STUDIES ON NOISE AND SIGNAL TO NOISE RATIO IMPROVEMENTS FOR MIE LIDAR

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Abstract**—** A Multi-wavelength laser radar has been designed and developed in-house and made operational at the location Cheeryal Village (17.51° N, 78.62° E), which is at about 20 Km in the suburbs of Hyderabad, India. The Nd:YAG laser (make M/S Bright Solutions, Italy) based multi-wavelength lidar operates at 532 nm and 1064 nm with a pulse energy of 50uJ at both the wavelengths. The two wavelengths are generated coaxially with a pulse width of 10ns and the laser operates from single shot to 4 KHz of PRF. The receiver system consists of a 360 mm Newtonian optical telescope, 10 nm of interference filters and 250 MHz Photon Counting recorder (make M/S Licel Gmbh, Germany). Radars and Lidars probe different layers of atmosphere mostly using pulsed mode of operation. In this paper, some of the critical intricacies of data acquisition and processing systems are discussed. The atmospheric Radars and Lidars require a significant amount of data to be collected to find periodicities of atmospheric phenomena which have large time constants. The atmospheric signals have got a broad dynamic range of the order 10-12 decades. Many times, signals are buried in noise and cross-correlation, and averaging techniques have to be used for extraction of signals from noise. The atmospheric Radars and Lidars have to use processing techniques.

Keywords— Lidar, Remote sensing, noise, signal to noise ratio, averaging

I. INTRODUCTION

Study of the Earth's atmosphere is done by various methods such as Balloons, Rocket, and satellite-borne experiments and by Ground-based Radars. Each method has its advantages and disadvantages. The Satellite-borne measurements have the tremendous advantage of global coverage whereas Rocket-borne and Balloon-borne instruments provide an accurate snapshot of vertical profiles of atmospheric parameters at selected locations. The Ground-based Radar systems have the advantage of using large powers to probe the atmosphere not necessarily restricted to a single direction and can collect returns from the atmosphere in a reliable and consistent way

Lidar is analogous to Radar with a major difference in the wavelength of electromagnetic radiation used for probing. In Lidar, a laser light pulse is sent into the atmosphere and is backscattered signal is measured using the optical detectors. The emitted laser beam interacts with the atmospheric constituents, causing alterations in the intensity, state of polarization and wavelength of the backscattered light. From the measurements of these parameters of the received backscattered light, one can deduce the properties of the atmosphere and its constituents. The distance to the scattering medium can be deduced with high accuracy from the time delay of the return signal. As the laser is pulsed, Lidar methods allow range-resolved measurement to obtain a vertical profile of the atmospheric parameters. Lidar systems can be operated in the wavelength range extending from the ultraviolet to the infrared (UV to IR) by using different types of lasers.

Elastic lidars, in which the transmitted and scattered back signals are at same wavelengths, aims to detect Rayleigh and Mie scattering from atmospheric gas molecules and aerosols respectively. These types of scattering are characterized from the detection of a photon by a gas molecule or dust particle in an elastic collision, meaning that the energy of the photon is conserved. It can map aerosol concentration in the atmosphere and to determine aerosol particle size (Hess *et al.*, 1998). This makes lidar an enormously useful tool for investigating air-quality, both generally and in the context of agricultural operations in particular. In fact, the use of lidar to map particulate matter (PM) concentration and estimate aerosol emission rates from an agricultural facility has been demonstrated previously, and lidar has been proven to be a versatile tool for investigating atmospheric aerosols and a useful means of characterizing and monitoring the air-quality impact of industrial and agricultural operations (Guasta *et al.*, 1994). The field of laser remote sensing has grown rapidly in recent years. The growth has been stimulated by the potential application of remote sensing systems to a wide variety of atmospheric measurements.

II. ATMOSPHERIC RADARS

Atmospheric Radars deal with distributed targets. The Radar equation for distributed target is

$$Pr = [PtG^2\lambda^2\Theta^2 h/512\,\pi^2 R^2]\,\sigma i \quad (1)$$

where
Pr =Received power
Pt =Transmitted power
G =Gain of the antenna
λ =Wavelength of the Radiofrequency used
Θ =Beam width
h =cτ. c is the velocity of the light, τ is the pulse width of the transmitted pulse
R = Range of the target
σ = Targets scattering cross-section

The Atmospheric Radars operate at different RF carrier frequencies, pulse repetition frequencies (PRF) and pulse widths (PW) to probe different layers of the atmosphere like Troposphere, Stratosphere, Mesosphere, and Ionosphere extending up to heights of several hundred Kilometers. These Radars operate in HF, VHF and UHF bands and are used to study Turbulence, Winds and Wave motions. Data Acquisition Systems along with online processing facilities to handle large amount of data are used for long periods of observation extending up to 'days'. The data collected can give results with good resolutions in Doppler Speeds and height. The Atmospheric Radars employ Doppler beam swinging technique to measure the vertical and horizontal Velocities of the different layers of the atmosphere. The electromagnetic energy is radiated into space by antenna array with switchable beams in different directions. The backscattered signals from different layers are passed through coherent Receiver where the signal is phase detected using two reference signals having Quadrature phase relationship. The In-phase and Quadrature phase components (I &Q) of the two-phase detectors have all the information contained in the backscattered received signal Viz., signal strength, range of the target and the magnitude and sign of the Doppler shift frequency suffered by the incident RF signal. Vertical motion can be studied by the Zenith beam, E-W and N-S motions can be studied by oblique beams. Also, E-W and N-S asymmetry can be studied by diametrically opposite beams.

The block diagram is shown in Figure 1. The Radar controller generates all the timing pulses and commands for the transmitter, Antenna, and Receiver. These include the transmitter pulse at proper power, pulse width PRF, antenna beam direction n and selection of bandwidth for the receiver system in relation to the pulse width. The timing diagram shown in Figure 2 gives the sequence of events. The Radar control software sets the parameters for data acquisition like number of pulses, number of range gates, sampling window within the interpulse period. A data acquisition scheme will be generated by the computer in an interactive mode and will be recorded in an Experiment set up file. Programmable timers are used for generating sampling pulses. The acquisition unit acquires data from the receiver and digitizes the data and records the data into computer Memory.

Present Atmospheric Radars make use of phase coded sub-pulses instead of a single wide pulse. The signal to Noise Ratio corresponds to the wide pulse and the Range resolution corresponds to the sub-pulse. Generally, Barker codes or Complementary codes are used for phase coding. These codes have a Peak autocorrelation output for zero shift and at all other bit time shifts, they have low autocorrelation outputs. Complementary codes make use of two types of codes. The side lobes of the first code (code A) are opposite in sign to the second code (code B) where as the main lobe at Zero-bit time shift is having the same sign. By combining the outputs of the correlator for both codes gives rise to an output of double the peak value at zero shift and zero output at all other time shifts. Atmospheric Radars allow us to make use of this type of codes because the atmospheric phenomena which we are studying are having time constants more than time interval between two transmitter pulses.

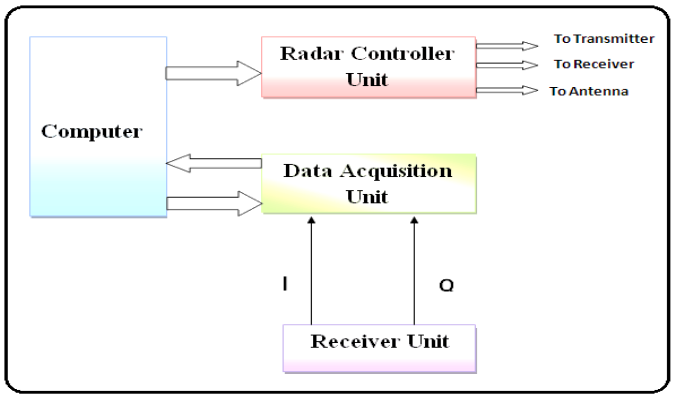

Figure 1. Block diagram of Data Acquisition and a processing unit for Atmospheric Radars

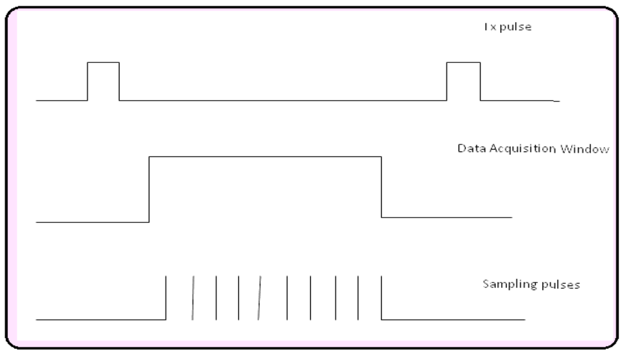

Figure 2. A timing diagram for Data Acquisition

III. Sub Units of a Data Acquisition System

Subunits of a Data Acquisition System for present-day state of the art, Atmospheric Radars are

1) Analog to Digital Converter
2) Digital Down Converter
3) Decoder
4) Coherent Integrator
5) FFT Computing unit
6) Spectral averaging unit
7) Moments Estimation unit
8) Velocity vectors computation (u, v, w) unit
9) Display unit

Figure 3 shows subunits of the data acquisition system

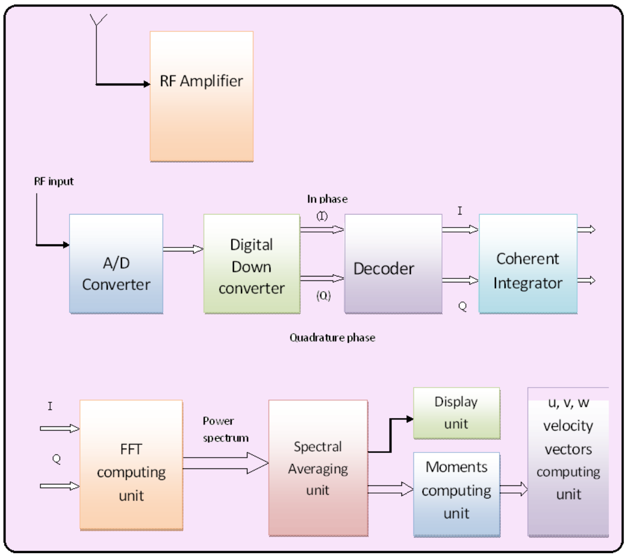

Figure 3 Subunits of the Data Acquisition system

IV. Unique features of present-day receiver unit of an atmospheric Radars

Atmospheric Radar receiver makes use of bandpass sampling for direct down conversion. When the signal is a baseband signal (a signal with frequency content from DC to fmax), the Nyquist sampling rate is 2fmax. For bandpass signals, however the sampling rate is 2(fh-fl) where fh is the highest frequency component and fl is the lowest frequency component of the bandpass signal. The sampling frequency is fs satisfying the following conditions

$$(2fh/K) \leq fs \leq 2fl/(K-1) \quad (2)$$

where K is restricted to integer values that satisfy

$$2 \leq K \leq fh/(fh-fl) \text{ and } (fh-fl) \leq fl \quad (3)$$

These equations show that certain ranges of sampling rates can be used if spectrum overlap is to be prevented. Bandpass sampling can be used to down-convert a signal from a bandpass signal at an RF or IF to band pass signal at lower IF or '0'IF. Since the band pass signal is repeated at integer multiples of the sampling frequency selecting the appropriate spectral replica of the original band pass signal provides the down conversion function. Band pass sampling enables us to use lower sampling rates for ADC, at the same time input bandwidth of ADC is sufficiently high to take care of the RF carrier and side bands. For atmospheric Radars typical probing frequency is 50 MHz. 14 bit ADCs with input bandwidth of more than 200 MHz with conversion speeds of 70MSPS are available and can be conveniently used for 50 MHz atmospheric Radars. In such case Quantisation noise power is

$$(LSB)^2/12R_{in} \quad (4)$$

where Rin is the input resistance of the ADC which is normally made equal to 50 Ω for high-speed applications. For a 14 bit ADC with a full scale range of 2.5 Volts and 50 Ω input impedance the quantization noise works out to be equal to -74dBm. Receiver noise power for a 50 MHz receiver with a bandwidth of 1 MHz (1 µs transmitter pulse width) and with thermal noise equivalent temperature of 30000 K works out to be equal to

$$Prn = -164dBm + 10logBW(Hz) + NF(db) \quad (5)$$

$$= -164dBm + 60dB + 6dB = -98dBm \quad (6)$$

where NF is the noise figure of the receiver, 6dB

The ADC noise is -74 dBm whereas the receiver noise is -98 dBm. Therefore a gain of +24dB is required to boost the receiver noise to the quantization noise power of ADC. AGC is required before the ADC, so that receiver noise roughly equals the quantization noise for low-level signals and the input power does not exceed the ADCs FSR for high-level signals.

Theoretically for ADC SNR is

$$6.02n + 1.76 + 10log(fs/fh - fl)dB \quad (7)$$

Time jitter less than 0.2 ps is required for a 14 bit ADC for digitizing 50 MHz RF signal to limit the SNR deterioration.

The Digital receiver which makes use of the latest technology provides a dynamic range of more than 70dB with an Image Rejection Ratio(IRR) of more than 60dB.

$$IRR = \{-6 + \log(\varepsilon^2 + \delta\theta^2)\}dB \quad (8)$$

where ε is the amplitude imbalance and δθ is the phase imbalance expressed as fractions in the I & Q channels of the Receiver system. Present day desktop PC with Intel dual core processor having MIPS rating of the order of 100,000 Flops rating of 5000 take 10µs for computing 1024 point complex FFT.

V. Description of the present Lidar System

The Lidar system has been designed developed and operationalised for regular scientific studies on aerosols and clouds in the atmosphere. The Schematic diagram of the Lidar system developed is shown below in Figure 4. Figure 5 and Figure 6 shows mechanical drawing and photograph respectively.

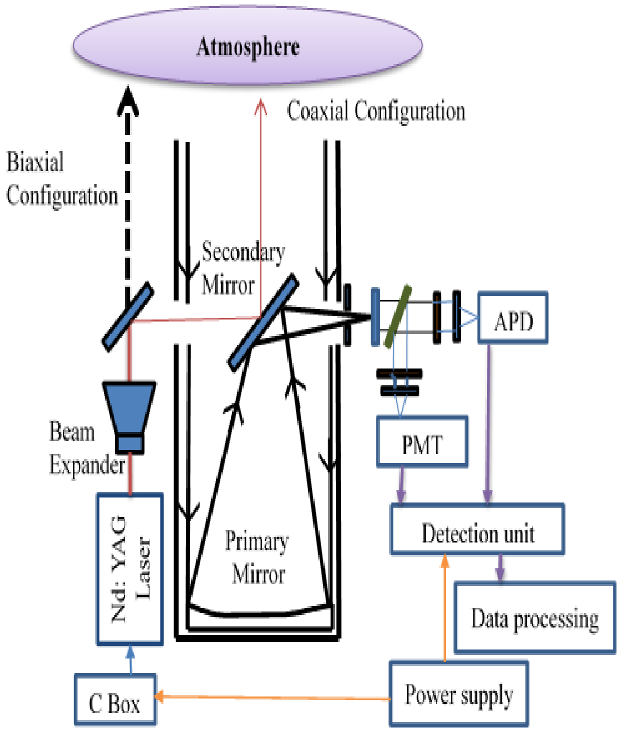

Figure 4. Schematic diagram of the lidar system developed

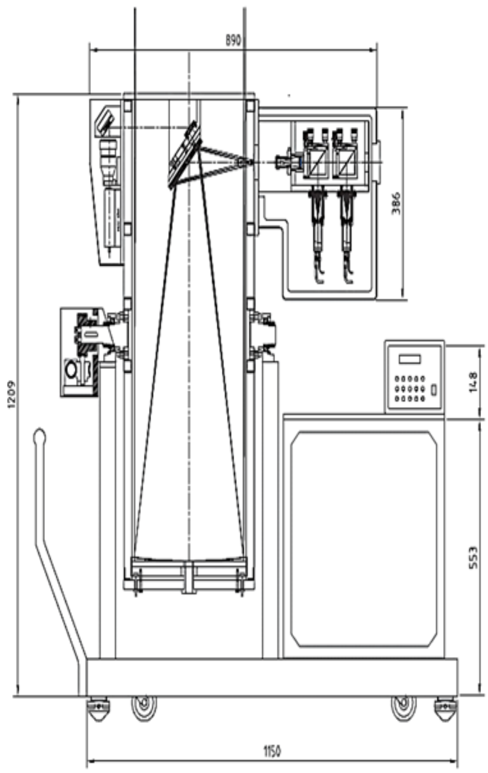

Figure 5. Mechanical drawing of the Lidar system

Figure 6. Photograph of the Lidar system

VI. SOURCE OF NOISE

The noise may be generated by the randomness associated with the detection of a signal (shot noise), the leakage current from the detector (dark current noise), or the current flowing through a resistor in the detection circuit (thermal noise or Johnson noise). Other sources of noise are stray light striking the detector that is not from the intended source (background noise), and noise in the post-detection circuit caused by an amplifier (amplifier noise). Probability density functions representing both signal and noise distributions, with a graphical representation of the probabilities of detection, false alarm and missed detection are shown in Figure 7.

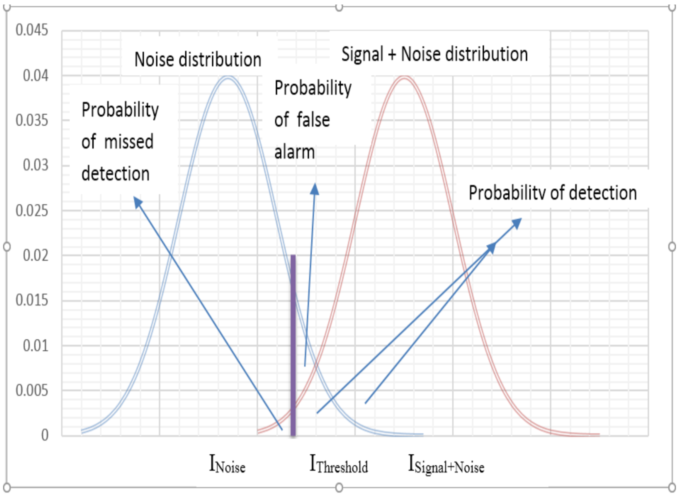

Figure 7 PDF of a Lidar return

VII. SIGNAL TO NOISE RATIO

The performance of an elastic Lidar is characterized by the detection range satisfying an appropriate SNR. The backscattered signal power from any altitude is given by the equation

$$P(r) = P_0 \frac{c\tau}{2} \eta \frac{\beta(r)}{r^2} A T^2(r) \quad (9)$$

The signal current at the photomultiplier cathode is given by

$$I_s = k P_r E \quad (10)$$

Where, k is the optical efficiency of the receiver telescope, E is the photomultiplier cathode sensitivity. The background sky radiance produces the background current which is given in another form by

$$I_{Bk} = B_r A \Omega_r \delta E \quad (11)$$

Where B_r is the background radiance, δ is the optical filter bandwidth used in the telescope, Ω_r is the divergence of the receiving telescope. In addition to this, the PMT generates the dark noise. The noise term can be written as

$$i_n = \{2qB[i_{SN} + i_{Bk} + i_{Dk}]\}^{\frac{1}{2}} \quad (12)$$

The signal to noise ratio is determined by the equation

$$SNR = \frac{i_s}{i_n} \quad (13)$$

$$SNR = \frac{i_s}{\{2qB[i_{SN}+i_{Bk}+i_{Dk}]\}^{\frac{1}{2}}} \quad (14)$$

The signal from higher altitudes will be progressively weak. Therefore, beyond a certain limiting altitude, the received photons will not be sufficient to produce a current at the PMT output. Beyond this altitude, the PMT will be used in the single photon counting mode. In the photon-counting mode, the signal is so weak that the photon never comes as bunches, and hence individual photon assumption is taken as valid. Usually the detection limit is defined as SNR=1; however, the practical range is obtained as the distance where the SNR is 3. Hence the error can be defined as the reciprocal of SNR, and it is 33%.

A challenge of Atmospheric Radars and Lidars is that they require large amount of data to be collected as the atmospheric phenomena have large time constants. The signals have large dynamic range of the order 10-12 decades. The signals are buried in noise. The SNR changes from low values to High value typically from -30dB to + 10 dB, and in many occasions it is less than '0' dB. Lidars encounters two types' noises. The Optical noise which follows Poisson distribution, which the signal dependent. The second is the electronic noise follows the Gaussian distribution and is signal independent. The noise is handled by the processes of threshold, coherent averaging and incoherent averaging. The coherent averaging technique, in which pulse to pulse averaging is done, improves SNR by 10logN, where N is the number of pulses averaged. On the other hand, the incoherent averaging technique, in which range bin to range bin averaging is done, improves SNR by 10log√m. Here m is the number of range bins. The uncertainty level in the photon counts measurement is shown in the Figure 8. The probability of error with respect to the photon counts is shown in Figure 9. The SNR is estimated from the measured data. Figure 10 shows SNR with respect to range. Various types of noises are also shown in this figure

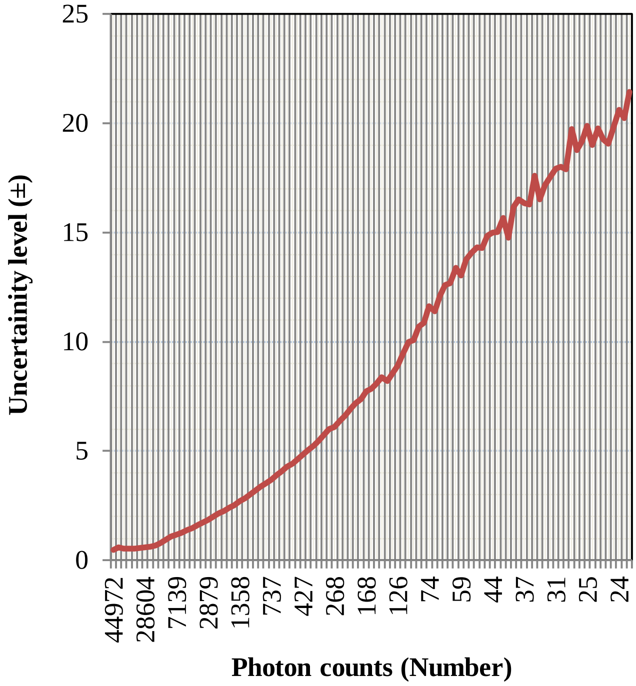

Figure 8 Uncertainties in photon counts measured

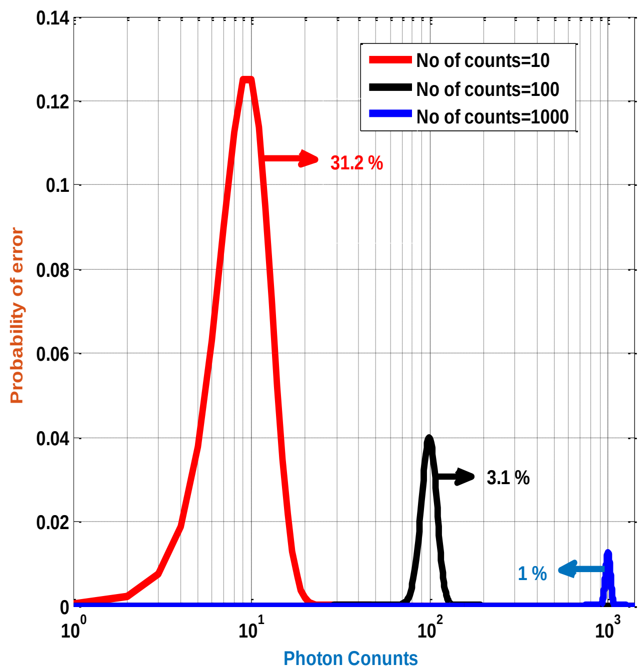

Figure 9 Photon counts vs Probability of error

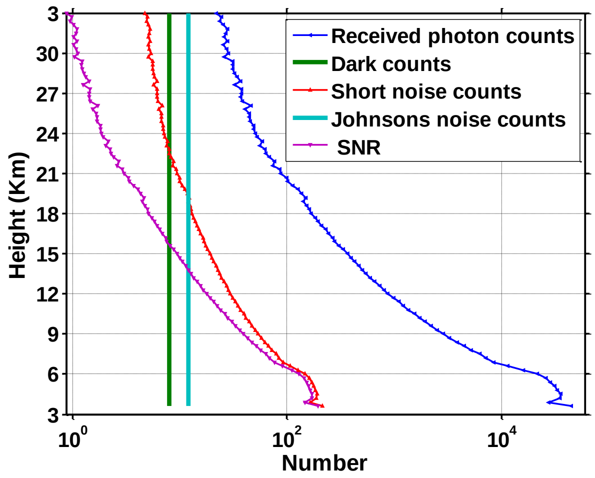

Figure 10 Estimation of SNR from the measured data

VIII. DATA PROCESSING

The LIDAR makes use of a short pulse of the order of 5 ns, which provides a spatial resolution of 0.75 m. The backscattered signals from the atmosphere due to the incident Laser pulse are having a wide dynamic range because of the widely varying backscatter coefficients of dust layers, clouds, aerosols etc.. A dynamic range of 6 – 7 decades is the requirement. The range of Backscatter coefficients encountered by the laser signal is listed below.

Back Scatter coefficient β (m-1 Sr -1)

For yellow sand	2 X 10-6 to 2 X 10-5
Tropospheric aerosols	2 X 10-6 to 2 X 10-5
Stratospheric aerosols	1 X 10-9 to 1 X 10-7
Water clouds	5 X 10-5 to 5 X 10-3
Cirrus clouds	1 X 10-6 to 2.5 X 10-4

This type of dynamic range can be provided by a 20 - 24 bit A/D Converter which is not readily available. This type of dynamic range requirement is met by two 12 bit digitizers set to different full-scale ranges. One digitizer is fed with direct signal either from APD or PMT the other digitizer is fed with an amplified version of the same. A dynamic range of more than 20 bit is provided by this scheme. The 12-bit digitizers are under the control of a computer and they are capable of digitizing up to 40 MSPS. 40 MSPS sampling rate will provide a spatial resolution of 3.75 m. For 1064 nm channel, only analog mode of acquisition is used.

The 532-nm channel is used for both aerosol measurement in the lower altitude region (0-30 km) and molecular measurement in the region above 30 km. Above 30 km, the returned signals are discrete in nature and the resultant pulses are to be counted. The pulses are very narrow of the order of 3 – 5 ns. The PMT output is of the order of 3-5 mV in amplitude. These pulses are due to photons

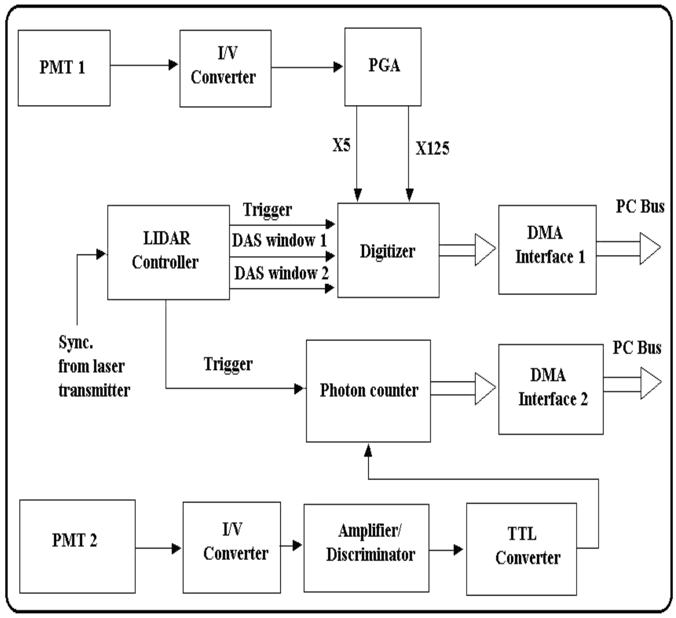

Figure 11 Block diagram of data acquisition system

incident on the photocathode. These pulses have to be counted. There is no other way of digitization of these pulses. The counter should be capable of counting these narrow pulses. The important parameter for the counter is the pulse pair resolution. The counter we have used is capable of counting upto 200 MHz with a pulse pair resolution of 2.5 ns. The photon counter works in totalizing mode. Rangebinwise data is provided by subtracting the previous count from the present count.

IX. CONCLUSION

An in-house developed mie lidar system for measurement of aerosols is presented. Various sources of noises, noise estimation and SNR improvement methods have described briefly. A brief outline of the Data Acquisition System and Data Processing techniques is given based on the state of art technology. It is shown that it is possible to realize the required dynamic range for Lidars and Radars using the methodology described based on the capabilities of the present day systems. It is possible to extract the weak atmospheric signal buried in noise with the help of new algorithms.

X. REFERENCES

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