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Passive remote sensing of aerosol layer height using near-UV multi-angle polarization measurements

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Abstract

We demonstrate that multi-angle polarization measurements in the near-UV and blue part of the spectrum are very well suited for passive remote sensing of aerosol layer height. For this purpose we use simulated measurements with different set-ups (different wavelength ranges, with and without polarization, different polarimetric accuracies) as well as airborne measurements from the Research Scanning Polarimeter (RSP) obtained over the continental USA. We find good agreement of the retrieved aerosol layer height from RSP with measurements from the Cloud Physics Lidar (CPL) showing a mean absolute difference of less than 1 km. Furthermore, we found that the information on aerosol layer height is provided for large part by the multi-angle polarization measurements with high accuracy rather than the multi-angle intensity measurements. The information on aerosol layer height is significantly decreased when the shortest RSP wavelength (410 nm) is excluded from the retrieval and is virtually absent when 550 nm is used as shortest wavelength.

1. Introduction

Measurements of the aerosol vertical distribution are highly valuable for radiative forcing studies, [e.g., Haywood and Boucher, 2000] and air quality investigations, [e.g., Wang and Christopher, 2003] and are also important to account for aerosol scattering in trace gas and ocean color retrieval algorithms [Gordon, 1997; Duforêt et al., 2007; Butz et al., 2011]. Knowledge of vertical distributions of aerosols is important for studies on aerosol-cloud interaction because aerosols can act as cloud condensation nuclei when they are at cloud base altitude [Gryspeerdt et al., 2015; Stier, 2016]. For aerosol direct effect studies, knowledge on the aerosol vertical distribution is particularly important to determine whether aerosols are located below or above clouds. Furthermore, measurements of aerosol height

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distribution can provide insight into aerosol transport processes since elevated aerosols are typically being carried over long distances, whereas aerosols confined to the primary boundary layers usually stay near the source region. To measure vertical distributions of aerosols on a global scale, satellite remote sensing methods are needed. The aerosol vertical distribution can be most accurately measured, albeit with a narrow swath, by active remote sensing techniques using LIDAR measurements. The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument is providing such measurements from space since 2006 [Winker et al., 2010]. The airborne Cloud Physics Lidar (CPL) instrument provides similar measurements as CALIOP and has been utilized in many aircraft campaigns to provide height resolved measurements of cloud and aerosol properties [McGill et al., 2002]. Improved High Spectral Resolution Lidar (HSRL) measurements have also been performed from aircraft [Hair et al., 2008] and will be performed in the near future from the Earth-Care satellite [Illingworth et al., 2015]. Also, a ground based infrastructure for active remote sensing, EARLINET, that provides important additional measurements on aerosol profiles at selected locations, but in principle continuous in time [Pappalardo et al., 2014; Wiegner et al., 2014]. Passive satellite remote sensing of aerosol layer height can by far not provide the same level of detail as active remote sensing, but adds an important extension compared to active remote sensing in terms of spatial coverage. Concerning passive remote sensing techniques for retrieving aerosol height, most focus has been on the use of the O_2 A-band. Synthetic studies indicate that the O_2 A-band technique is a valuable tool to retrieve layer height in case of a aerosol layer with relatively large optical thickness in the free troposphere [Sanders et al., 2015; Geddes and Bösch, 2015; Hollstein and Fischer, 2014; Sanghavi et al., 2012]. Achieving agreement between retrieved aerosol height from real O_2 A-band measurements and LIDAR measurements is challenging and depends on ad hoc assumptions [Sanders et al., 2015]. Further, stereoscopic retrievals have been successfully applied to measurements of MISR for the retrieval of aerosol plume height close to the emission source [Kahn et al., 2007].

It has been shown in many papers that multi-angle, multi-spectral polarimetric measurements can provide valuable information on aerosol microphysical properties [Mishchenko and Travis, 1997; Chowdhary et al., 2001; Hasekamp and Landgraf, 2005, 2007; Waquet et al., 2009; Hasekamp et al., 2011; Dubovik et al., 2011; Knobelspiesse et al., 2011, 2012; Wu et al., 2015]. In this paper, we demonstrate the capability of multi-angle intensity and polarization measurements for the retrieval of aerosol layer height. The aerosol height information mainly comes from measurements at near-UV and blue wavelengths in visible spectrum where the Rayleigh scattering dominates. Here, an elevated aerosol layer partly shields the polarization signal from Rayleigh scattering providing sensitivity to aerosol layer height [Hasekamp and Landgraf, 2005; Kalashnikova et al., 2011]. We use simulated measurements and airborne measurements of the Research Scanning Polarimeter (RSP) during the PODEX (Polarimeter Definition Experiment) and the SEAC^{4}RS (Studies of Emissions and Atmospheric Composition, Clouds and Climate Coupling by Regional Surveys) campaigns in 2013 [Toon et al., 2016]. We compare the retrieved aerosol layer height from RSP with measurements of the Cloud Physics Lidar (CPL), which operated simultaneously on-board the ER-2 aircraft during both campaigns. CPL provides information on the vertical distribution of aerosols. By performing retrievals for different measurement configurations (spectral range, with and without polarization), we investigate what the most important source of information is for aerosol height retrieval.

2. Data

RSP [Cairns et al., 2003, 1999] measures Stokes parameters *I, Q* and *U*, for one ground pixel at 152 viewing angles (±60° from nadir) in nine wavelength bands between 410–2250 nm. RSP has a radiometric uncertainty of ~ 2.0% and a polarimetric uncertainty of ~ 0.2% (absolute). The PODEX and SEAC^{4}RS measurement campaigns used in this study were performed over the continental USA. For these campaigns the ER-2 high altitude aircraft, with RSP on-board, flew at its nominal altitude of 20 km (94% percent of the Earth's atmosphere is below this altitude). The CPL, which also flew on the ER-2 during PODEX and SEAC^{4}RS, provides vertically resolved, high spatial resolution measurements of aerosol and cloud optical properties at 3 wavelengths: 1064, 532, and 355 nm [McGill et al., 2003]. The CPL data products include cloud and aerosol layer boundaries, optical depth for clouds and aerosol layers, extinction profiles, and planetary boundary layer (PBL) height [Yorks et al., 2011]. We use RSP data that have been co-located at the same ground pixel for the different angles and then averaged over a distance of 5 km to reduce the error from co-registration between angles [Wu et al., 2015]. For our retrievals we use measurements of the RSP bands at 410, 470, 550, 670, 865 and 1590 nm and 9 evenly sampled viewing angles in the range [−60, 40°] because outside that RSPs view is obstructed by the ER-2 aircraft.

To investigate the aerosol height retrieval capability of the RSP measurements, we compare the retrieved aerosol layer height from RSP with the the averaged geometric mean height weighted by optical depth of each aerosol layer τ_i provided by the CPL,

$$z_m = \frac{\sum_{i=1}^{N}\left(\tau_i\sqrt{z_i^{bottom}\cdot z_i^{top}}\right)}{\sum_{i=1}^{N}\tau_i}, \quad (1)$$

where N is the number of aerosol layers detected by CPL and z_i^{bottom} and z_i^{top} are bottom and top layer heights of the ith layer detected by the CPL.

The NCEP reanalysis data are used to provide temperature, pressure and relative humidity profiles in atmosphere for the corresponding RSP measurements[Kistler et al., 2001].

3. Method

For the aerosol retrievals in this study, we use the SRON algorithm for aerosol retrieval from multi-angle measurements of intensity and polarization [Hasekamp et al., 2011; Stap et al., 2015; Wu et al., 2015]. The retrieval approach is based on iteratively fitting the multi-angle photo-polarimetric measurements with simulations calculated using the linearised vector radiative transfer (RT) model developed at SRON [Hasekamp and Landgraf, 2002, 2005; Schepers et al., 2014].

We use a bimodal log-normal function to describe the aerosol size distributions including a fine and coarse mode. Each mode is characterized by effective radius, effective variance, real and imaginary refractive index and particle number column. These parameters are all included in the retrieval state vector. For the coarse mode, also the fraction of non-spherical particles is retrieved using the method proposed by Dubovik et al. [2006]. Spectrally dependent refractive indices are included using the method of Wu et al. [2015]. For the aerosol relative distribution with altitude z, we consider a function $h(z)$ such that the aerosol sub-column N_i in layer i of the forward model atmosphere, with height z_i, is given by: $N_i(z_i) = N_{tot} * h(z_i)$. Here N_{tot} is the total aerosol column and $h(z)$ is given by a Gaussian function:

$$h(z) = A \exp(-4 \ln 2(z - z_c)^2/\sigma^2), \quad (2)$$

where z_c is the center height, which we define as the Aerosol Layer Height, σ is the width of the aerosol height distribution and A is a normalization factor. The Gaussian function can peak at the surface or below in which case only the part above the surface is considered. In our retrieval, z_c is included in the state vector as an additional unknown parameter. For surface reflection, the Rahman-Pinty-Verstraete (RPV) model of Rahman et al. [1993] and a linear one-parameter bidirectional polarization distribution function (BPDF) model of Litvinov et al. [2011] are used for intensity and polarization, respectively. We also include the eight surface reflection parameters of the RPV model and the parameter of the BPDF model in the state vector. The first guess state vector for the iterative retrieval is obtained from lookup table (LUT) based retrieval as discussed in detail by Wu et al. [2015]. In Table S1, we list aerosol parameters and their ranges used in our study. For center height z_c, we do retrievals three times with different first guess and prior values of 1, 3 and 5 km and select the retrieval for which the best fit with RSP is obtained.

4. Synthetic Study

To study the theoretical capability of multi-angle intensity and polarization measurements for the retrieval of aerosol layer height, we create 2000 simulated measurements for the six RSP bands mentioned above for 13 viewing angles (evenly spaced between ±60.0° from nadir in the principal plane). Surface parameters of RPV and BPDF models and the generation of aerosol parameters including size distribution, refractive indices and optical depth (randomly sampled between 0.0 and 0.7 for each mode at 550 nm) are the same as we used in Wu et al. [2015] with the only difference being that the aerosol layer center height z_c varied randomly in the interval 100–6000 m where the width σ was set to 2000 m. Here, we assume that only one aerosol layer is present in the atmosphere. The intensity vector was simulated at an ER–2 representative height of 20 km. For our baseline retrievals, we add a random noise to the simulated measurements of 1.0% on intensity and 0.2% on degree of linear polarization to account for measurement uncertainties. Figure 1 compares the retrieved center heights with the truth for different measurement configurations. Although in these retrievals the assumed width of the Gaussian height distribution is consistent with the value used in the synthetic measurements, we obtain virtually the same results if the width is not consistent between retrieval and synthetic measurement (see Fig. S5–Fig. S7 in supporting material). On the other hand, the retrieval performance is sensitive to the choice of the first guess for aerosol height. If we use a fixed first guess value of 3 km the comparison between retrieved and true height degrades compared to our baseline where try 3 different first guess values (see Fig. S1).

Figure 1(a) compares the retrieved aerosol layer center height z_c with true values for retrievals using the 410–1590 nm spectral range. It shows a high correlation between true and retrieved values and the retrieved center heights agree well with true values with a mean absolute error < 250 meter. For aerosol layers above 5 km the retrievals become more noisy. This is because the air density, and hence the Rayleigh scattering coefficient, decreases with altitude. So, when the aerosol layer height is increased from 5 to 6 km the additional amount of Rayleigh scattering that is ’shielded’ by the aerosol layer is less than when the aerosol layer height would be increased e.g. from 2 to 3 km.

The error on the retrieved aerosol layer height does not show significant correlation with the value of other aerosol parameters, like SSA or size (see Fig. S8).

To analyze the importance of polarization measurements for height retrieval, we performed aerosol retrievals based on intensity-only measurements for the same wavelength range. Figure 1(e) compares the retrieved center height to the true values for the intensity-only retrievals. Compared to the retrievals using both intensity and polarization, the errors on the center height are a factor 2–3 larger for retrievals without polarization. When compared with Fig. 1(a), there are more cases with retrieved heights that remained near the a priori values in Fig. 1(e). Comparing Figs. 1(a) and 1(e), it is clear that for an important part the height information comes from polarization measurements. Moreover, in Fig. 1(d) we show the center height retrieval using measurements with the same radiometric accuracy as in Fig. 1(a) but with a polarimetric accuracy of 2% which is representative for the POLDER and 3MI instruments [Fougnie et al., 2007]. From this figure it follows that the retrieval error of center height are significantly larger (factor 2–3) for this measurement configuration than for the one used in Fig. 1(a) and are almost the same as for intensity-only retrievals. This clearly demonstrates the importance of high polarimetric accuracy for aerosol layer height retrieval. Here we do comparisons under a certain intensity accuracy(1.0%). Incidentally, as shown in Fig. 1(f), if the intensity error increases from 1.0% to 4.0% the height retrieval error also becomes larger but still less than in Fig. 1(d).

In order to investigate which spectral range provides most of the aerosol height information, in Figs. 1(b) and 1(c) we show retrieval results for measurements with reduced spectral ranges of 470–1590 nm and 550–1590 nm. As explained before, height information mainly comes from the shielding effect by an elevated aerosol layer of the Rayleigh scattering signal below the aerosol layer. Since the Rayleigh scattering optical thickness decreases towards longer wavelengths, the sensitivity to aerosol layer height is expected to decrease for the reduced spectral ranges used here. As can be seen in Figs. 1(b) and 1(c), the retrieval performances get gradually worse when the lower wavelength limit is increased from 410 to 470 and 550 nm, where in the latter case the information on aerosol height has largely disappeared. Therefore, the height information mainly comes from measurements at shorter wavelengths and it shows polarization measurements at 410 nm are very beneficial.

Overall, the use of polarization measurements is very important for the retrieval of aerosol layer height from multi-angle data. For future satellite instruments, it is important to provide the polarization measurements with high accuracy to enable aerosol layer height retrievals.

5. Retrieval using RSP Data

As shown in Wu et al. [2015], our aerosol retrievals from RSP compare well with measurements from the Aerosol Robotic Network (AERONET) for aerosol optical depth (AOD), refractive index, effective radius, and single scattering albedo (SSA). In the present study we focus on the retrieval of aerosol layer height where we compare RSP retrievals with CPL. For RSP, we only consider retrievals for which a goodness of fit criterion of $\chi^2 \leq 6.0$ is satisfied. This χ^2 threshold is somewhat adjusted for other retrieval set-ups (see below) to ensure that the number of valid retrievals is the same. We screen out measurements that are flagged as cloudy by CPL and use only measurements including 90° scattering angle where the maximum linear polarization of Rayleigh scattering occurs. Figure S2 in supporting material shows the validation without scattering angle range screening. Moreover, in Fig. S3, we also show the height retrieval errors with respect to the scattering angle range.

Figure 2 shows comparisons between the retrieved center height from RSP measurements and the geometric mean height provided by CPL using different measurement configurations. Figure 2(a) shows the comparison using both intensity and polarization measurements. Here, we include only cases where the retrieved aerosol optical depth (AOD) > 0.2 at 550 nm because the retrieved height values are less reliable for small AOD cases for both RSP and CPL. A similar comparison including small AOD cases can be found in Fig. S4 of the supporting material. The retrieved heights from RSP measurements agree well with CPL. The correlation coefficients between the two data sets is ~ 0.85 and the mean absolute difference is ~ 0.9 km. The agreement between RSP and CPL depends on layer height with a less favourable comparison above ~ 6 km, like for the synthetic retrievals.

Fig. 3 shows a comparison between the retrieved Gaussian height distribution from RSP and the actual high vertical resolution extinction profile measured by CPL for 3 characteristic cases. For single layers the retrieved aerosol layer height (i.e. where the peak of the Gaussian is located) corresponds well to the physical height where the extinction profile peaks. For multiple layers the retrieved height is in between different aerosol layers, closest to the layer that is most optically thick.

We also investigated the added value for aerosol height retrieval of polarization measurements compared to intensity-only measurements using real RSP measurements. As can be seen in Fig. 2(d), the intensity only retrievals mostly stay at their first guess value and thus poorly compares with CPL. This confirms the importance of polarization measurements for aerosol layer height retrievals, where the importance is even more pronounced for real RSP measurements than for the synthetic measurements.

Moreover, the capability for aerosol height retrieval is also investigated using RSP measurements with spectral ranges of 470–1590 and 550–1590nm (see Figs. 2(b) and 2(c)).

From Figs. 2(b) and 2(c) it follows that the performance get gradually worse when the lower wavelength limit is increased from 410 to 470 and 550 nm. For example, the absolute mean difference in aerosol layer height between RSP and CPL is increased from 0.903 to 1.159 and 1.568. Meanwhile, the correlation coefficient is decreased from 0.85 to 0.75 and 0.53. In the retrievals using RSP measurements with the lower wavelength limit of 550 nm, the retrieved heights mostly stay at the first guess value.

In general, the retrievals using real RSP measurements confirm what we found with the sythetic study: Multi-angle photo-polarimetric measurements in the blue and near-UV provide an important capability for passive remote sensing of aerosol layer height. The information on aerosol layer height mostly comes from the polarization measurements rather than the intensity measurements.

6. Conclusion

In this paper we demonstrate that multi-angle polarization measurements in the near-UV and blue part of the spectrum are very well suited for passive remote sensing of aerosol layer height. By using simulated measurements and airborne measurements from the RSP, it was found that measurements in the range 410–1590 nm are well capable of retrieving aerosol layer height in addition to other aerosol parameters. The retrieved aerosol layer height from RSP was found to be consistent with the aerosol height profile from co-located active remote sensing measurements by CPL, yielding a mean absolute difference of less than 1 km. Given that Definitions of layer height are not exactly the same between RSP and CPL we consider this as a good agreement between the two instruments.

Our study demonstrates that the information on aerosol layer height is provided for a large part by the polarization measurements rather than the multi-angle intensity measurements. It was found that aerosol layer height can be retrieved significantly more accurately using a lower wavelength limit of 410 nm compared to 470 nm, and that for 550 nm as lower limit the information on aerosol layer height is virtually absent. Concerning the scattering angle range, it was found that retrievals get gradually worse when the lowest scattering angle becomes larger than 90°, where the Rayleigh scattering induced polarization shows it's maximum. For future satellite instrument, it is expected that the height information can be better retrieved if shorter wavelengths than 410nm are included. Also polarimetric accuracy was found to be very important. If the polarimetric accuracy is degraded from 0.2% to 2%, polarization measurements lose a significant part of the information about aerosol height and errors in retrieved layer height are a factor 2–3 larger.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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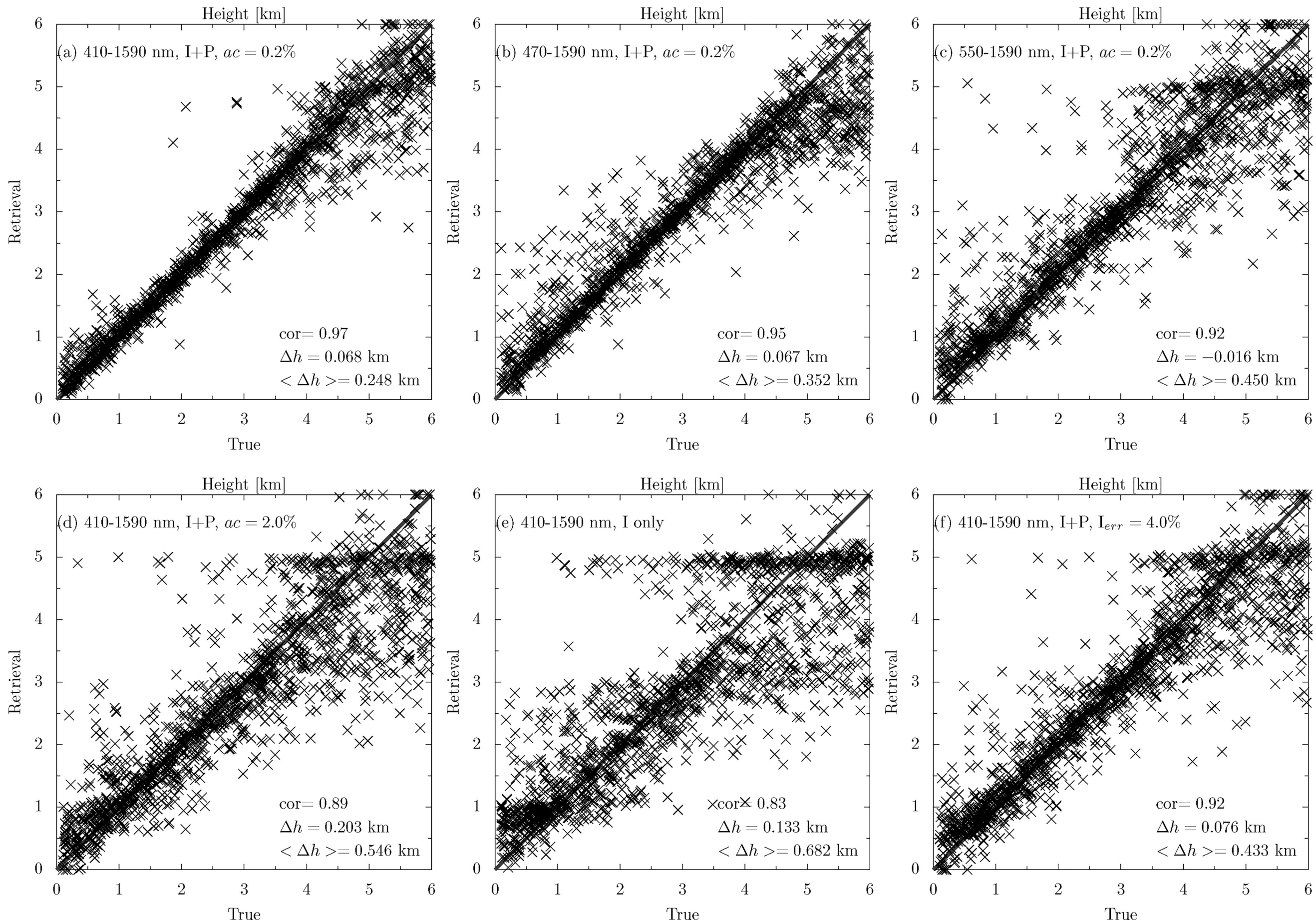

Figure 1.

Comparison between retrieved and true values of aerosol center height using different measurement configurations including spectral range, measurement type(intensity and polarization ”I+P” or intensity only ”I only”), polarimetric accuracy(”ac”) and intensity accuracy(”I_{err}”). The correlation coefficients (cor), mean error (Δh) and mean absolute error ($< \Delta h >$) between retrieved and true values of center height are included.

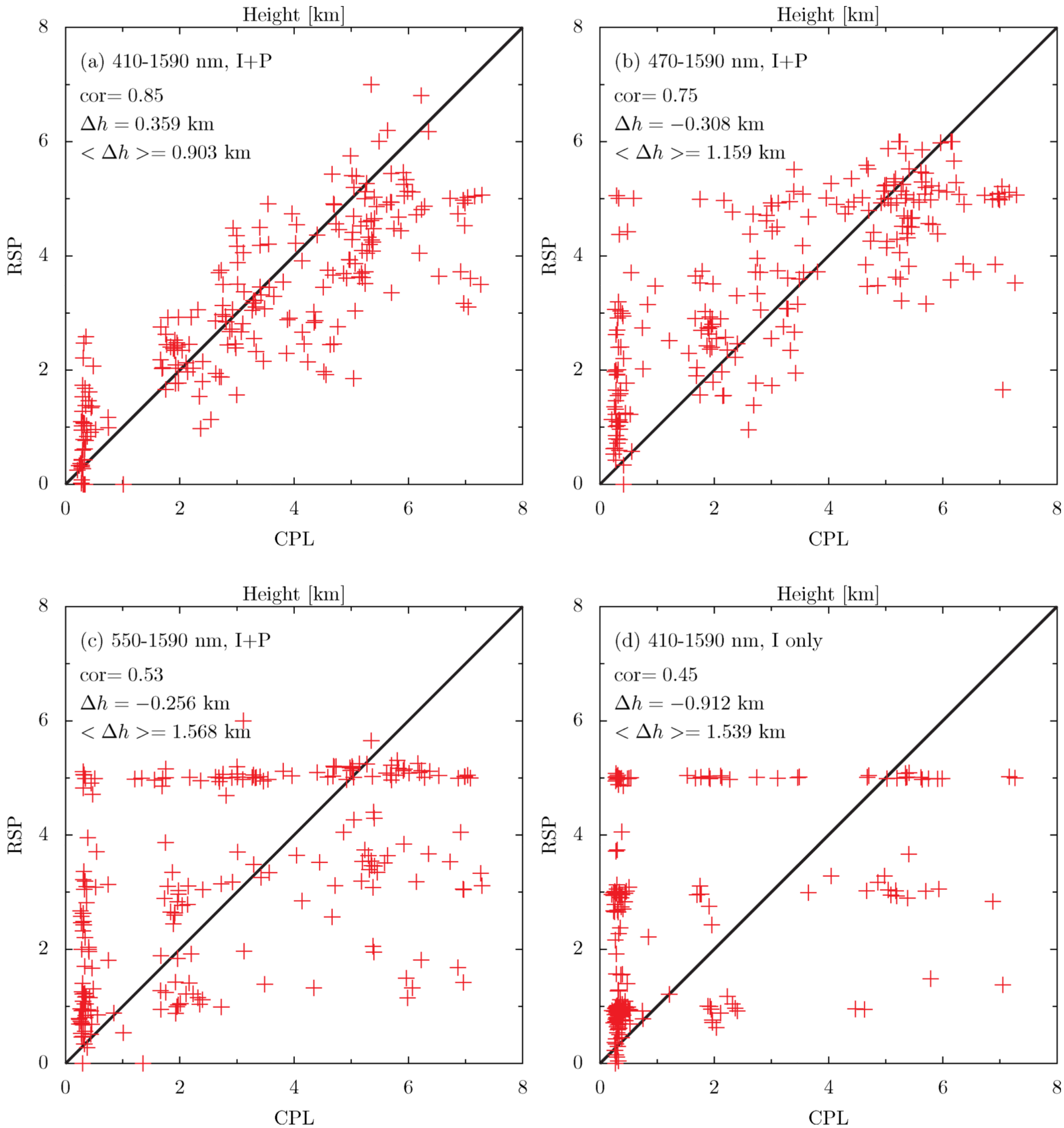

Figure 2.

Height comparison between the retrieved center height of RSP measurements and CPL product using different measurement configurations including spectral range and measurement type(intensity and polarization ”I+P” or intensity only ”I only”). The correlation coefficient (cor), mean error (Δh) and mean absolute error ($<\Delta h>$) of aerosol layer heights between RSP and CPL are included.

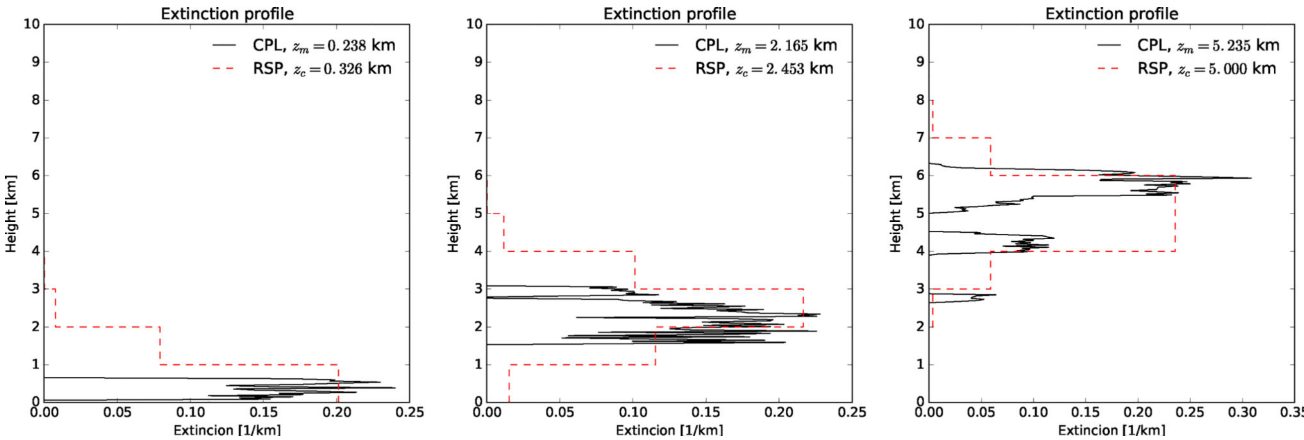

Figure 3.

CPL extinction profile and retrieved RSP height profile comparison for 3 characteristic cases. RSP height profiles are calculated in atmosphere layer grids used in the retrieval.