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Signal analysis for ground based LiDAR

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Abstract

Light Detection and Ranging (LiDAR) is an indispensable active remote sensing tool used to study vertical structure and dynamics. The variations in the atmospheric constituents such as aerosols, dust, clouds, water vapor and temperature can be studied using LiDARs depending upon the operating wavelengths. It is the optical counterpart of the well known Radio Detection and Ranging (RaDAR). This article presents the fundamental approaches involved in analyzing the LiDAR signals. The language used for the signal analysis is MATLAB and the data acquisition board is of ORTEC make.

Keywords: LiDAR, RaDAR, Data Acquisition, atmosphere, MATLAB.

Introduction

Remote sensing is the technique through which a volume or area of the atmosphere is observed to study certain parameters. Atmospheric RaDARs, LiDARs, and satellites are some of the instruments to carry out such observations. Remote sensing is needed to observe our environment and to understand how the atmosphere and the climate are getting affected by human activities. Remote sensing tools have advantage of being able to make multiple measurements from a range of heights simultaneously with high resolution at both space and time, compared to the in-situ measurements[1,2]. They emerge as the best tool to study the dynamically changing environments due to their repetitive capability and synoptic coverage.

The optical probing of the atmosphere is primarily achieved using LiDAR, which probes the atmosphere by two means i.e. ground based as well as airborne or space-borne[3,4]. The LiDAR is an active remote sensing instrument that relies on the propagation of light waves, and its principle of operation is very similar to RaDARs, thus many time refer as 'Optical RaDARs'[3]. The principle of a LiDAR system can be described in simplest way as: a pulse of 'light' emitted towards the sky where the target under investigation is located and its 'echo' is measured some time later. By measuring this time delay and knowing the speed of propagation of the emitted light we get the distance of the target. The 'light' source referred here is always a monochromatic, coherent and directional Light Amplification by Stimulated Emission of Radiation (LASER). The LASER beam travels upward in the atmosphere, interacts with various objects and a part of it is reflected back, which is collected by the telescopes[5]. A generalized schematic of the LiDAR system is illustrated in Figure-1.

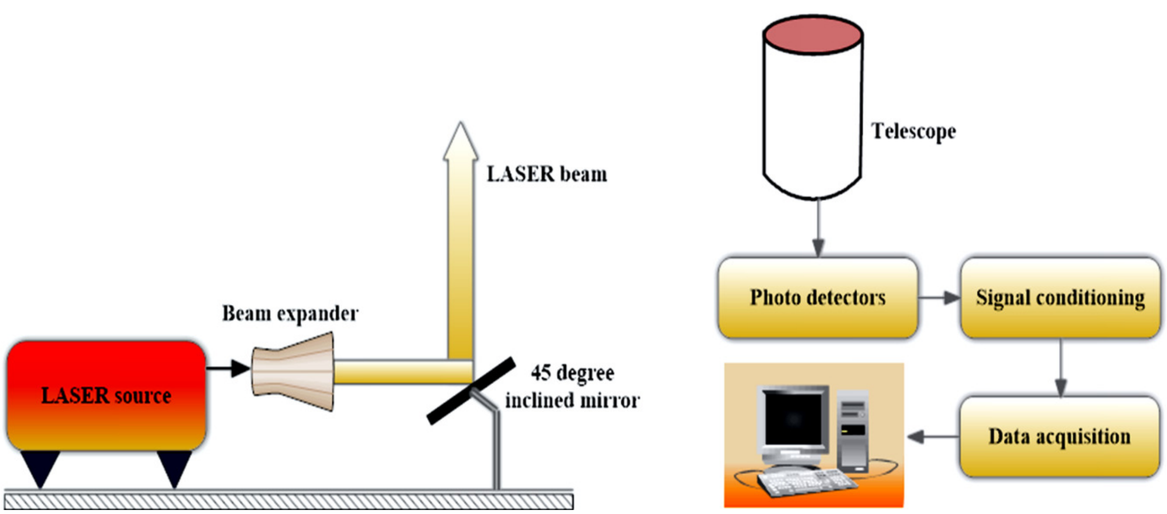

Figure-1: A schematic representing a typical ground based LiDAR instrumental setup.

The ground based LiDAR system plays a vital role in calibration and validation of space-borne missions such as Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO), and sometimes used in synergy with them to study various characteristics of the atmosphere[4,6,7]. With the advancements in technology, the ground based LiDAR systems have now become highly robust, and the use of small diode pumped Neodymium-doped Yttrium Aluminum Garnet (Nd:YAG) and Neodymium-doped Yttrium Lithium Fluoride (Nd:YLF) LASERs, solid state Avalanche Photo Diodes (APDs) photon counting detectors and cost-effective signal acquisition boards, have made the system much compact and portable than the earlier days[8-10].

The LiDAR Equation

The LASER beam probing the atmosphere gets scattered in all directions at all altitudes, and the backscattered echoes are received by the telescopes and their intensities are measured. The intensity of the backscattered signal obtained from any LiDAR system is expressed in terms of an equation, known as LiDAR equation, described as[5]:

$$P(R) = P_T \eta \left(\frac{A}{R^2}\right)\left(\frac{c\tau}{2}\right)\beta(R)\exp\left[-2\int_0^R \alpha(x)dx\right] \quad (1)$$

where, $P(R)$ is the backscattered received power collected by the receiving telescope at a given instance T from height R. P_T is the average LASER transmit power of width τ, c is the speed of light (= 3 X 10^8 m s^{-1}), η is the overall system efficiency factor that depends on both the transmitter and receiver efficiencies, and A is the effective area of the receiving telescope's primary mirror.

Description of general LiDAR system

Transmitter: The transmitter generates the light pulses and direct them into the atmosphere. It usually employs Nd:YAG pulsed LASER as signal source[8]. The source generates an output of 532nm wavelength, 550mJ energy per pulse with a pulse width of 7 n sec and repetition rate of 20 Hz (all the values are the typical values).

Receiver subsystem: The receiver system generally comprises of two independent telescopes: namely Newtonian and Schmidt-Cassegrain type. The Newtonian telescope collects photons from height > 25 or 30km, whereas the Schmidt-Cassegrain telescope collects photons from < 25 or 30km heights. Figure-2 illustrate these two types of telescopes employed for the purpose of collecting backscattered photons.

The collected backscattered photons are converted into electrical signals by using a transducer called Photo Multiplier Tube (PMT). It provides very high gain and low dark current. Other transducers that may be used is APD.

Data acquisition and signal processing: The output of the PMT is obtained through impedance matching network and is fed to pulse discriminator unit, which consists of pulse amplifier, comparator and wave shaping circuit. The output of the pulse discriminator unit is connected to a high-end photon counting data acquisition board called Multi Channel Scalar (MCS) by ORTEC[8]. The typical electronics of the LiDAR system is given in Figure-3.

Use of MCS board to derive spatial photon profile: When a scan starts, the MCS starts counting the input events in the first range and it continues till the last range bin. The time to switch from one range bin to other can be pre-selected from 1 μs to few seconds. If the time taken by the LASER pulse to encounter with the target and return is τ, the range R is given by:

$$R = \frac{c\tau}{2} \quad (2)$$

where, c (= 3 X 10^8 m/s) is the speed of light. The factor 2 in the denominator is due to two way propagation of light wave.

For example,

If $\tau = 1\times10^{-6}$ second, $R = \frac{3\times10^8 \times 1\times10^{-6}}{2}$ = 150 m

Similarly, if $\tau = 2\times10^{-6}$ second, $R = \frac{3\times10^8 \times 2\times10^{-6}}{2}$ = 300 m

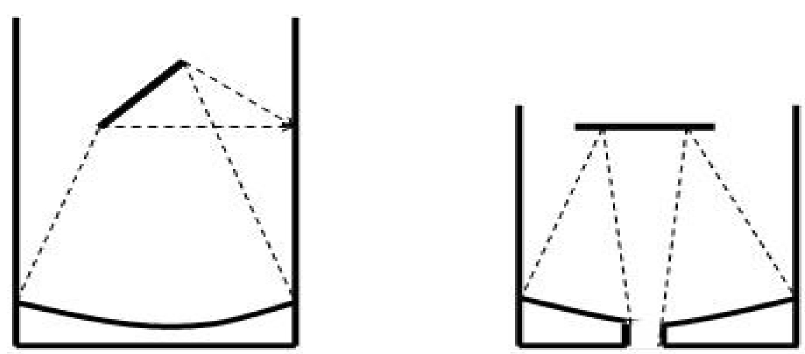

Figure-2: Two types of telescopes used for collection of backscattered photons. Depending upon configurations of primary and secondary collecting mirrors, telescopes are classified.

In other words, τ (sampling time) determines the vertical resolution of measurement. If the data acquisition board samples the data at an interval of 1µs, then it can store the photons scattered from each 150 m layer of the atmosphere. Similarly, if sampling is done at the rate of 2µs, the board can acquire photons scattered from each 300m layer of the atmosphere. If the board has 1024 such range bins, it means data can be acquired up to 1024×300 = 307200m (i.e. ≈307km). But the signal received from higher heights are very feeble and merged into noise and need enough signal processing to get any useful information. Practical observations show that data up to ≈80km has good Signal to Noise Ratio (SNR), and can also be utilized for upper atmospheric studies, which essentially has great advantage, as far as high resolution (temporal and spatial) measurements are concerned. Therefore, we consider the photon profile upto 80km for further processing. This basic relationship is used to analyze the data captured by this board and to plot the height versus photon count. This mechanism of data capturing is illustrated in Figure-4. In all the experiments carried out, sampling time was kept 2 µs.

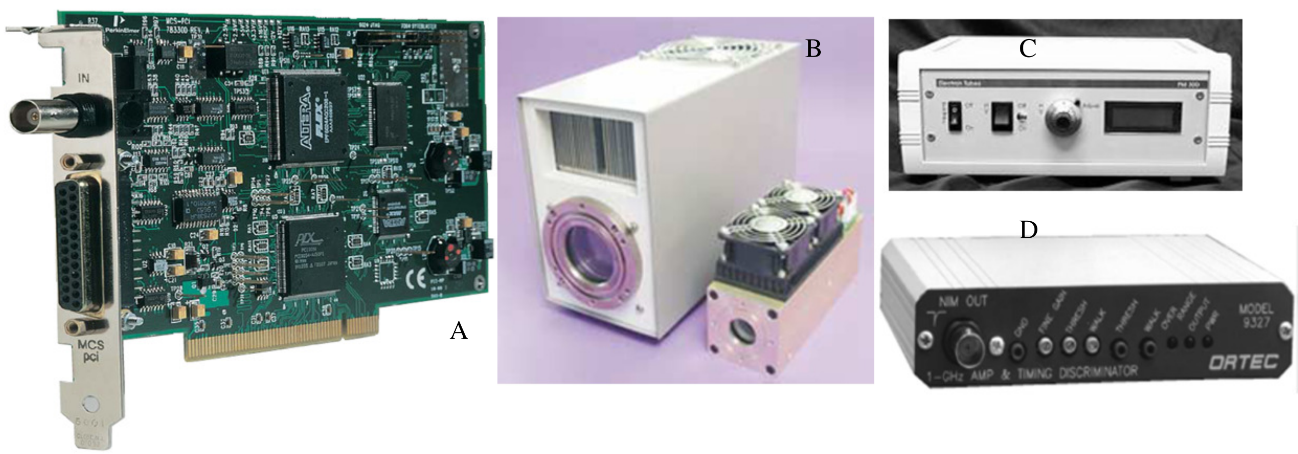

Figure-3: Typical electronics of the LiDAR system – (A) data acquisition board, (B) PMT, (C) its power supply, and (D) pulse discriminator unit.

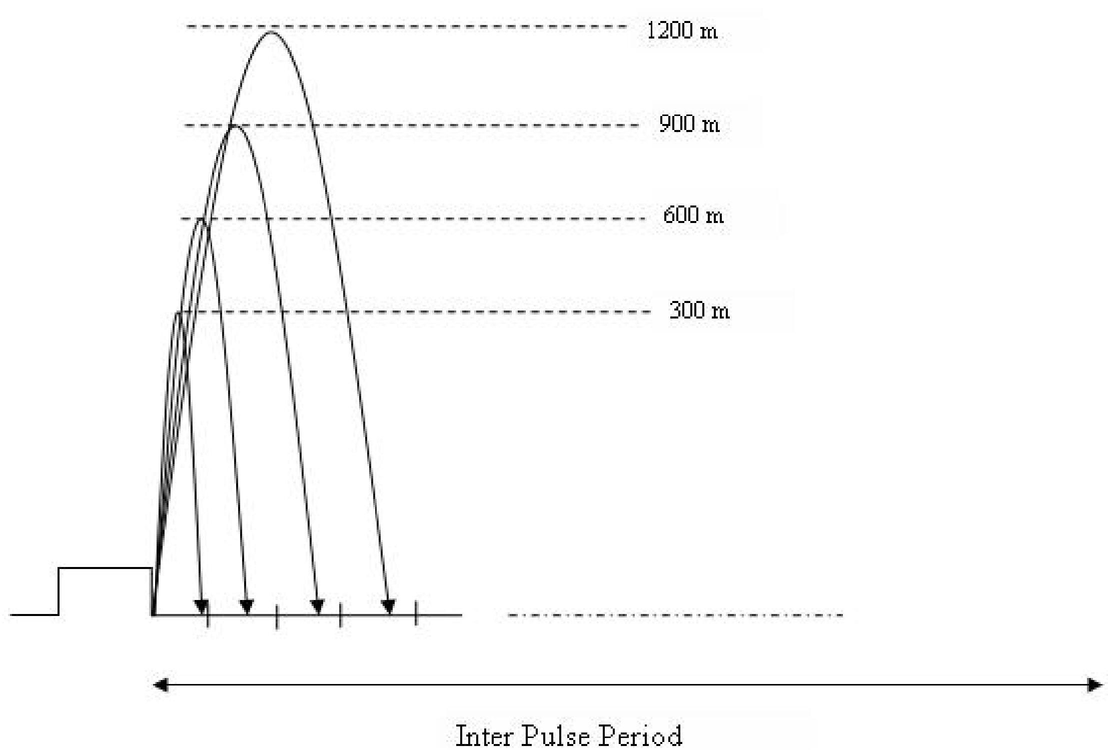

Figure-4: Diagram represents sampling process in inter-pulse period. Each range bin corresponds to one height range and stores the counts in one memory location of board in 32 bit integer format.

The data acquisition board stores the photon counts and many other parameters into binary format. After data acquisition is complete, data is written on hard drive of the PC. The structure of the binary file created by the board is given in Figure-5.

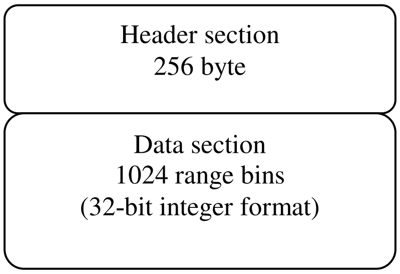

Figure-5: Structure of the binary file, consisting of header and data sections.

If the LASER source has a repetition rate of 20Hz, then it will send 20 pulses per second and there is an inter-pulse period (time difference between two pulses) of few msec, data acquisition is done in this period. Photon counts are sampled at the rate of 2µs, so that we get echoes with a spatial resolution of 300m. It simply means we have the backscattered photon counts at an interval of each 300m of the atmosphere starting from surface to the desires height.

The data acquisition board integrates all the photon counts for the defined time, and the purpose of integration is to improve SNR. After completion of the integration time, the binary file is written to hard drive; data acquisition board resets and starts the same process again.

MCS Spectral Data Files Format: The MCS spectral data file contains the channel-to-channel contents in 32-bit integer format. It has two sections: Header Block and Data Block. The header is 256 byte long and contains many relevant parameters such as start time, start date, dwell time, various calibration coefficients for the board, upper and lower voltage levels etc.

The next part of the file contains the spectrum stored as 32-bit integers, this structure is illustrated in Figure-5. The format is an array of unsigned integers, characters, and float numbers but for programming the data can be seen like below defined pseudo-codes:

```
struct  Binary_Format
{ unsigned trigger;
unsigned dwell time;
unsigned dwell unit;
:
:
char strttime;
char startdate;
float calibration_coefficient;
:
:
Long int data[1024];
};
```

Results and discussion

Simulation results: To interpret the binary information, MATLAB, a very powerful programming language for scientific computing, is used. The LiDAR observation are made in the night time only are often subjected to clear sky condition. After acquiring the data we need to process and analyze it, so that useful scientific conclusion can be drawn. The primary objective is to get a graph of photon counts versus height. In clear sky condition an exponentially decaying curve can be seen, whereas from cloudsthere will be heavy attenuation of the signal. By analyzing this curve, precise location of cloud, its thickness, cloud base and cloud top heights can be deduced. This information is very useful from atmospheric research point of view. As the received signal is sampled in inter-pulse period with a rate of 2µs (typical), we get the desired information from each 300m layer of atmosphere. The echoes coming from higher heights are very weak and merged in the noise, therefore integration is done to improve SNR.

A typical photon profile is always exponentially decaying as it follows LiDAR equation. In absence of any noise the profile will be very smooth. The ideal profile is simulated using LiDAR equation and is shown in Figure-6 (top panel). In practice various factors contributes to measurements such as solar noise, dark current and jitter at receiver. A photon profile corrupted by such random noise is also shown in Figure-6 (bottom panel). Figure-7(a) is the actual photon counts stored in board and Figure-7(b) shows its equivalent interpretation in terms of altitude, with the resolution of 300m.

Further, not only the individual profile but also the photon count profile for entire period of operation can be plotted to study the appearance and evolution of aerosols and clouds in a time span. Thus user can have a view of temporal as well as the spatial data.

Analysis on the actual LiDAR profiles: The LiDAR technique is applied to measure many atmospheric attributes. The most common measurements are the clouds, aerosols, temperature, and water vapor. The binary file contain all these information stored by MCS board. A software is developed to read this information and to convert this binary file into ASCII file.

By observing each profile, the presence of cloud can also be studied. Figure-8(a) shows a typical photon count profile when the sky is clear i.e. free from clouds, whereas the Figure-8(b) shows a photon profile in presence of cloud.

A peak in the profile indicates presence of cloud, also the base and top of the cloud can be measured which gives thickness of the cloud. This measurement is very important to classify different types of cloud structures. The cloud base height is determined from the rising edge in the LiDAR photon profile, whereas the cloud top can be detected from the falling edge in the photon profile. The cloud top determined from the LiDAR profile is not necessarily the real cloud top, for example, when the optically thick clouds are dominant in the atmosphere, the LASER beam in several cases may not able to penetrate them completely, and hence an accurate cloud top information is not obtained

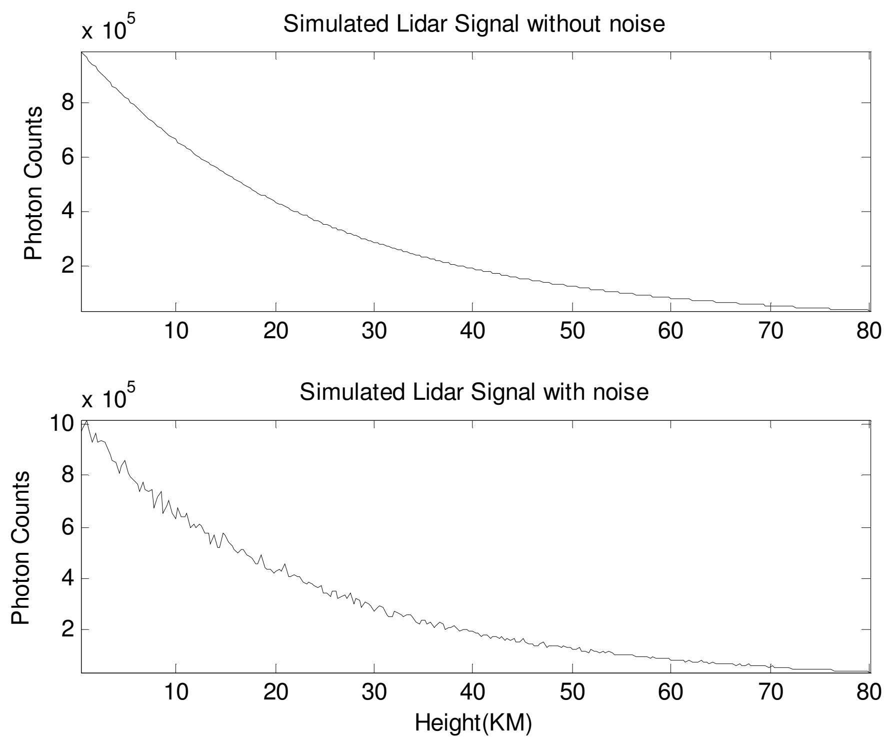

Figure-6: Simulated signal using LiDAR equation with and without noise.

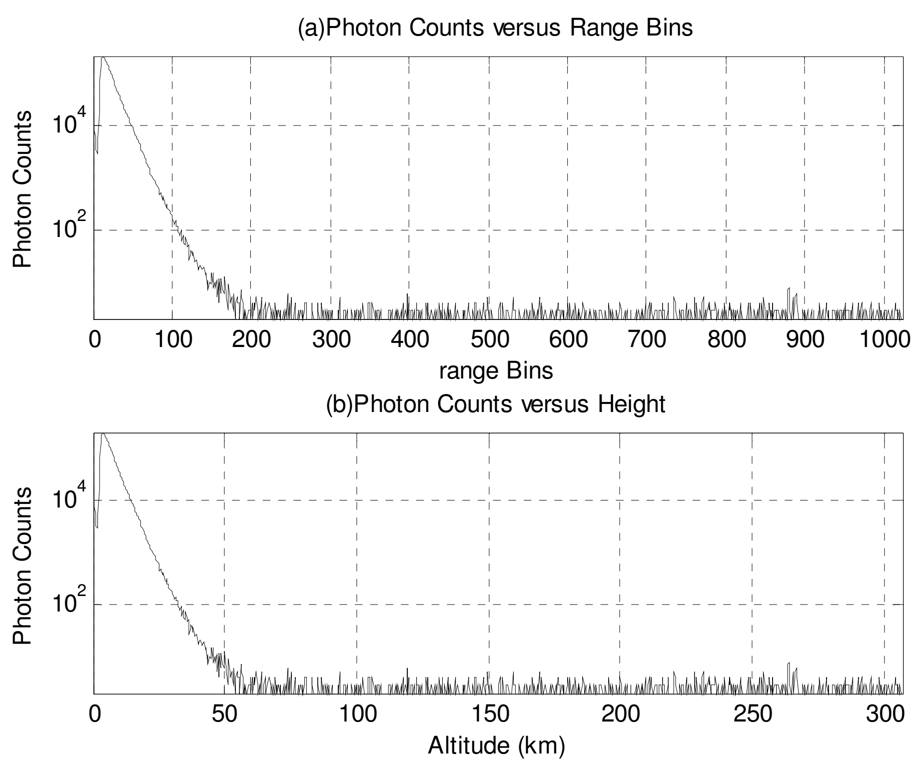

Figure-7: Real photon profile acquired by board, (a) represented in form of range bins, and (b) represented in form of equivalent altitude.

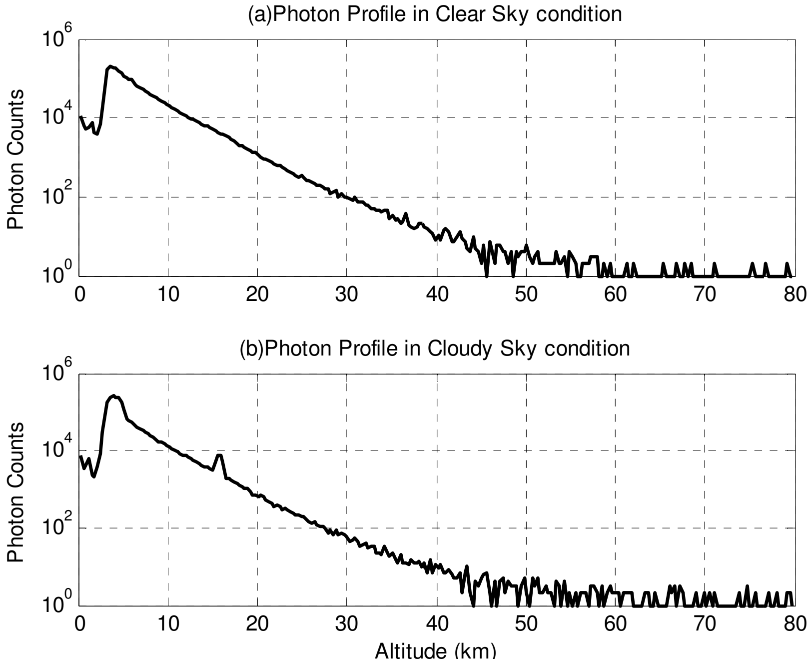

Figure-8: Photon profile captured on (a) clear and (b) cloudy sky conditions. The location of cloud is clearly visible in cloudy profile.

Conclusion

The analysis tool developed for processing the LiDAR signal will be helpful to the researchers who are new in this field. At the same time, the discussion on clear sky and cloudy LiDAR profiles, with or without noise, makes this study a good reference to distinguish between clouds and aerosols.

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