ADVANCES IN RESEARCH PRODUCTS FROM CALIPSO:
OPTICAL DEPTH DIRECT RETRIEVAL OVER OCEAN, WATER CLOUDS AND LAND

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ABSTRACT
We present a general overview of the recent advancement we made on direct optical thickness retrieval of optically thin atmospheric features (aerosol, cirrus clouds) using CALIPSO lidar return from dense targets (liquid water clouds, ocean and land surface). Data fusion with this direct optical thickness retrieval and collocated passive remote sensing measurements (e.g., PARASOL) will enable an AERONET-like of retrieval concept from A-train measurements. We first present the theoretical advances we made on lidar equation for surface and its significance for ocean color research, then the status of our advancement on aerosol optical depth retrieval along with, an example of cirrus optical depth retrieval over the ocean and a few words on over land AOD retrieval.

1. INTRODUCTION
The quantification of aerosol optical depth and the retrieval of accurate aerosol extinction profiles are of high importance for climate change analysis. Despite the increased sophistication and realism of the aerosol properties retrieval algorithms from spaceborne instruments, discrepancies exist even over ocean regions. Those discrepancies are coming from assumptions on aerosol microphysical properties and cloud clearing algorithm. A significant advancement to this respect is the combined take-off of the A-Train supported by the continued deployment of surface based remote sensing sun-photometer sites such as AERONET which provide direct measurements of Aerosol Optical Depth (AOD). Ground based coverage is however more limited than space observations and lack of coverage may lead to a lack of understanding. For cirrus clouds, there are only few direct measurement of their optical depth. They include in-situ measurements, Sun and Aureole Measurements and lidar when two layer of clear air above and under the cloud may be identified. None of them can address global scale yet. We have shown that we can use different A-Train instruments combined with CALIPSO signal from ocean surface and liquid water clouds to measure directly the AOD [1,2,3]. We will present here our recent advancement in this respect and our first results for ice cloud optical depth, and introduce land AOD retrievals.

2. LIDAR EQUATION
We have recently consolidated the theoretical formalism of the lidar equation applied to the ocean surface. The lidar equation for ocean surface and subsurface for a nadir pointing system (at low wind speed when whitecaps influence can be neglected) can be written as [4]

\[
\gamma = T^2_{\text{ATM}} \left( \frac{\rho}{4\pi <S^2>} + \frac{(1-R_s) T_s R_s}{(1-rR_s) m^2 Q} \right)
\]

\(\gamma\) (sr\(^{-1}\)) is the lidar integrated backscatter coefficient of ocean surface return, \(T^2_{\text{ATM}}\) is the two-way transmittance of the atmosphere, \(\rho\) is the Fresnel reflectance and \(<S^2>\) is the variance of the wave slope distribution more commonly referred to as the mean square slope (MSS). \(R_s\) is the specular reflectance for a rough ocean surface and \(T_s\) is the Fresnel transmission of the air-water interface. \(m\) is the refractive index for ocean water. The multiple scattering is expressed through the use of water–air Fresnel reflection for the whole diffuse upwelling irradiance \(\bar{r}\). \(R_s\) is the underwater reflectance and \(Q\) is expressing the ratio of irradiance to radiance.

2.1 Parallel and perpendicular polarization
At first order, Eq. (1) can be decomposed into parallel \(\gamma_{\text{par}}\) and perpendicular \(\gamma_{\text{perp}}\) polarized signals and can simply be expressed as

\[
\gamma_{\text{par}} = T^2_{\text{ATM}} \left( \frac{\rho}{4\pi <S^2>} + \frac{(1-R_s) T_s R_s}{2(1-rR_s) m^2 Q} \right)
\]

\[
\gamma_{\text{perp}} = T^2_{\text{ATM}} \left( \frac{\rho}{4\pi <S^2>} + \frac{(1-R_s) T_s R_s}{2(1-rR_s) m^2 Q} \right)
\]
A direct follow-on of the validation of the AOD product is the achievement of a direct lidar ratio retrieval at global scale over oceans. This opens a lot of possibilities in term of aerosol typing but also on the coupling between CCSRM and the CALIPSO vertical extinction profiling (multilayer AOD retrieval constrained by CCSRM). It is prospective but the integrated column particulate lidar ratio ($S_p$) retrieval of Fig. 3 shows a qualitatively good agreement with HSRL data. Some differences are observed which have to be investigated. Considering the AOD is smaller than 0.1 and that we expect the lidar ratio retrieval to become more accurate at high AOD, it is a very encouraging result.

Figure 3. Same as Fig. 2 but for the integrated column particulate lidar ratio.

3.1 Lidar ratio retrieval

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3.2 Estimating non sphericity problem in MODIS retrieval

With no assumption made about the aerosol microphysical properties, the CCSRM is a well adapt tool to study the effect of aerosol non sphericity in passive retrievals. Fig. 4 shows the collocated AOD retrieval for CCSRM as a function of MODIS and POLDER for a dust event (2-9 August 2008 West of Saharan desert, the latitude taken for the comparison depends of the day but is included in the 0-25N range). The slope is $1.32X - 0.05$ for MODIS/CCSRM and $0.82X - 0.005$ for POLDER/CCSRM. CCSRM and POLDER are in better agreement than CCSRM and MODIS. This may be an indication of a problem in MODIS retrieval for non spherical particles. The multiviewing angle capabilities of POLDER and direct...
retrieval of CCSRM are indeed expected to provide a better result, however, more research have to be performed before strong conclusions can be reached. We will perform the same comparison using CALIPSO v3 to lower any possible bias coming from lidar calibration and continue the statistical analysis to better understand if non sphericity is a systematic issue or not.

Figure 4. Comparison of CCSRM as a function of MODIS (left) and POLDER (right) AOD at 532 nm for a dust event.

4. ICE CLOUD OPTICAL DEPTH RETRIEVAL

The method we have developed is based on the non attenuation of CLOUDSAT by aerosols. If we want to study ice clouds, we have first to address the radar beam attenuation by cloud particles. Using MPM93 [8], one can find the attenuation for a 4 km thick ice cloud of different ice water content (Fig. 5). As we do not expect to reach an optical depth accuracy better than a few percents in the near future (reaching 0.02 would be half the error bar of MODIS and a great advancement), the ice cloud attenuation can be neglected (an ice water content of 0.1 g.m$^{-3}$ being in the upper range of what we expect to observe).

Figure 5. Effect of the attenuation of a 94GHz wave by a 4km thick ice cloud with different constant ice water content to the retrieved cloud optical depth.

CALIPSO and CLOUDSAT ocean surface echoes can thus be used in combination of water cloud returns to retrieve cirrus optical depth as we showed for aerosols. It provides a reference not affected by cirrus microphysical properties that can be used to better understand the cirrus radiative effect on climate. Fig. 6 shows the optical depth retrieval for a cirrus cloud, for CCSRM, WCM and MODIS. Using CCSRM and WCM retrieval in combination with the 12 micrometer cirrus optical depth provided by the Infrared Imager Radiometer (IIR) onboard CALIPSO should provide useful information on the cirrus microphysical properties as the wavelength variation is depending on ice particles size (the absorption OD in the IR is about half the one at visible wavelength but the ratio increases for small particle sizes).

Figure 6. Top: CALIPSO quicklook showing a cirrus layer at 15 km above the tropical ocean (February 2nd 2008 1847TU). Bottom: cloud optical depth coming from CCSRM (black), WCM (blue), MODIS (red) and IIR (green).

5. LAND SURFACE AEROSOL OPTICAL DEPTH RETRIEVAL

CALIPSO surface return can also be used to retrieve aerosol optical depth over land. We discussed the use of CALIPSO alone to achieve this goal [9,10], and here again, CALIPSO can be used in combination to other A-Train sensors. We are showing on Fig. 7. how a simple combination of CALIPSO and MODIS 2.13 micrometer radiance can be used to retrieve aerosol optical depth for a fire event over the Amazonian forest (24th august 2006 1800TU, north of 15S here). We can see a good overall agreement with MODIS (which is expected to be accurate there as forest is a dark surface). Some work is still needed to address the land surface small scale variations but the goal of over land AOD retrieval using surface information seems quite reachable.
Figure 7. The (half logarithm) ratio of CALIPSO 532 nm surface echo and the MODIS 2130 nm channel (corrected from cosine of zenithal angle and divided by \( \pi \)) and MODIS AOD 550 nm (red dots) as a function of latitude. A high correlation with MODIS is observed.

6. CONCLUSION

We presented here advanced results on direct optical depth retrieval obtained in the frame of the CALIPSO mission. Two big advantage of our method are the high signal to noise ratio and the absence of any microphysical assumption on cirrus or aerosol microphysical properties. A lot of work is still in progress, such as the validation of the ocean surface and liquid water cloud methods as well as for the development of land surface algorithm. Still, the direct optical depth retrieval at global scale opens the possibility of using these bright targets for direct optical depth estimates, and combining it with collocated multi-angle/multi-wavelength passive remote sensing measurements for AERONET like algorithm developments for both aerosols and clouds. And hopefully this type of data fusion approach would drastically reduce the uncertainty of the cloud and aerosol measurements from space and thus open a new era to address the interannual variability and trends of atmospheric radiative forcing and climate energy budget.

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REFERENCES