Compact Dual Polarization Lidar System description and data processing

Y.Bhavani Kumar, Member *IEEE*
Project Leader, LIDAR Project
National Atmospheric Research Laboratory (NARL), Department of Space
Gadanki-517112, Chitoor (District), AP, India

Abstract—This paper describes the constructional features of a compact dual polarization lidar (CDPL) system developed for remote sensing the suspended particulate matter and clouds in the atmosphere. The new lidar system employs a rigid biaxial configuration and uses the latest technology in the transmitter and receiver configurations. The low cost lidar system is able to provide the continuous measurement of atmosphere during day and night without pause at very fine spatial and temporal resolutions, first of its kind of development in India.

Keywords-component; Dual polarization lidar; remote sensing; aerosol particles; clouds

I. INTRODUCTION

Rising level of pollutants, particularly those arising from industrial and automobile emissions, is a major concern, both in terms of human health and in terms of global warming. The altitude at which the aerosols are suspended in the atmosphere is an important factor as they can affect the human health as well as the global environment.

Lidars are the best suitable instruments for remote sensing the particle load and clouds in the atmosphere [1-3] because they provide range resolved measurements. Wide varieties of lidar systems have been developed for profiling the aerosol particles and clouds in the atmosphere. However, most of the lidars developed up to now are research-based systems except the technology of micro pulse lidar [4-6]. On the other hand, the available portable micro pulse lidar technology has a limitation in the observational range and needs longer time integration for obtaining the good signal to noise ratio. Moreover, these lidar systems use diode pumped lasers and hence require frequent replacement after a period of operation due to the limited lifetime of the pumping diodes. This process involves enormous cost and downtime.

Novel advances in the solid-state lasers, detectors and data acquisition systems have enabled the development of a new generation of lidar technology that provides sufficient signal strength for conducting studies on the atmospheric dynamics at excellent temporal resolutions. Recently a compact dual polarization lidar (CDPL) system was developed at the National Atmospheric Research laboratory (NARL), Gadanki (13.5°N, 79.2° E, ~375 m above MSL), a rural site in the tropical part of India, for studies related to the atmosphere [7]. The CDPL employs a compact single flashlamp pumped solid-state laser as the transmitter and a pair of mini PMTs associated with the front-end optics as the receiver. The data acquisition and signal processing system employed in the lidar was an advanced transient recorder system that supports both photon counting and analog detection methods. Moreover, the entire system was developed in a compact construction at an effective low cost. The newly developed lidar technology offers several advantages like the observation of atmosphere at any inclined position, measurements at a very fine range resolution (7.5 m), operation during day and night and measurement of atmospheric signals simultaneously using the analog and photon counting techniques. The combination of analog and photon counting allows more than 40 db dynamic range in day and nighttime measurements. However, the only disadvantage of this type of lidar configuration is the lack of eye-safety.

II. CDPL SYSTEM DESCIPTION

Fig.1 The photograph of Compact Dual Polarization Lidar

The CDPL is an independent custom-built system that housed in a movable construction. Fig. 1shows the photograph of the

CDPL system and Tab.1 gives its major technical specifications.

Tab.1 CDPL major technical specifications

1. Laser	:	Nd-YAG, Quantel make,Ultra model
2. Wavelength used	:	532 nm, Nd:YAG 2nd Harmonic
3. Pulse-Energy	:	10 mJ typical, 30 mJ max
4. Repetition rate	:	20 Hz
5. Beam-divergence	:	0.7 mrad
6. Telescope	:	Schmidst-Cassegrainin telescope [150 mm dia and F ratio-10]
7. Field of View	:	Variable from 1.0 to 12 mrad [2.0 mrad typical]
8. Data acquisition	:	Both analog and photon counting
9. Range	:	60 m to tropopause height (day)
10. Vertical resolution	:	7.5 m fine, 30 m typical
11. Size	:	0.7 m^3

Fig. 2 illustrates the arrangement of different parts inside the CDPL. The CDPL is designated as **100** in Fig.2. The CDPL **100** is contained in a mechanical housing having wheels beneath, thereby providing a greater mobility to the system. Further, a titling mechanism is provided to the CDPL, thereby enabling the lidar system for continuously scanning the atmosphere from various angles.

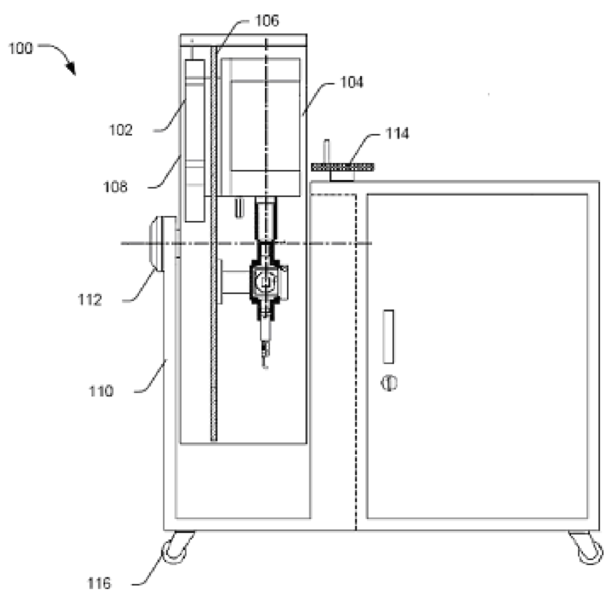

Fig.2 Display of parts inside the CDPL shown with numbers

The CDPL **100** includes a transmitter subsystem **102** and a receiver subsystem **104**. The CDPLS **100** employs a biaxial configuration. The CDPLS **100** further includes an optical separator **106**. The optical separator **106** isolates optical axes of the transmitter subsystem **102** and the receiver subsystem **104**, thereby providing the biaxial configuration. The optical separator **106** aligns the optical axes of transmitter subsystem **102** and the receiver subsystem **104** parallel to each other. The optical separator **106** is hinged to the transmitter subsystem **102** and the receiver subsystem **104** using mechanical components such as shafts and gears. This prevents a mismatch of the optical alignment caused due to vibration. The mechanical housing **108** thus enables a compact arrangement of the LIDAR system **100** for a greater mobility. The mechanical housing **108** is accommodated on a rack **110** having two compartments. The mechanical housing **108** is supported in one of the two compartments of the rack **110** using bearing supports **112**. Further, a titling mechanism **114** is employed on the rack **110** to facilitate tilting of the mechanical housing **108**. This provision of titling the mechanical housing **108** enables the CDPLS **100** to scan the atmosphere from various angles, thereby increasing an area of scanning the atmosphere for aerosol particles. In the present scheme, the tilting mechanism **114** is implemented using a pulley mechanism operated manually. Thus, misrepresentation of the atmosphere due to a vertical LIDAR system is prevented and a better analysis is performed.

A. Laser Transmitter

In the present configuration, a linearly polarized laser source, Ultra model Quantel France make, is employed as transmitter for probing the atmosphere. The used laser source is a Q-switched, single flashlamp-pumped Nd:YAG solid-state pulsed laser. During the operation of lidar, a continuous pulse train of laser beam is emitted from the transmitter subsystem **102** into the atmosphere. The laser operates at 20 Hz repetition rate with a maximum energy of 30 mJ per pulse. The spatial profile of laser at far field is Gaussian in shape. The far-field ($1/e^2$ power) divergence full angle is 0.7 mrad. Fig. 3a shows the photograph of laser source and its controller unit. The internal constructional features of laser are shown in Fig.3b. It is a compact folded resonator (CFR) design, which halves the length of the laser for a given resonator length without significantly affecting other dimensions. The CFR laser mirrors are hard-mounted side by side in the same plane, with a folding prism at the other end. The CFR lasers contain lithium niobate based Pockels cells, which are non-hygroscopic and work properly over a wide temperature range. A cube polarizer is used, which is stable over a wide temperature range. Generally many lasers use KD*P, which must be kept temperature stabilized and is susceptible to moisture. Because of these special features, the laser used can sustain for vertically mounting, rigorous vibrations during mobility and provides very long lifetime for single flashlamp (>40 million shots).

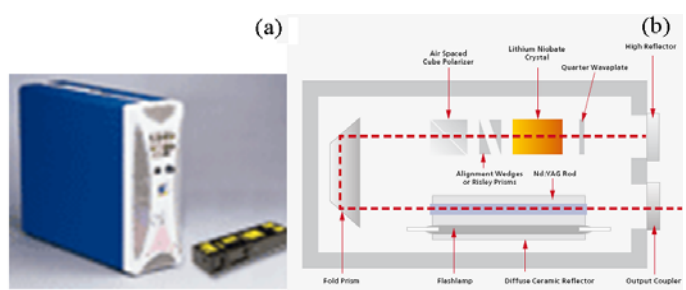

Fig.3 Panels show (a) Compact laser source and its controller unit (b) The compact laser source internal construction details

B. Receiver telescope

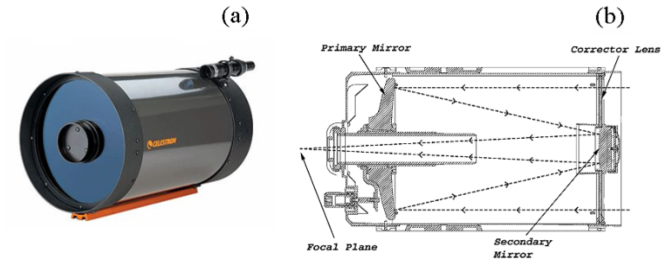

Fig.4 Pictures show (a) Celestron make Optical tube assembly (b) Internal design details of Schmidt Cassegrain telescope

A small telescope is used as the optical front-end for collecting the laser-backscattered photons. It is a Celestron make, optical tube assembly (OTA) model, 150 mm aperture unit. The telescope employs the schmidt-cassegrain design, which is shown in Fig.4. For a given aperture size and F-ratio, the schmidt-cassegrain telescopes are particularly compact in the long-dimension because light traverses almost the whole length of the scope three times between the primary and secondary mirrors. A disadvantage with these scopes is the central obstruction where the secondary mirror is mounted (see Fig.4b). Besides reducing the effective aperture area by 11%, this obstruction has no spatial effect on light scattered from far enough away. The telescope is 33 cm long. Its focal length is specified as 1500 mm (making it f/10), but a focus knob on the telescope back makes the location of the focus variable. The celestron telescope uses XLT star bright coating for the reflecting optics (>90% reflectivity) and covers the spectral range of 400 to 900 nm.

C. Polarization beam splitter assembly

Generally, a field stop assembly controls the receiver field. In the present lidar design, a variable pinhole assembly is used for this purpose. It controls the receive field of view (FOV) setting from 1 to 12 mrad. After the variable field stop a collimating lens (an achromat with a focal length of 80 mm) is used to output the collected backscattered light into parallel rays. The collimated beam is then passed through a narrow band interference (IF) filter. The IF filter used is a custom band pass optical filter (BARR, USA make) with a central wavelength of 532.1 nm. The IF Filter's full-width at half-maximum (FWHM) transmission window is 0.4 nm with a maximum transmission at about 50%. The filter transmission is sensitive to temperature fluctuations. Due to this reason, the CDPL is maintained at a room temperature of approximately 23°C for maximum transmission at 532 nm. The narrowband IF filter discriminates the excited wavelength from the received light spectrum. In lidar, a polarization cube is usually employed for dividing the collected backscatter into Co- (P-channel) and Cross-polarized (S-Channel) signal components. In the present lidar design, a high performance polarizing beam splitter (PBS) cube is used to split the received laser returns into two orthogonally polarized components. The specifications of used PBS are given Tab. 2.

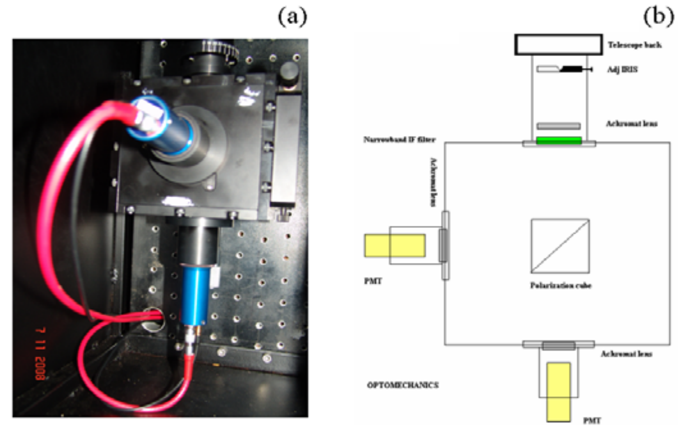

Fig.5 Pictures show (a) light tight compartment containing a field stop, IF filter, field and polarization beam splitter optics, neutral density filters and a pair of detector units. The assembly is provided with a fine adjustment control (100 TPI) for aligning the polarization cube optics (b) internal details of polarization beam splitter assembly

Tab2. Polarization beam splitter optics specifications

1. PBS make	-- CVI optics, USA make
2. Extinction ratio	-- Tp/Ts -- >1000:1
3. Transmission efficiency (Tp)	-- 95%
4. Reflection efficiency (Ts)	-- 99.9%

The photograph and internal details of polarization beam splitter assembly are shown in Fig. 5. A pair of detector units, mini photomultiplier tubes (R7400), convert the collected light photons into equivalent electrical signals. The specifications of mini PMTs used are given in Tab.3. The PMTs are operated in the linear range (HT at about -800 V range) specified by the manufacturer. The outputs of PMTs are digitized using a two channel transient recorder with 50 ohms input impedance. The signals are generally averaged over 600-1200 shots, which correspond to 30-60 sec integration, to achieve a good signal to noise ratio (SNR) profile.

Tab3. Specifications of Mini PMTs, Hamamatsu, Japan make

1. Type	-- Multialkali cathode
2. Spectral range	-- 300 – 850 nm
3. Dark counts	-- 80 counts per sec (CPS)
4. Rise time	-- <2 nsec
5. Operating HT supply (max)	-- About 1 KV DC, Negative

D. Data acquisition and signal processing unit

In general, the majority of lidar detection electronics are optimized for measuring the low-light signal intensities using the single photon counting technique. However, at strong light levels this approach results in a nonlinear signal response. In the real atmosphere, due to the presence of large amount of aerosol particles at the lower heights, the application of photon counting method of detection undergoes nonlinear process and fails to produce the true atmospheric response. So to overcome the turbid characteristics of atmospheric boundary layer, the analog measurement (current mode) of photomultiplier current is therefore necessary in addition to the photon counting signal detection. Because of this reason, the CDPL uses the advanced transient recorder technology offered by Licel, Germany. The transient recorder system employs both analog and photon counting modes for recording the data. The combination of analog and photon count detection techniques greatly extend the dynamic range of receive channels and removes the need of neutral density filters, which in turn greatly improves the signal-to-noise ratio.

Analog and photon counting detection techniques require different signal conditioning background. High speed and high gain amplification is needed for photon counting, whereas a strictly linear amplification below the Nyquist frequency of the A/D converter is necessary for analog measurement. Only the integration of two complete acquisition chains from the preamplifier to the summation memory will therefore enable one to combine both techniques for increased linear dynamic range.

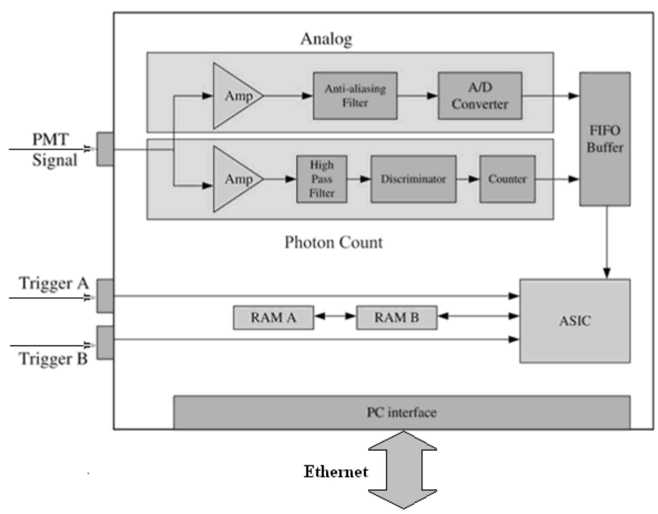

Fig.6. Block diagram of the Licel transient recorder [FIFO-Fist in First Out; ASIC-Application Specific Integrated Circuit]

The TR20-160 model Licel transient recorder system was employed in the CDPL system. It is capable of sampling at 20 MHz and has a memory depth of 4096 bins. A schematic diagram of the transient recorder (TR) is shown in Fig.6. The TR system comprises of two simultaneous detection channels, each with its own pre-amplifiers. The TR system employs a fast transient digitizer with on-board signal averaging, a discriminator for single photon detection and a multichannel scalar combined with preamplifiers for both systems. For analog detection, the signal is amplified according to the selected input range and digitized by a 12-Bit-20 MHz A/D converter. The TR system A/D converter, operated at 20 MHz sampling frequency, was used to build a high end transient digitizer with a signal to noise ratio greater than 74 dB up to the Nyquist frequency of 10 MHz. The analog channel's amplifier is optimised for high linearity, while the photon count channel's amplifier is optimised for maximum speed and gain. The photon counting acquisition system includes a fast three-stage preamplifier and a discriminator with 64 threshold levels, controlled by the host computer. With a maximum count rate of 250 MHz, the single photon counting is pressed to new limits when the preferred photomultipliers are used. The data is buffered in a first-in-first-out (FIFO) buffer, before being accumulated in the respective random access memory (RAM) bank. Each sample is checked for over range to control clipping in the average signal. A time resolution of 50 ns (7.5 m range resolution) without any dead time or overlap between two memory bins is reached by using a continuous counter together with a multichannel scalar burnt into the silicon of a custom designed chip (ASIC). The key specifications of the transient recorder are shown in Tab. 4. The TR system was procured with the Lab VIEW software, which allows the experimenter to acquire signals without the need for immediate programming. The control and communication of TR system was accomplished with a Laptop system through Ethernet connection. This universal type of interface can support the required data transfer rates and eliminates the need for additional interfacing hardware.

Tab. 4. Licel Transient Recorder specifications

Parameter description	Parameter value
Analog acquisition	
Voltage ranges	20/100/500 mV
Sampling rate	20 MHz
Resolution	12 bit
Photon count detection	
Maximum count rate	250 MHz
Threshold	0–100 mV
Discriminator	64 levels (Software controlled)
LIDAR spatial resolution	7.5 m
Trigger	
Threshold	2.5 V, 50 ns rise time
Memory depth	4096 bins
Personal computer interface	Ethernet
Spurious free dynamic range	74 dB
Protection	Diode clamped
Coupling	50 Ohm, DC
Trigger delay and jitter	50 ± 12 ns

The acquired data using the TR system are stored in an ASCII-binary data format. The first three lines of data file are given in ASCII form. This indicates the header information. The header describes the details on location of measurement, timings of start/stop of the experiment, number of laser shots employed, repetition rate of the laser etc. The header is followed by the dataset in binary form. The lab VIEW offline software can read the binary data stored. This software provides information on the archived analog or photon count dataset such as the PMT voltage set, the laser wavelength used, polarization employed, the setting of analog voltage range and the photon count discriminator level set. The unique feature of lab VIEW software supplied along with the TR system is such that it allows the experimenter to infer the recorded data simultaneously while the CDPL is in operation. The real-time data under observation can be visualized in several styles such as raw form, noise corrected form and range corrected form using the available features of the software supplied along with the TR system.

III. LIDAR DAY AND NIGHTTIME PERFORMANCE

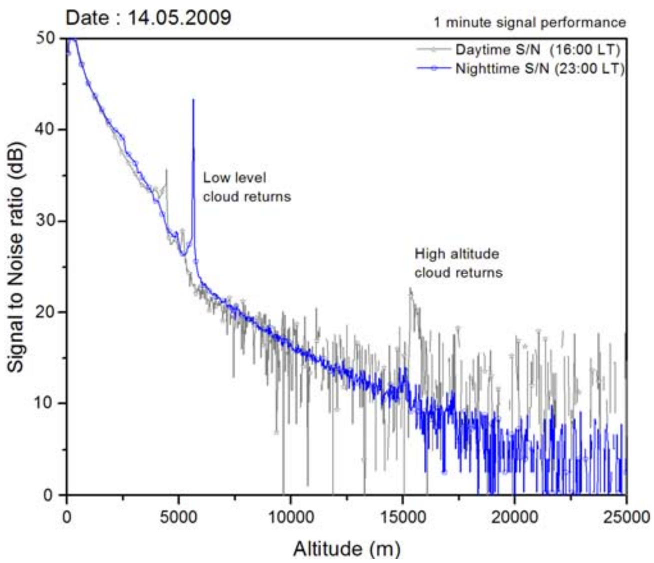

Fig.7 Day and nighttime performance of lidar system

The CDPL has been in operation at NARL site since 2009. The unique feature of CDPL system is its day and night functional capability. Usually the lidar system is operated at a laser energy setting of 10 mJ per pulse. The data acquisition at 1200 shots per file with 30 m of vertical resolution permits the atmospheric high resolution analysis per minute. The typical lidar performance during day and night is shown in terms of signal to noise ratio (SNR) in Fig. 7. The SNR computation shown is relevant to analog signals only rather than the photon count output from the detector. This is due to the fact that the photon count detection process fails during daylight hours [1]. The lidar measurements shown were conducted at lidar site on 14 May 2009 at 16:00 and 23:00 LT respectively. The lidar daytime action presents the clear detection of local dust layer and high altitude clouds. The lidar daytime data displays the location of local mixed layer top at around 5km and the profile beyond this indicate Rayleigh scattering from atmospheric molecules conspicuously seen up to 15 km height. An occurrence of high altitude cirrus cloud was clearly sensed as a strong spike at an altitude of 16 km above ground level. This type clouds are known as cirrus (ice clouds) which play significant role in atmospheric environment and climate [7-8]. The nighttime performance of lidar system is also shown for analog output of the detector for the measurement made at 23:00 LT. The nighttime measurement shows signal profiling capability beyond 20 km altitude. A thin layer of cloud was observed as a sharp spike at 5 km altitude due to passage of low level clouds over the lidar site during the period of observation. Since these clouds are generally optically dense, light is prevented from passing through.

However, the combination of simultaneous analog and photon count (PC) data offers the extension of lidar range beyond 25 km. This requires post processing analysis, which involves merging of the analog and PC datasets into a single return signal. Generally combination of analog and PC signals permit experimenters to employ the analog data in the strong signal portion and the PC data in the weak signal region. Since the output from the analog data converter is given in terms of voltage (V) and the output from the photon counter is generated in terms of counts or count rates (MHz), we need a conversion factor between these two outputs to make a 'virtual' profile. This virtual profile preparation is given in detail by Newsom *et al* [(2009)]. In the first step, the merging algorithm employs conversion of photon counts to count rates in units of megahertz, and the raw accumulated digitized analog values to millivolts. Later, the electronic background level is measured and deducted from the respective channels data. Initially the PC is corrected for dead-time correction and analog signal is corrected for delay [9].

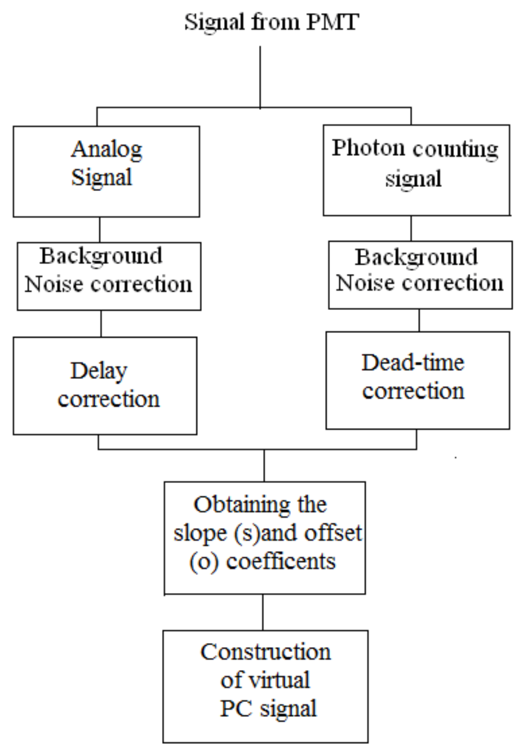

Fig.8 Flowchart showing the steps involved in the construction of virtual PC signal

Later, the dead-time corrected virtual photon count signal is then shown by the relation, PC = s* AS + o, over a range where the PC data reacts linearly to the analog signal [AS]. Here s is the slope and o is the offset, which are referred as glue coefficients. These coefficients are computed by the linear regression method employing the least squares fitting. This process is performed in the offline analysis and the steps involved in the process are shown in Fig. 8 in form of a flowchart.

IV. TEMPORAL PERFORMANCE OF CDPL SYSTEM

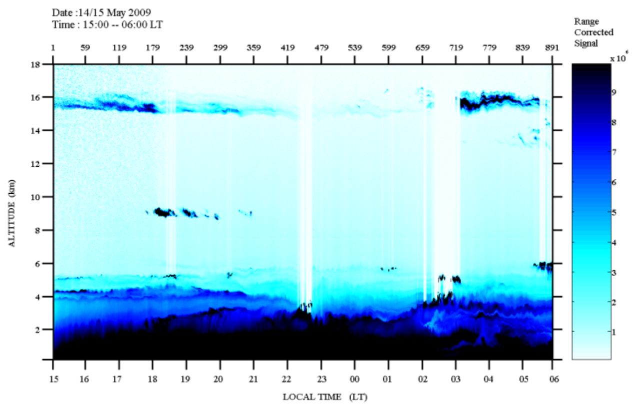

Fig.9a. The CDPL detection of aerosol particles and high altitude clouds. The lidar was operated continuously between 15:00 and 06:00 LT during 14-15 March 2009.

The lidar system has been operated on many occasions both in day and night periods. The typical observation presented here indicates the day and night performance of the system. This experiment was conducted to verify the performance of the CDPL during day and night transition. This measurement was commenced on 14 May 2009 at 15:00 LT and then it continued to the next day morning up to 06:00 LT. The continuous 15-hour measurement covering day and night is shown in Figures 9a and b. These measurements are performed at 30m range resolution and one minute time sampling. The measurements were presented in terms of height-time intensity maps. Fig.9a illustrates the range corrected backscatter intensity data over 15 hour period. This data illustrates the presence of thin high altitude cloud layer [Cirrus] located at 16 km height much above the local dust layer.

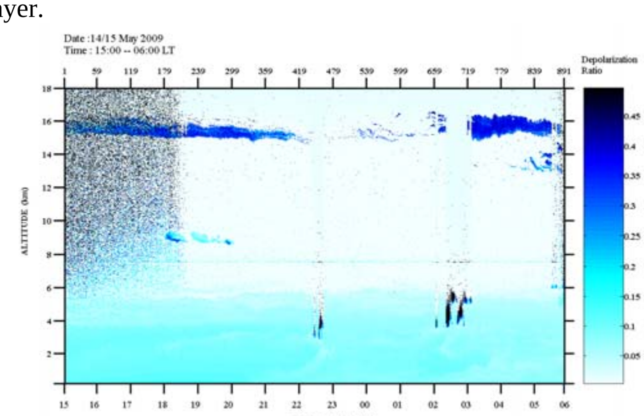

Fig. 9b. Height-time variation of total depolarization ratio showing the presence of dust and ice clouds in the atmosphere. This data was recorded on 14 May 2009 between 15:00 and 06:00 LT at the NARL site

The importance of measurement is the detection of high altitude cloud during the bright daylight hours. Moreover, an elevated local dust layer was detected clearly on this day. This could be due to the strong surface temperatures that are common in summer months. A few patches of low-level stratus clouds were seen at 9 km altitude during the transition period. Fig. 9b is presented as the height-versus-time zenith-lidar displays of the total depolarization ratio [TDR][δ]. The TDR is an indicative of the presence of non-spherical particle content or dust in the atmosphere. The measurement shows that the lower atmosphere is mixed with the non-spherical aerosol particle content [dust]. The detected high altitude cloud contains stronger depolarization indicates the presence of ice crystals, which are generally non-spherical in shape [8].

ACKNOWLEDGMENT

The author would like to thank the officials of National Atmospheric Research Laboratory (NARL), Gadanki and Atmospheric Science Programme (ASP) office of Department of Space, ISRO Head quarters, Bangalore, for funding the project *BLL development and studies* under which the present study is carried out.

REFERENCES

[1] V.A. Kovalev and W.E. Eichinger. Elastic Lidar - Theory, Practice, and Analysis Methods, Wiley Interscience, 615 pages, 2004.
[2] Weitkamp, Claus. LIDAR: Range-resolved optical remote sensing of the atmosphere, Springer, 460 pages, 2005.
[3] T. Fujii and T. Fukuchi . Laser Remote Sensing, CRC Press, Taylor & Francis Group, 888 pages, 2005.
[4] J.D. Spinhirne, J. D. Micro pulse lidar, IEEE Trans. Geos.Rem. sen.,**31**, 48-54, 1993.
[5] N. Lagrosas, Y. Yoshii, H. Kuze, N. Takeuchi, S. Naito, A. Sone, H. Kan. Observation of boundary layer aerosols using a continuously operated, portable lidar sytem, Atmos. Environ., **38**, 3885-3892, 2004.
[6] Y. Bhavani Kumar. Portable lidar system for atmospheric boundary layer measurements, Opt. Eng. **45** (7), 076201-5, 2006.
[7] Y. Bhavani Kumar, Development of LIDAR techniques for environmental remote sensing and mathematical analysis of atmospheric data, Doctoral thesis submitted to Sri Venkateswara University, 2009 (Awarded).
[8] Y. Bhavani Kumar, C.Nageswara Raju, and M. Krishnaiah. Indo-Japanese Lidar observations of tropical middle atmosphere during 1998 and 1999, Adv Atm Sci, **23**(5), 711-725, 2006.
[9] Rob K. Newsom, David D. Turner, Bernd Mielke, Marian Clayton, Richard Ferrare and Chitra Sivaraman, Simultaneous analog and photon counting detection for Raman lidar, App.Opt., **48** (20), 3903-3914,2009

AUTHORS PROFILE

Dr. Y. Bhavani Kumar presently working as the Project Leader for LIDAR project at NARL. He has developed several lidar systems such as portable micro pulse lidar, Resonance Lidar, Dual polarization Lidar, Infrared backscatter lidar and recently Raman lidar for studies related to the atmosphere. He is currently a member of IEEE and the Fellow of Optical Society of India.