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Integrating LIDAR simultaneous Photoncounting and Analog detection measurements for the analysis of Arctic Cirrus Clouds

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Abstract: The net radiative cooling or warming of the cirrus clouds is still considered the biggest uncertainty in the climate models, especially in the Arctic region due to a lack of measurements due to extreme environmental conditions. In this regard, Light Detection and Ranging (LIDAR) is considered one of the most efficient photoncounting techniques to measure low intensity signals but often leads to nonlinear signals at higher intensities. Nevertheless, this problem can be tackled if the Analog (AN) and Photocount (PC) signals are combined. Therefore, this study focuses firstly on the methodology adopted to obtain a single glued (AN+PC) backscattered LIDAR profile. Subsequently, the macro-physical properties, including the cloud base and top information, are obtained in this study using the Wavelet Covariance Transform (WCT) technique. This LIDAR will also contribute to the calibration and validation part of the upcoming EarthCARE (2024) mission.

1. Introduction

Clouds can warm the earth by absorbing long-wave radiation (known as the cloud greenhouse effect) or cool the earth by reflecting solar radiation. However, the long-wave radiative flux increases with the height of the clouds in the atmosphere [1]. Cirrus clouds are considered to be cold clouds composed of ice crystals and are located high in the troposphere and can even extend to the stratosphere when temperatures fall below -40°C. Nevertheless, the resulting net radiative effect of cirrus clouds depends on their macro-physical and micro-physical properties. Accurate determination of the macro and micro-physical properties of these ice clouds is necessary for their realistic model parametrization.

The understanding of the optical properties of cirrus clouds can be achieved via in-situ or remote sensing (including ground-based and space-borne) measurements. In this regard, Light Detection and Ranging (LIDAR) is one such promising remote sensing instrument available to study the changing pattern of these clouds with the advantage of performing measurements with high temporal resolution.

Also, we are well aware that there have been a lot of tremendous changes in the energy budget of the Arctic region recently due to the positive feedback effect of the melting of ice. However, precise cloud parametrization of the Arctic is still a challenging task [2]. Considering this, the eventual goal of this study is to make a serious effort to understand the long-term changing patterns in the optical properties of cirrus clouds over Kiruna (68°N, 20°E), situated in the Arctic region, using more than a decade of LIDAR dataset. But for now, the initial methodology involved in the estimation of cloud top and cloud base altitude of the backscattered glued signal will be discussed in detail.

2. Methodology

LIDAR, an optical remote sensing technology, works on the principle of time-of-flight technique, which provides the range distance at which photons are backscattered by estimating the time delay between the transmission pulse and the received photons and hence can be best described with the following equation:

$$P(r,\lambda)=P_0\frac{C}{r^2}\beta(r,\lambda)\,T^2(r) \qquad (1)$$

where $P(r,\lambda)$, is the detected backscatter power, P_0 is the emitted laser pulse power, λ is the wavelength (m), C is the system efficiency of transmitting and receiving optics, r is the distance between the emission of laser and scattering processes (m), $\beta(r, \lambda)$ is the wavelength dependent total volume backscatter coefficient (1/m-sr), and T^2(r) is the probability of two-way (to and fro) single scattering transmission of light, defined as follows:

$$T^2(r)=\exp\left(-2\int_0^r \alpha\,(\mathrm{r},\lambda)\mathrm{dr}\right) \qquad (2)$$

where $\alpha\,(\mathrm{r},\lambda)$ is the wavelength dependent total volume extinction coefficient (1/m). The complete details of the specifications of the LIDAR installed in Kiruna (IRF LIDAR) can be found in [3].

However, there are a few steps involved before the LIDAR equation can be solved or the optical properties of cirrus clouds can be retrieved and hence are discussed as follows:

a). The Analog (AN) signal detects the much stronger backscattered signal in the near range compared to the photoncounting (PC) signal which is used for measuring weaker signals at the far range. Therefore, a combined PC and AN signal are firstly determined. To accomplish this, a conversion factor between the AN and PC signal is established by scaling the AN signal to the PC signal by using the following equation [4]:

$$I_{AN}^{new}=\frac{I_{AN}-C}{k} \qquad (3)$$

where I_{AN}^{new} is the new scaled AN signal, the original AN signal (I_{AN}) is subtracted by a constant background C and divided by a constant k. On the other hand, the PC signal is corrected firstly for dead-time intervals using the formula below [5]:

$$\mathrm{S}=\frac{N}{1-N\tau_d} \qquad (4)$$

where N is the observed count rate, S is the true count rate and τ_d is the system dead time. Also, both the AN and PC signals are background corrected before the glueing can be performed.

The finally obtained glued signal undergoes some corrections such as signal-to-noise ratio and range correction, before the optical properties can be determined.

b). After this, one of the crucial steps in obtaining the optical properties is the careful screening of cirrus clouds. In this study, we have applied the Wavelet Covariance Transform (WCT) technique to the backscattered glued profiles to obtain the cloud top and cloud base altitude information [6]. The WCT function is defined as follows:

$$W_f(a,b)=\frac{1}{a}\int_{z_b}^{z_t} f(z)h\left(\frac{z-b}{a}\right)dz) \qquad (5)$$

where, $f(z)$ is the normalized range corrected signal, z is altitude, z_b and z_t are lower and upper limits of the profile, h is a step function known as the Haar function defined as,

$$\mathrm{h}\left(\frac{z-b}{a}\right)=\{+1,\ \mathrm{b}-\mathrm{a}/2 \le \mathrm{z} \le \mathrm{b},\quad -1,\ \mathrm{b} \le \mathrm{z} \le \mathrm{b}+\mathrm{a}/2,\quad 0,\ \text{elsewhere}\} \qquad (6)$$

where b is called translation and a is called dilation of the Haar function.

c). Once the cloud top and base information is obtained, the next objective is to estimate the optical properties of cirrus clouds using both the following methods:

i). Klett

The Klett method [7] considers the scattering and extinction properties due to both the aerosols and molecular components. Hence, there becomes 4 unknown quantities (including α^{mol} (molecular extinction coefficient), α^{par} (particle extinction coefficient), β^{mol} (molecular backscatter coefficient), and β^{par} (particle backscatter coefficient)) to solve in a single LIDAR equation. Here, β^{mol} can be obtained using the temperature and pressure profiles of the atmosphere as it is linearly related to the density of nitrogen molecules present in the atmosphere.

However, few assumptions are considered for the estimation of the remaining variables (i.e., α^{par} and β^{par}) by considering a relation between the two. For instance, Lidar Ratio ($\mathrm{LR}=\frac{\alpha^{par}}{\beta^{par}}$) is introduced and is considered to be a constant value.

Finally, after including all the assumptions, the modified equation contains the structure of the second-order Bernoulli equation. After solving this equation, the total backscatter coefficient is finally obtained as follows:

$$\beta\,(r)=\frac{RCS\,(r)*\exp\left(2\,(S-S_m)*\int_r^{r_{ref}}\beta_{mol}(r')dr'\right)}{\frac{RCS\,(r_{ref})}{\beta_{aer}(r_{ref})+\beta_{mol}(r_{ref})}+2\,LR\int_r^{r_{ref}}RCS\,(r')*\exp\left(2\,(S-S_m)*\int_{r'}^{r_{ref}}\beta_{mol}(r'')dr''\right)dr'} \qquad (7)$$

where RCS is the Range Corrected Signal and S is Lidar ratio.

ii). Sassen

The retrieval of the total backscatter coefficient using the Sassen method [8] includes the estimation of variable backscatter to extinction ratio for the individual profile, unlike Klett method where the LR is kept constant. The total backscatter coefficient obtained by this method is defined as follows:

$$\beta(r) = \frac{G(z_0,z)}{1-\frac{2\eta}{k}\int_{z_0}^{z} G(z_0,z')dz'} \qquad (8)$$

where

$$G(z_0, z) = \beta_{mol}\frac{S(z)z^2}{S(z_0){z_0}^2}$$

$$*\exp[2(\frac{8\pi}{3}-\frac{\eta}{k})\int_{z_0}^{z}\beta_{mol}(z'')\,dz''] \quad (9)$$

where z_0 denotes the height just below cloud base where the scattering is predominantly due to molecules and corresponds to minima of lidar signal $S(z_0){z_0}^2$, k is the backscatter to extinction ratio, η is multiple scattering parameter. The molecular backscatter coefficient ($\beta_{mol}(r)$) is subtracted from the total backscatter coefficient ($\beta(r)$), to finally derive the cloud (in this case) backscatter coefficient ($\beta_{cloud}(r)$).

3. Discussion

The IRF LIDAR is a backscattered LIDAR installed at Kiruna (68°N, 20°E). It has been in operation since March 2005 till Nov 2018. The receiver system of the LIDAR utilizes photomultiplier modules that were developed by Licel (Berlin, Germany) which allows for the recording of both the backscatter AN and PC signal. In this way the dynamic range of detectors is increased significantly, a feature that is beneficial for cirrus observations where the signal strength can vary considerably. Since the output from the AN signal is in voltage whereas from the PC signal is in counts, scaling is performed to fit the AN signal to the PC signal. Finally, a combined signal includes the dead-time corrected PC signal for a count rate below 10 MHz and an AN signal above this point. A typical example of the glueing performed on the IRF LIDAR on a random day is shown in Figure 1.

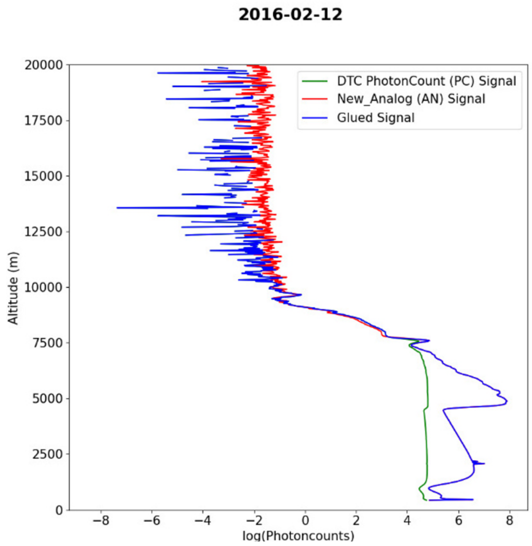

Figure 1. The dead-time corrected PC signal (green), scaled AN signal (red), and combined (or glued) signal (blue) were determined from LIDAR for a random day over Kiruna. Measurement was performed on 12 Feb, 2016 at 10:05 LT and is integrated over 133 sec (4000 shots).

Since the cirrus clouds play a crucial role in the earth's radiation balance, any changes in their altitudes of occurrence can impact how it is trapping the outgoing heat radiations. Therefore, after extracting the combined (glued) single backscattered profile, cloud top and base altitude information are determined using the WCT technique, as explained in the methodology section.

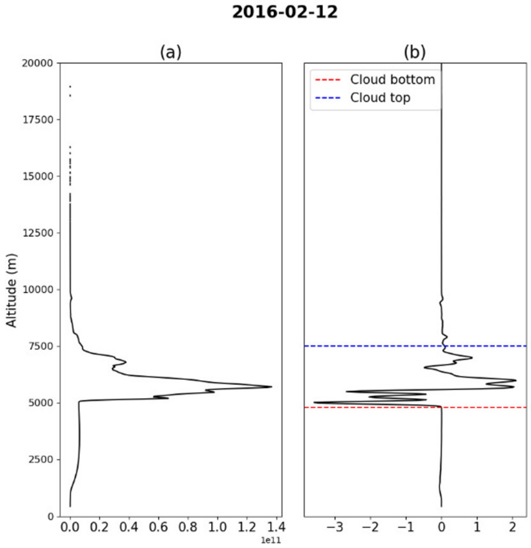

Figure 2. The (a) normalized range corrected signal and the corresponding (b) WCT profile, obtained on a random day over Kiruna. The Cloud top (blue) and base (red) altitudes are superimposed in panel (b).

The characteristic shape of the WCT signal allows for the detection of multiple cirrus clouds present in the signal. A typical example of the extraction of the WCT profile on a random day is given in Figure 2. In this figure, a strong backscattered signal is detected at an altitude ranging from 5 to 7.5 km. A corresponding WCT profile shows the detection of cloud base when there is a steep decrease in the profile followed by a substantial increase in the signal at the cloud top altitude.

Once the ice cloud information is obtained, both the Klett and Sassen methods will be applied to obtain the backscattered coefficients and Depolarization ratio parameters. Ultimately, both of these methods will be used to compare the IRF LIDAR data with the dataset obtained from the EarthCARE satellite project to be launched in May, 2024 (as IRF LIDAR is part of the EarthCARE calibration and validation teams).

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