may introduce large errors).

*A reference to LR measured during SAMUM campaign has been added (Tesche et al., 2009). This study based on a Raman lidar reports pure-dust LR of  $53 \pm 8$  sr.*

Page 1339, line 21, Again: Because the Klett forward integration method must be used in the case of CALIOP this may introduce large errors in the profile, when not constraint to some AOD observations. This aspect is the main goal when combining MODIS and CALIPSO observations.

*This error source has been considered in the Monte Carlo simulations which have been realized with the same Klett forward integration method.*

Page 1340, line 10, this paper fulfils the validation requirements of CALIOP operational algorithm over a polluted area. I do not understand what you mean? May be skip this sentence.

*The sentence has been removed.*

One should state that the whole approach is ok (provides satisfying agreement and products) when most of the aerosol is in the polluted boundary layer. The method may not be that good and, at least to some extent, questionable in the case of an optically thick Saharan dust layer over the polluted Po valley haze so that the lidar ratio is highly variable.

*We agree with this comment and we have added this remark.*

Figure 8, in general, the lidar ratios are, to my opinion, too high (BER values are too low, BER values varying around 0.012 means lidar ratios varying around 85!), is that a



special thing of Po Valley? Or just a bias introduced by your retrieval : : . There are some European Raman lidar observations of the lidar ratio available in northern/central Europe and southern Europe (e.g., Greece, : : should be comparable to Po Valley: : , Amiridis et al, ACP, JGR). Please check.

*We didn't find any Raman lidar observations in the Po Valley but references to lidar measurements in central Europe have been added in the manuscript (Müller et al. (2007) and Mattis et al. (2004)). If consider only daytime inversions the mean LR are  $70 \pm 11$  sr for Aqua and  $74 \pm 14$  sr for Terra. These values are higher than the one found for pollution continental aerosols in Müller et al. (2007) and Mattis et al. (2004): 50-55 sr and 53 sr, respectively. But they are comparable to other LR values found in the literature (60-70 sr for Doherty et al. (1999); 50-70 sr for Ansmann et al. (2001);  $71 \pm 10$ sr for Catrall et al. (2005)). The inversion of nighttime CALIOP profiles with daytime AOD show unrealistic values higher than 100 sr and thus must not be considered. These different comments have been added in the text.*

Figure 9, the plot B: : , the discrepancies can easily be caused by the Klett forward approach: : . Did you check nearby AERONET data (AOD values). Who is right?

*Klett forward approach has been taken into account in the Monte Carlo simulation to assess the uncertainty on LR. It is not possible to compare here AOD since CALIOP orbit track is in the East of the Po Valley (near Trente) too far away from Ispra Aeronet station. However, AOD obtained from AERONET stations have been compared against MODIS-derived AOD over the same areas (Fig. 4).*

All in all, the paper is a nice application of state-of-the-art satellite observations. This is the first time that the approach is applied to observations over land (may be that should be stressed clearly, contrast to Liu et al. 2008). Po Valley is an interesting, heavily polluted area. But more links to the real world (Raman lidar observations) will improve the paper.

*Comparisons with Raman lidar observations in central Europe have been added in the*

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manuscript to compare with our LR retrievals.

#### References:

Klett, J. D.: Lidar inversion with variable backscatter/extinction ratios, *Appl. Opt.*, **24**, 1638–1643, 1985.

Balis, D., Giannakaki, E., Müller, D., Amiridis, V., Kelektoglou, K. Rapsomanikis, S., and Bais, A.: Estimation of the microphysical aerosol properties over Thessaloniki, Greece, during the SCOUT-O<sub>3</sub> campaign with the synergy of Raman lidar and Sun photometer data, *J. Geophys. Res.*, **115**, D08202, doi:10.1029/2009JD013088, 2010.

Liu, Z., Omar, A., Vaughan, M., Hair, J., Kittaka, C., Hu, Y., Powell, K., Trepte, C., Winker, D., Hostetler, C., Ferrare, R. and Pierce, R.: CALIPSO lidar observations of the optical properties of Saharan dust: A case study of long-range transport, *J. Geophys. Res.*, **113**, D07207, doi:10.1029/2007JD008878, 2008.

Mattis, I., Ansmann, A., Müller, D., Wandinger, U., and Althausen, D.: Multiyear aerosol observations with dualwavelength Raman lidar in the framework of EARLINET, *J. Geophys. Res.*, **109**, doi:10.1029/2004JD004600, 2004.

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#### Anonymous Referee #4

In this paper the authors combine observations from CALIOP and MODIS to study aerosols in the Po Valley. MODIS column AOD is used to constrain CALIOP aerosol

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retrievals, yielding aerosol extinction profiles and column-average lidar ratio (or BER).

This is an interesting study showing the synergy between these two instruments and shows various intercomparisons which provide insight into data quality.

First, I agree with the other reviewers – use lidar ratio instead of BER. The vast majority of lidar literature expresses the lidar ratio as S (or Sa), the inverse of BER.

*All BER occurrences have been replaced by LR in the text and in the figures.*

1) I see two areas where greater care is required:

a) Results of an error analysis are shown in Figure 5 but the results shown are not directly applicable to the BER retrievals shown later. The analysis is applied to the mean AOD, with a mean error of 17%, whereas some of the AODs are much smaller and have errors of 100% or more (figures 3 and 4) which must lead to very significant BER errors. Indeed, some of the lidar ratios (BER values) are much larger (smaller) than seems reasonable based on modeling and other measurements. This error analysis should be extended and used to add error bars to the values shown in Figure 8.

*The sensitivity study has been significantly improved in the new version of the manuscript. Monte Carlo simulations have been performed for different mean AOD (0.05, 0.15, 0.25, 0.35 and 0.45) and results have been reported on Fig.7b. Uncertainties for each LR value have been computed taken into account the corresponding mean AOD, the SNR of the lidar profile and the relative humidity in the PBL. Errorbars relative to all values shown in Fig.8 have been included on the temporal evolution of LR. The mean uncertainty on LR is  $\sim 12$  sr, giving an overall uncertainty of the method detailed in this paper.*

b) Uncertainties introduced by using MODIS-Terra AOD and applying daytime MODIS AOD to nighttime CALIOP profiles should be addressed in more detail. The lowest values of BER are due to applying MODIS AOD to nighttime CALIOP data, implying the MODIS AODs may not be representative of nighttime conditions. Given the significant

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AOD differences between MODIS-Terra and MODIS-Aqua shown in Figure 4, there seems little justification for applying daytime AODs to nighttime profiles.

*We agree that daytime AOD values used to constraint nighttime CALIOP measurements are sources of large uncertainties. As mentioned in Sect.5.1, the higher values of LR (higher than 100 sr) are exclusively linked to the inversion of nighttime CALIOP profiles. Different colors have been used on histograms and temporal evolution of LR to distinguish between daytime and nighttime LR values.*

Specific comments:

2) The uncertainties stated in the last sentence of the second paragraph of Section 2.1 are unsupported and should be deleted.

*This sentence has been removed.*

3) The retrieval algorithm should be discussed in more detail. The Klett algorithm which is referenced is a single component retrieval and not appropriate for the cases of interest here.

*The reference to Klett algorithm has been replaced by to the appropriate one for the case of interest here (Klett, 1985).*

In particular, what are the conditions for convergence and what causes the algorithm to diverge?

*Does not converge means that the LR is not comprised between 20 and 200 sr. The following sentence has been added in text to precise the reasons of divergence: 'Among the 16 cases where the algorithm did not converge (i.e. not comprised between 20 and 200 sr), 2 were night-time tracks constrained with MODIS daytime AOD and 12 had an AOD lower than 0.1 with uncertainties on  $\tau_{MO}$  higher than 30% corresponding to uncertainties on LR higher than 15 sr.'*

How does error in MODIS AOD propagate to the retrieved BER?

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When AOD is overestimated, LR is also overestimated. The results of the Monte Carlo simulation performed to assess this source of uncertainty are presented on figure 7b. Other Monte Carlo simulations have been performed for mean MODIS AOD of 0.05, 0.15, 0.25, 0.35 and 0.45.

4) The description of the CALIOP retrieval algorithm in Section 4.2 is not entirely correct, perhaps because the references cited are either incomplete or outdated. The CALIOP aerosol typing algorithm is best described in (Winker, et al. 2009) and (Omar, et al. 2009).

*The corrections have been done in the text:*

*'The CALIOP operational retrieval of  $\alpha_a$  is computed using an aerosol extinction-to-backscatter ratio (LR) determined with the selection algorithm described in the Scene Classification Algorithms (PC-SCI-202.03, Vaughan et al., 2004a) of the CALIOP Lidar Level II Algorithm Theoretical Basis Document (ATBD). Aerosol extinction profiles are given with a vertical resolution of 120 m from the ground up to 8.2 km above the mean sea level (a.m.s.l.). The aerosol type is determined in each layer using a model-matching scheme (Omar, 2009). Optical (attenuated backscatter coefficient at 532 nm, and depolarization ratio), geographical (e.g. latitude, longitude, surface type), aerosol layer elevation, and temporal (season) characteristics are used to select the most likely LR for each layer. There are 6 different aerosols types: polluted continental (LR=70 sr at 532 nm), biomass burning (LR= 70 sr), desert dust LR=40 sr), polluted dust (LR=65 sr), clean continental (LR=35 sr) and marine (LR=20 sr). The uncertainties on aerosol backscatter and extinction coefficients are respectively 20-30% and 40% assuming an uncertainty of 30% on LR (Omar, 2009).'*

5) Section 2.2 – Terra is not in the A-train

*The correction has been made in this sentence:*

*'Moderate Resolution Imaging Spectroradiometers (MODIS, Salmonson et al., 1989;*

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King et al., 1992) are aboard Aqua and Terra platforms. Aqua has joined the A-train constellation on December 1999 whereas Terra has been launched on May 2002.'

6) Section 4.2 – The purpose of the long discussion of other BER values in the literature is not clear. BER values derived here should be explicitly discussed relative to other values in the literature.

*We didn't find any Raman lidar observations in the Po Valley but references to lidar measurements in central Europe have been added in a table (Tab. 3) in the manuscript (Müller et al. (2007) and Mattis et al. (2004)). They found LR values for pollution continental aerosols of 50-55 sr and 53 sr respectively. These values are lower than the one retrieved with the synergy between CALIOP and MODIS (~70 sr) and also lower than other values found in the literature (60-70 sr for Doherty et al. (1999); 50-70 sr for Ansmann et al. (2001);  $71 \pm 10$ sr for Catrall et al. (2005)).*

7) Table 1 only considers local sources. What about long range transport of smoke or dust?

*Observations of dust events are discussed in the paper (Sect. 5.1): 'The Po Valley can also be episodically influenced by long-range transport of dust. The lowest LR values (under 60 sr) are mainly observed in spring and summer and can be associated to desert dust transport over the Po Valley, which mainly occur at these seasons. This has been confirmed by backward trajectories performed using the Hysplit model (<http://ready.arl.noaa.gov/HYSPLIT.php>) and higher depolarization ratio observed with CALIOP lidar (not shown). Dust particles can be transported above Mediterranean Sea as described by Hamonou et al. (1999). Moreover, several dust events have been observed by Bonasoni et al. (2004) at Mt Cimone in the Italian northern Apennines.'*

8) Figure 7 – It is hard to determine the bin boundaries – please re-plot to make clearer.

*The figure has been replotted to make it clearer.*

9) Fig 9 – Are these profiles averaged over 40 km? Explain these profiles in more

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detail. Give AOD and lidar ratios for each of the four profiles.

*Some explanations have been added in the text. CALIOP level-1 and -2 profiles are both averaged over the same portions (red portion on figure 1) in the Po Valley. AOD and LR values have been added in the 2 figures.*

*‘Two examples of aerosol extinction coefficient on the 15 September 2007 at 12:30 GMT and 8 September 2007 at 12:24 GMT are represented in Fig. 10a and 10b. These profiles have been averaged in the Po Valley from CALIOP level-2 operational product (red lines) and from CALIOP level-1 data inverted with the LR retrieved from the synergy with MODIS (blue lines). In the first case, the two extinction coefficient profiles are in good agreement with mean square difference of  $0.02 \text{ km}^{-1}$ . LR and Aerosol optical depth derived from MODIS and CALIOP are in good agreement ( $\sim 67 \text{ sr}$  and  $\sim 0.28$  respectively). A significant discrepancy can be observed in the second example (mean square difference of  $0.15 \text{ km}^{-1}$ ). In this last case, the integration of the CALIOP level-2 aerosol extinction profile gives an AOD of 0.20 compared with the value of 0.26 measured by MODIS-Aqua radiometer at the same time. This underestimation of AOD values can be explained by an underestimation of LR values (80 sr retrieved from the CALIOP/MODIS synergy against 67 sr for CALIOP level-2 operational algorithm).’*

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