Application of Finite Difference Technique to Raman Lidar Signals to Derive the Altitude Profiles of Atmospheric Aerosol Extinction

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Abstract:– Lidars (Laser radars) are the best suitable instruments to derive the range resolved parameters of atmosphere. Single wavelength and simple backscatter lidars have been widely used to study the height profiles of particle scattering and extinction in the atmosphere. However, atmospheric extinction derived using these lidars data undergo several assumptions and hence involve a significant amount of error in estimation of extinction. The Raman lidar methodology of deriving particle extinction in the atmosphere is a simplified straight-forward method that does not involve any assumptions. The Raman lidar method of atmospheric extinction computation employs derivative of logarithm of normalized range corrected Raman backscattered signal. Usually this causes gaps in the height profiles wherever there is a gradient in the signal under examination. In the present study, a new method is proposed to derive the particle extinction in the atmospheric boundary layer. In this new method, a scheme of alternative solution methodology has been proposed using "Finite Difference Technique". The method has an advantage that, it does not involve the gradient as compared to conventional technique and hence reduces the error. Using this method, the height profiles of particle extinction has been derived. A code in MATLAB is developed to derive the altitude distribution of aerosol extinction. In this connection, the NOAA-REDY site data has been used as the reference data for calculating the molecular extinction in the lower atmosphere.

Keywords: –Raman Lidar, Altitude Distribution, Aerosol Extinction, Finite difference method

I. INTRODUCTION

Aerosols are the tiny solid or liquid phase particles suspended in the atmosphere. A large number of aerosols present in the atmosphere whose scattering characteristics influence the radiation budget of the planet Earth and also play a significant role in the formation of clouds. The altitude distribution aerosol scattering is difficult to ascertain. Lidars (Laser radars) are the best suitable instruments to derive the range resolved parameters of the atmosphere. A lidar system with Raman and elastic backscattering capability [1] was demonstrated at National Atmospheric Research Laboratory (NARL), Gadanki (13.5°N, 79.2°E, and 375 m MSL), for measurements on particle extinction and temperature in the lower atmosphere

Single wavelength and simple backscatter lidars have been widely used to study the height profiles of the particle scattering and extinction in the atmosphere. For the past few decades, several methods [2, 3, 4] have been developed to derive the particle backscattering and extinction height profiles from lidar signals. However, the derivation of particle scattering from simple backscatter lidar technique uses an assumed relationship between particle backscattering and extinction in the retrieval methodology. This introduces a large amount of error in the quantification of particle load of the atmosphere. A lidar system with Raman scattering channel eliminates this assumption and hence provides a method to derive the aerosol extinction directly from lidar signals. Raman lidar employs visible or ultraviolet laser transmitter and generates signals corresponding to elastic and in-elastic laser backscatter. The Raman scattering from molecules such as Nitrogen (N_2), Oxygen (O_2), and Water vapor (H_2O) is responsible for in-elastic signals in the Raman lidar.

The Raman lidar methodology of deriving particle extinction in the atmosphere involves derivative of logarithmic of normalized range corrected signal [5, 6, 7, 8, 9]. This causes gaps in the height profiles wherever there is a gradient in signal under examination. In the present study, a new method is proposed to derive the particle extinction in the atmospheric boundary layer.

Aerosols, a foreign matter injected by the surface sources into the atmosphere, influence the Earth's environment in many ways. It is well established that aerosol particles play a key role in the climate related studies [10, 11, 12]. Aerosol scattering and absorption properties influence the radiation budget of the earth's atmosphere [13].They act as condensation nuclei (CCN) and participate in the cloud formation. Their scattering characteristics modify the precipitation properties of clouds [14]. Aerosol particles are dispersed freely in the atmosphere and their concentrations vary widely with location. In situ measurements of aerosolsprovidetemporal variation of their surface level characteristics. However, it is difficult to make measurements of spatially distributed aerosols using in situ methods. Modeling of radiative forcing of the earth's atmosphere requires assessment of optical properties of spatially distributed aerosols. Passive remote sensing measurements employed by artificial satellites provide the global aerosol optical depth (AOD) information. However, the distribution of aerosol load and its temporal variation is absent from such measurements.Active laser remote sensing provides the range resolved characteristics aerosols with fine spatial and temporal resolutions. Aerosol lidars utilize the time of flight information for ranging the particles suspended in the atmosphere. Single wavelength aerosol lidars provide quantitative measurements on backscattering properties of atmospheric aerosols.

II. AEROSOL LIDAR TECHNIQUE FOR DERIVING ATMOSPHERIC EXTINCTION

Aerosol lidars backscatter depends on Mie scattering. Aerosol size distribution is proportional to wavelength of lidar. Mie scattering is elastic scattering mechanism that usually experienced from particle part. Atmospheric boundary layer (ABL)is rich in aerosols and backscattering arises from particlesthat generatesignal returns in this type of lidars. Altitude profiles of photon returns constitute the basic signal in lidar. Light sources like moon, stars and solar background contribute noise to the lidar signal. Assessment of noise levels in aerosol lidars is difficult during daylight. Noise estimation during nighttime is less complex and is generally made at heights much above the signal period. Range correction to noise corrected signals provides the path loss compensation. The path loss corrected lidar signals obey the Rayleigh profile at heights beyond ABL. Retrieval of scattering characteristics of particles requiresbackground molecular distribution. The method of computation of particle characteristics from lidar signals requires application of inversion mathematics. Elastic backscatter lidars uses the popular inversion technique [2,15]. This technique inverts the range corrected signals to compute the scattering characteristics of aerosols. The Klett method [2] of inverting the lidar signals requires prior information on the size distribution of particles suspended in the atmosphere.

The equation (1) expresses the elastic backscatter lidar return power.

$$P(z) = kT_m^2 T_a^2 T_c^2 \left(\frac{L_p \lambda_L \tau}{hc}\right)\left(\frac{A}{4\pi z^2}\right)[\beta_T(z)]\Delta z + P_n \tag{1}$$

Where $\beta_T(z) = \beta_m(z) + \beta_a(z) + \beta_c(z)$ =Total backscatter. $P(z)$ = Expected total photon count ΔZ = Resolution of receiver range bin length (m) P_n = Photon count due to background noise L_p = Laser power (W)	τ = Integration time (s) h = Plank's constant (6.63 x 10^{-34} J/s) c = Light velocity (3 x 10^8 m/s^{-1}) λ_L =Laser wavelength A =Receiver telescope aperture area (m^2) k = System efficiency

The parameters $\beta_m(z)$, $\beta_a(z)$ and $\beta_c(z)$ represent the volume backscattering coefficient (m^{-1}sr^{-1}) arises from air, aerosol and cloud particles, respectively. The terms T_a and $T_c$indicate the one-way transmittance of particle atmospherewhereas Tmolforms the one-way molecular transmittance of atmosphere. The term T (z) refers to the atmospheric transmittance for the laser photons traveling from ground to a given distance in the atmosphere and back to the source. This is usually expressed as follows

$$T^2(z) = \exp(-2\int_0^z \sigma_T(z)dz)$$

Where, $\sigma_T = \sigma_m + \sigma_a$, the term σ_T represents the total atmospheric extinction (m^{-1}) contributed by air molecules and particles present in the atmosphere. The molecular extinction is computed using the molecular Rayleigh cross section and number density of molecules present in the atmosphere. The atmospheric particles occur in different sizes and laser backscattering from them requires the support of Mie theory. It becomes simpler if there exist a relationship between backscattering and extinction of particles. Klett [2] assumeda relationship between particle extinction and backscatter as indicated in equation (2)

$$\beta_T(z) = K\sigma_T{}^k(z)\,, \tag{2}$$

Where K is the constant of proportionality and 'k' is the wavelength dependence factor. Klett [2] indicated the value of k varies between 0.67 and 1.0.

Noise and range correction to the equation (1) provides path loss correction to lidar signal and indicated by*X(z)*.

$$X(z) = \frac{[P(z) - P_n](z^2)}{C} = \beta_T(z)T^2(z)$$

Where C is the calibration coefficient can be extracted from the actual lidar signal $P(z_c)$ at a reference calibration range z_c by

$$C = \frac{z_c^2 P(z_c)}{\beta_m(z_c)R(z_c)T^2(z_c)E_0}$$

Here, $R(z_c)$ be the mixing ratio at range z_c and E_0 denotes the laser pulse energy.The logarithm of *X(z)* provides a new altitude dependent parameter, proportional to $S(z) - S(z_0)$, where $S(z_0)$ is an appropriate reference value at range (z_0)

Differentiation of equation (1) simplified as

$$\frac{dS(z)}{dz} = \frac{1}{\beta_T(z)}\frac{d\beta_T(z)}{dz} - 2\sigma_T(z) \tag{3}$$

This equation is a function of two variables namely $\sigma_T(z)$ and $\beta_T(z)$. It cannot be solvable unless a relation between extinction and backscattering coefficient is assumed, the relation termed as lidar ratio (LR). For homogeneous atmosphere the term $\frac{d\beta_T(z)}{dz}$ becomes negligible and hence the atmospheric extinction becomes the slope of the logarithm of range corrected signal. However, for turbid atmosphere this assumption do not hold good. Since particles backscatter cross section bears a relationship with particle extinction as indicated in equation (2), we eliminate $\beta_T(z`)$ in terms of $\sigma_T(z)$, then equation (3) becomes

$$\frac{dS(z)}{dz} = \frac{k}{\sigma_T(z)}\frac{d\sigma_T(z)}{dz} - \sigma_T(z)$$

The above equation represents the first order differential equation and its solution is in the form shown. This form represents the solution to lidar equation given by [2].

$$\sigma_T(z) = \frac{e^{-\{S(z_0) - S(z)\}/k}}{\frac{1}{\sigma_T(z_0)} + \frac{2}{k}\left(\int_z^{z_0} e^{-\{S(z_0) - S(z)\}/k} dz\right)} \tag{4}$$

By applying the above inversion methodology to elastic backscatteringsignalsat 355 nm, collected on 26 September 2011, we obtain the altitude distribution of aerosol extinction as shown in Figure 1.

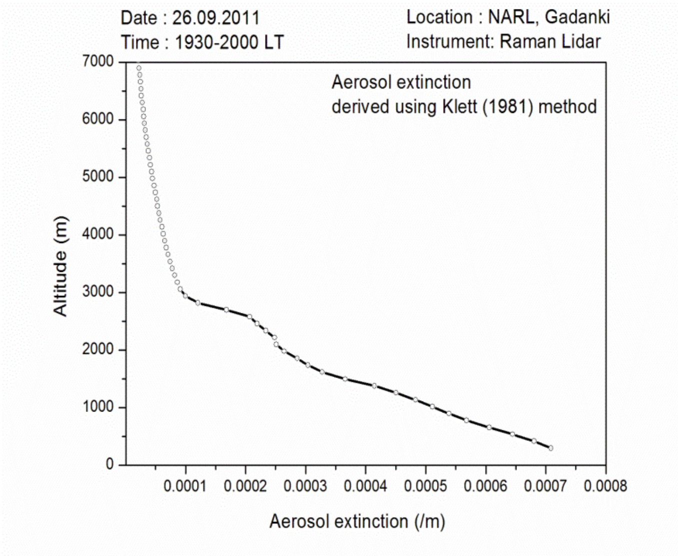

Figure 1: Particle extinction deduced from UV lidar signalusing Klett method.

Although this solution appears to work reasonably well for conditions ranging from clear to haze atmosphere, however, produces error during the fog or cloudy conditions [16]. Computations using the equation (4) require a priori for k value. Since k varies with altitude [15], it introduces a large amount of error in the quantification of particle load in the atmosphere, if a fixed valueassumed for k in the retrieval process. The altitude variation of k is difficult to determine and hence elastic Lidars using the fixed value of k in the computation of optical characteristics of aerosols introduce around 30% uncertainty in the assessment of aerosol load in the atmosphere[17].

Lidar(s) equipped with Raman scattering [5]reduces this uncertainty. These lidars equipped with in-elastic backscatteroffersdetermination of aerosol extinction in addition to the particle backscatter.This technique permits the determination of the aerosol extinction without any critical assumptions.The advantage of the Raman [5]method over the Klett [2] method lies in the closed form solution of the former as opposed to the recursive formula of the later. Dynamic instabilities are common in the Klett [2] method; however, do not occur in Raman methodology. The Raman method of atmospheric extinction is a straight forward method and do not need any contribution from input parameters.

III. RAMAN LIDAR TECHNIQUE

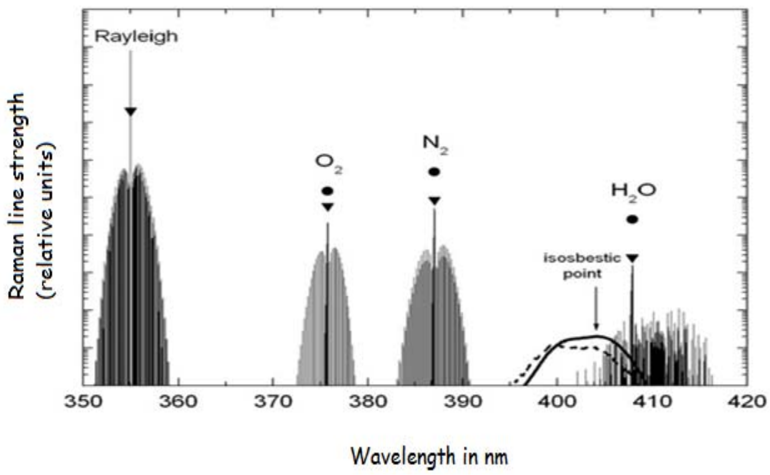

Figure 2:Relative strengths of Raman shifted lines for dominant atmospheric gases at atmospheric excitation of 355 nm [UV] wavelength

Molecular medium produces Raman scattering at weak intensity levels. It is an instantaneous process like molecular/Raleigh scattering. Strong molecular medium produces Raman scattering at shifted wavelengths from the excited laser line. Each gas molecule produces a Raman shift and remained unique to that molecule alone. The prime vibrational shifts of molecules generate the Raman scattering. Figure 2 illustrates the Raman shifts for dominant gases at 355 nm atmospheric excitation.The Raman scattering level depends strongly on the strength of the molecular species present in the atmosphere. Based on this wavelength shift, lidars incorporated with Raman scattering provides information on the altitude and temporal distribution of gases in the atmosphere. This technique uses single laser for profiling the atmosphere and employs spectral separation in the receiver to obtain the height profiles of relative strengths of molecular constituents in the atmosphere. Raman lidar technique suffers from weak molecular backscatter and hence its operation is limited to nocturnal conditions. Atmospheric Raman spectroscopic studies contributed significantly to atmospheric aerosols. High optical depth (OD) Dichroic mirrors utilized in Raman Lidars provide the high spectral separation [18]. High Spectral Resolution Lidars (HSRL) also contributes such type of information in addition to Raman Lidars. Cooney [19]showed that Raman scattering from atmospheric Nitrogen can be used for determination of atmospheric attenuation coefficient.Assessment of atmospheric AOD requires the altitude distribution of aerosol extinction. Raman Lidars provide accurate profiles of aerosol extinction. Simultaneous molecular and particle measurements provide detailed information on the microphysical parameters of atmospheric aerosols.

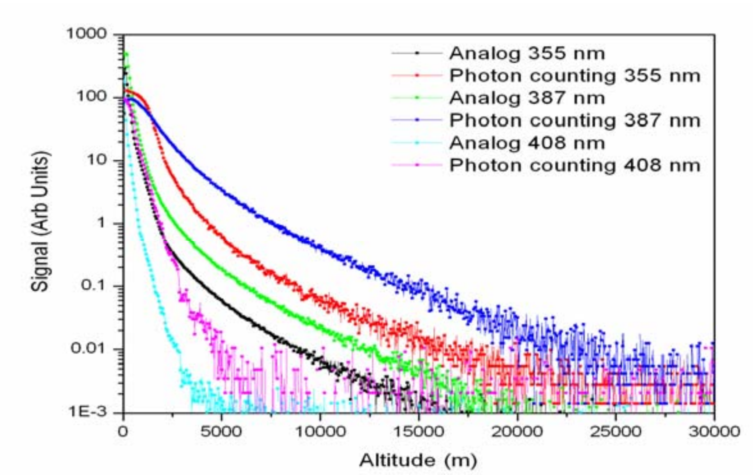

Fig. 3: Analog and Photon counting signals measured using NARL Raman Lidar.

The National Atmospheric Research Laboratory (NARL), Gadanki (13.5°N, 79.2°E, 375 m AGL), a unit of Department of Space,recently developed a low cost Raman lidarfor measurements on atmospheric water vapor and aerosols in the lower atmosphere. The Raman Lidar operates at UV wavelengths in night periods and provides altitude profiles of laser backscatter at 355, 387 and 408 nm wavelengths simultaneously. The lidar collects laser backscatter data both in analog and photon counting (PC) modes. Figure 3 illustrates the sample analog and PC data collected using the NARL Raman Lidar. Range normalization of elastic backscatter with the Nitrogen Raman backscatter provides the altitude profiles of aerosol scattering Ratio (ASR). The altitude profiles of ASR utilized for derivation of particle volume backscattering cross section at 355 nm wavelength. At NARL site, the Ansmann [5] technique implemented for computation of aerosol extinction from lidar signals.

IV. RAMAN LIDAR TECHNIQUE OF DERIVING AEROSOL EXTINCTION

The laser backscattered signals measured using Raman lidarcan be expressed as follows.

$$P(z, \lambda_L, \lambda_R) = K * \frac{O(z)}{z^2} * \beta(z, \lambda_L, \lambda_R) * exp\left\{- \int_0^z [T(\mathrm{Z}, \lambda_L) + T(\mathrm{Z}, \lambda_R)] dZ\right\} \quad (5)$$

Where,

$P(z, \lambda_L, \lambda_R)$= The number of photons collected at altitude z from the Raman shifted wavelengthλ_R, and at excited laser wavelengthλ_L.

$O(z)$=Beam overlaps function of the Telescope field of view.

K= The system constant contains efficiencies of all system parameters.

$\beta(z, \lambda_L, \lambda_R)$= The volume backscatter cross section measured at $\lambda_R$andλ_L.

$T(\lambda_L, Z)$=$E_{m,\lambda_L}(Z) + E_{a,\lambda_L}(Z)$ and $T(\lambda, Z) = E_{m,\lambda_R}(Z) + E_{a,\lambda_R}(Z)$ represent the volume extinction coefficients of elastic at the wavelengthsλ_L, and at Raman wavelengthλ_R respectively.

The altitude dependent of backscattering coefficient $\beta(z, \lambda_R)$for Raman wavelength can be expressed as in equation (6)

$$\beta(z, \lambda_R) = N_d(z) * \frac{d\sigma(\pi)}{d\Omega} \quad (6)$$

Where, $N_\mathrm{d}(z)$ represents the number density of molecules responded to Raman backscatter at wavelength at of λ_R and $\frac{d\sigma(\pi)}{d\Omega}$indicate the differential scattering cross section of Raman atλ_R.

Substituting the above relation (6) into (5) we can represent the signal due to Raman wavelength as follows.

$$P_{\lambda_R}(z) = K_{\lambda_R *} \frac{O(z)}{z^2} * N_d(z) * \frac{d\sigma(\pi)}{d\Omega} exp\{-\int_0^z [T(Z,\lambda_L) + T(Z,\lambda_R)]dZ\} \quad (7)$$

At NARL, Raman Lidar uses N_2 as the molecular gas under study for aerosol extinction calculation; the modified equation of (7) is expressed as

$$P_{n_2}(z) = K_{n_2} \frac{N_{d\,n_2}(z)}{z^2} \frac{d\sigma_{n_2}(\pi)}{d\Omega} \exp\{-\int_0^z [E_{m,\lambda_L}(Z) + E_{a,\lambda_L}(Z)]d\xi - \int_0^z [E_{m,\,\lambda_R}(Z) + E_{a,\,\lambda_R}(Z)]dZ\},$$

follows that

$$\left(\frac{z^2 P_{n_2}(z)}{N_{d\,n_2}(z)}\right) = \left(K_{n_2} \frac{d\sigma_{n_2}(\pi)}{d\Omega}\right) \exp\{-\int_0^z [E_{m,\lambda_L}(Z) + E_{a,\lambda_L}(Z)]dZ - \int_0^z [E_{m,\lambda_R}(Z) + E_{a,\,\lambda_R}(Z)]dZ\} \quad (8)$$

Where $E_{m,\,\lambda_L(\,\lambda_R)}$ and $E_{a,\,\lambda_L(\,\lambda_R)}$ implies volume extinction coefficients due to molecular and aerosol components respectively. Also the overlaps function $O(z)$ becomes unity as transmitted beam within the field of view of the optical receiver and hence neglected for simplification.

By taking the logarithm of equation (8), we get

$$ln\left(\frac{z^2 P_{n_2}(z)}{N_{d\,n_2}(z)}\right) = ln\left(K_{n_2} \frac{d\sigma_{n_2}(\pi)}{d\Omega}\right) - \int_0^z [E_{m,\lambda_L}(Z) + E_{a,\lambda_L}(Z)]dZ - \int_0^z [E_{m,\;\lambda_R}(Z) + E_{a,\;\lambda_R}(Z)]dZ \quad (9)$$

Since the first term of right hand side of (9) is constant; and on differentiating equation (9) with respect to z, we get

$$[E_{m,\lambda_L}(z) + E_{a,\lambda_L}(z) + E_{m,\,\lambda_R}(z) + E_{a,\;\lambda_R}(z)] = \frac{d}{dz}\left[ln\,(\frac{N_{d\,n_2}(z)}{z^2 P_{n_2}(z)})\right] *$$

$$\left[E_{m,\lambda_L}(z)\left(1 + \frac{E_{m,\,\lambda_R}(z)}{E_{m,\lambda_L}(z)}\right) + E_{a,\lambda_L}(z)\left(1 + \frac{E_{a,\,\lambda_R}(z)}{E_{a,\lambda_L}(z)}\right)\right] = \frac{d}{dz}\left[ln\,(\frac{N_{d\,n_2}(z)}{z^2 P_{n_2}(z)})\right] \quad (10)$$

The wavelength dependence of extinction for air molecules and aerosol particles expressed by the equations (11) and (12) as

$$\frac{E_{m,\,\lambda_R}(z)}{E_{m,\lambda_L}(z)} = \left(\frac{\lambda_R}{\lambda_L}\right)^{-4} \quad (11)$$

$$\frac{E_{a,\;\lambda_R}(z)}{E_{a,\lambda_L}(z)} = \left(\frac{\lambda_R}{\lambda_L}\right)^{-k(z)} \quad (12)$$

Where *k (z)* represents the angstrom coefficient, depends on the particle size, shape, and its refractive indexusing equations (10), (11) and (12), we get

$$\left[E_{m,\lambda_L}(z)\left(1 + \left(\frac{\lambda_R}{\lambda_L}\right)^{-4}\right) + E_{a,\lambda_L}(z)\left(1 + \left(\frac{\lambda_R}{\lambda_L}\right)^{-k(z)}\right)\right] = \frac{d}{dz}\left[ln\,(\frac{N_{d\,n_2}(z)}{z^2 P_{n_2}(z)})\right]\ldots \quad (13)$$

After simplification of equation (13), the aerosol extinction coefficient ($E_{a,\,\lambda_L}(z)$) at an excited wavelength λ_L is expressed as follows.

$$E_{a,\,\lambda_L}(z) = \frac{1}{\left(1+\left(\frac{\lambda_R}{\lambda_L}\right)^{-k(z)}\right)} * \left\{\frac{d}{dz}\left[ln\,(\frac{N_{d\,n_2}(z)}{z^2 P_{n_2}(z)})\right] - \left(1 + \left(\frac{\lambda_R}{\lambda_L}\right)^{-4}\right) * E_{m,\lambda_L}(z)\right\}\ldots \quad (14)$$

For derivation of atmospheric extinction, generally, Raman lidars use backscattering from dominant gases like nitrogen and oxygen. Since the Raman scatter cross-section is weak in nature, the molecular gas used under study requires comparably a larger concentration in the atmosphere. The Nitrogen gas considered as the reference gas in Raman Lidars used for deriving the aerosol extinction in the atmosphere. Ansmann [5] discussed the method of deriving aerosol extinction using nitrogen Raman signal as the reference. The method discussed by Ansmann [5] uses the equation (14), this equation employs the terms like $\frac{d}{dz}\left[ln\,(\frac{N_{d\,n_2}(z)}{z^2 P_{n_2}(z)})\right]$, which represents gradient of the signal computed. This method fails to produce good results if computed signal contains variation in spatial scale. This condition arises due to gradients present in the signal and causesbreaks in the computed signal if subjected to derivative analysis. Hence the method of Ansmann [5] produces smooth extinction profile only if the derivative of computed signal is subjected to heavy smoothing. This method of heavy smoothing results in lack of consistency in the computation of extinction profiles from Raman lidar and highly depends on the level of smoothing incorporated. Figure (4) represents the computation of extinction profiles from Raman signal without application of smoothing using the method of Ansmann [5]. Note that the breaks observed in the data derived from the Raman Lidar are due to application of derivative to the computed signal. Any small variation in the computed signal causes this type of breaks in the extinction profiles. Breaks in the height profile of aerosol extinction lead to a misleading informationthat presents aerosol free region in the atmosphere, however, in reality it is not so. This problem arises due to the mathematical artifact in the aerosol extinction computational process. This can be overcome if one adopts finite difference technique to the Raman lidarextinction estimation.

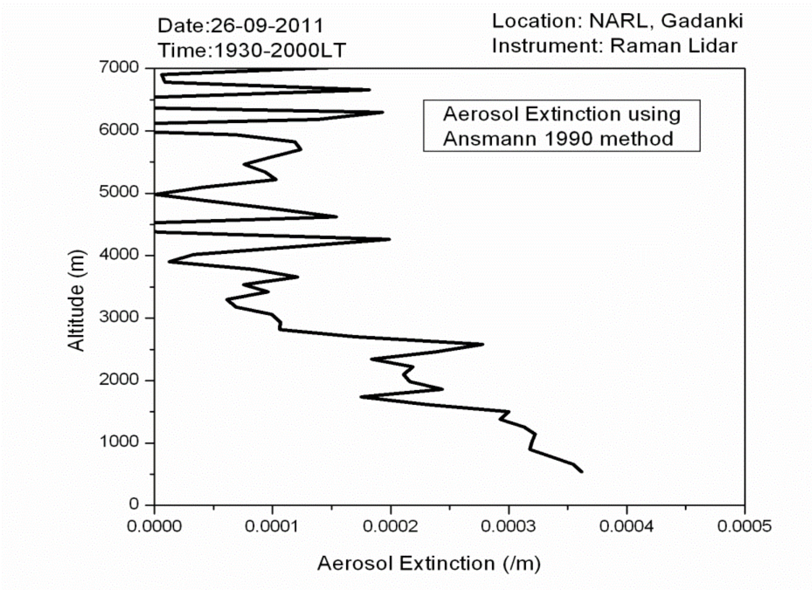

Figure 4: Computation of extinction profile from Raman lidarsignals using Ansmann [5]method.

V. ALTERNATE SOLUTION TO THE COMPUTATION OF AEROSOL EXTINCTION FROM RAMAN LIDAR SIGNALS

Now consider equation (9),

$$\left[\ln\left(\frac{N_{d\,n_2}(z)}{z^2 P_{n_2}(z)}\right)\right] = ln\left(N_d(z)\right) - \ln(z^2) - \ln\left(P_{n_2}(z)\right), \text{ which}$$

Implies that, $\frac{d}{dz}\left[\ln\left(\frac{N_{d\,n_2}(z)}{z^2 P_{n_2}(z)}\right)\right] = \frac{d}{dz}\left[ln\left(N_{d\,n_2}(z)\right)\right] - \frac{d}{dz}\left[\ln(z^2)\right] - \frac{d}{dz}\left[\ln\left(P_{n_2}(z)\right)\right]$.

From the first principle of differentiation, the above expression can be described as a finite difference form with the interval difference δz, as indicated below.

$$\frac{d}{dz}\left[ln\left(\frac{N_{d\,n_2}}{z^2 P_{n_2}(z)}\right)\right] = \frac{ln\left(N_{d\,n_2}\left(z+\frac{\delta z}{2}\right)\right) - ln\left(N_{d\,n_2}\left(z-\frac{\delta z}{2}\right)\right)}{\delta z} - \frac{ln\left(z+\frac{\delta z}{2}\right)^2 - ln\left(z+\frac{\delta z}{2}\right)^2}{\delta z} - \frac{ln\left(P_{n_2}\left(z+\frac{\delta z}{2}\right)\right) - ln\left(P_{n_2}\left(z-\frac{\delta z}{2}\right)\right)}{\delta z}$$

$$= \frac{1}{\delta z}\left[ln\left(N_{d\,n_2}\left(z+\frac{\delta z}{2}\right)\right) - ln\left(N_{d\,n_2}\left(z-\frac{\delta z}{2}\right)\right) - ln\left(z+\frac{\delta z}{2}\right)^2 + ln\left(z+\frac{\delta z}{2}\right)^2 - ln\left(P_{n_2}\left(z+\frac{\delta z}{2}\right)\right) + ln\left(P_{n_2}\left(z-\frac{\delta z}{2}\right)\right)\right],$$

On simplifying the above expression, we get

$$\frac{d}{dz}\left[ln\left(\frac{N_{d\,n_2}(z)}{z^2 P_{n_2}(z)}\right)\right] = \frac{1}{\delta z}\left[ln\frac{P_{n_2}\left(z-\frac{\delta z}{2}\right) * \left(z-\frac{\delta z}{2}\right)^2 * N_{d\,n_2}\left(z+\frac{\delta z}{2}\right)}{P_{n_2}\left(z+\frac{\delta z}{2}\right) * \left(z+\frac{\delta z}{2}\right)^2 * N_{d\,n_2}\left(z-\frac{\delta z}{2}\right)}\right] \quad (15)$$

Substituting equation (15) in (14) we obtain the final equation (16) for computation of aerosol extinction from Raman lidar using Nitrogen Raman signal as the input signal with a wavelength dependence parameter indicated by *k(z)*, this new methodology of computation of aerosol extinction from Raman Lidarsignals employingfinite difference technique successfully implemented in MATLAB. Figure 5 represents the algorithm of the novel method used in the retrieval of aerosol extinction.

$$E_{a,\lambda_L}(z) = \frac{1}{\left(1+\left(\frac{\lambda_R}{\lambda_L}\right)^{-k(z)}\right)} \left\{ \frac{1}{\delta z}\left[\ln\left(\frac{P_{n_2}\left(z-\frac{\delta z}{2}\right)*\left(z-\frac{\delta z}{2}\right)^2 * N_{d\,n_2}\left(z+\frac{\delta z}{2}\right)}{P_{n_2}\left(z+\frac{\delta z}{2}\right)*\left(z+\frac{\delta z}{2}\right)^2 * N_{d\,n_2}\left(z-\frac{\delta z}{2}\right)}\right)\right] - \left(1+\left(\frac{\lambda_R}{\lambda_L}\right)^{-4}\right)E_{m,\lambda_L}(z)\right\} \ldots\ldots\ldots (16)$$

VI. ALGORITHM – FLOW CHART

Figure 5shows that the flowchart of the MATLAB code developed for retrial of aerosol extinction using the Finite Difference Technique. The code developed derives the altitude distribution of aerosol extinction using the NARL Raman lidar data. The developed algorithm reads the raw data from lidarand converts in to the ASCII format. The code also performs pre-processingworks like noise and range correction to lidarsignals.The algorithm also uses the real-time pressure and temperature data from NOAA-READY site for computation of Nitrogen molecular number density. Finally the aerosol extinction computation carried out using the range corrected signals, Nitrogen number density and molecule extinction by employing the finite difference methodology given by equation (16). The finite difference method finds advantageous compared to the gradient methods given by Ansmann[5]because the first method does not requires smoothing and hence can produce consistent results.

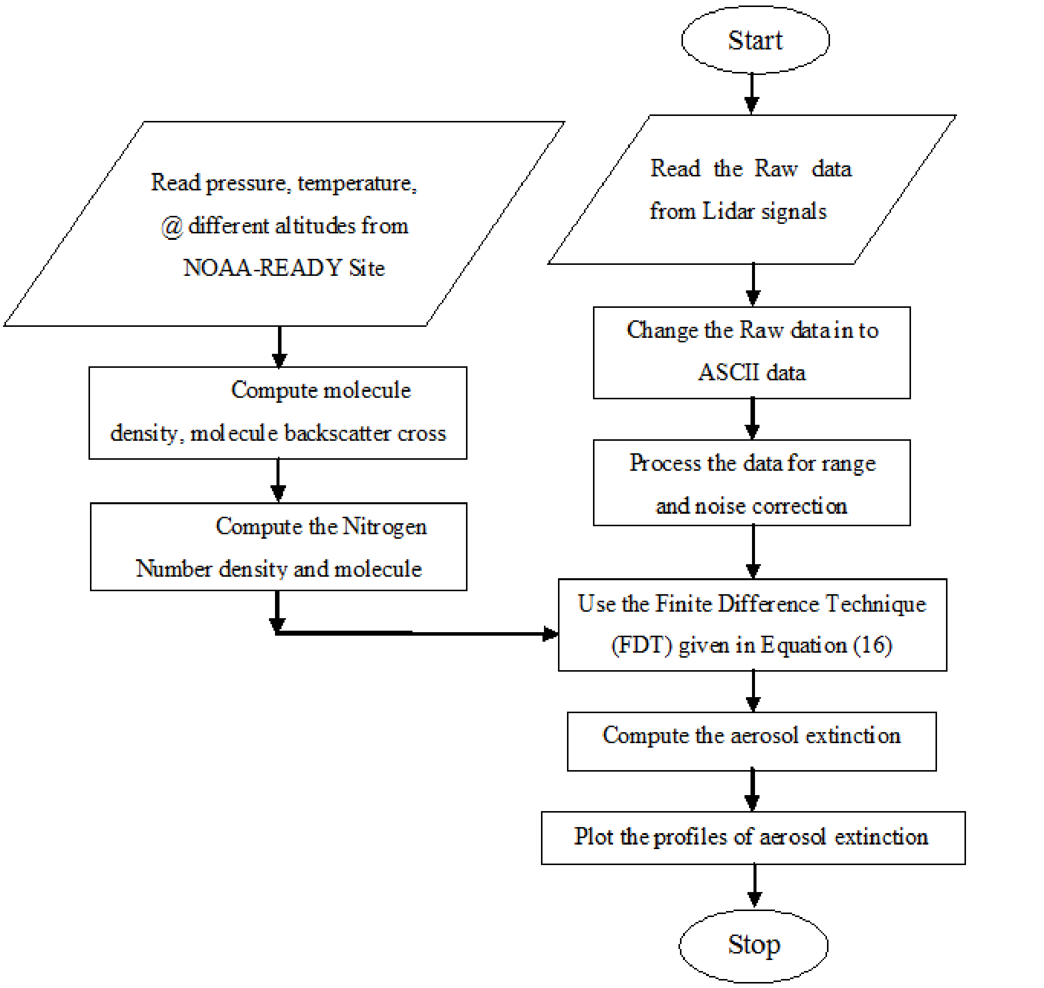

Figure 5: Flow chart of Finite difference methodology implemented in MATLAB

VII. EXPERIMENTAL OBSERVATIONS

The developed finite difference technique subjected to Raman lidardata for retrieving the aerosol extinction. The Raman lidar data corresponding to 26 September 2011 employed in this study. The Raman lidar data collected during the time period between 1930 and 2000 LT on 26.09.2011 utilized in the derivation of aerosol extinction. Figure 6 illustrates the range corrected Nitrogen Raman Lidarsignalsused for extinction analysis. Figure 7 represents the computed altitude dependent data obtained using Nitrogen number density and pre-processed Nitrogen Raman backscatter data. Figure 8 presents the computed aerosol extinction from Nitrogen Raman signals using the new finite difference method.

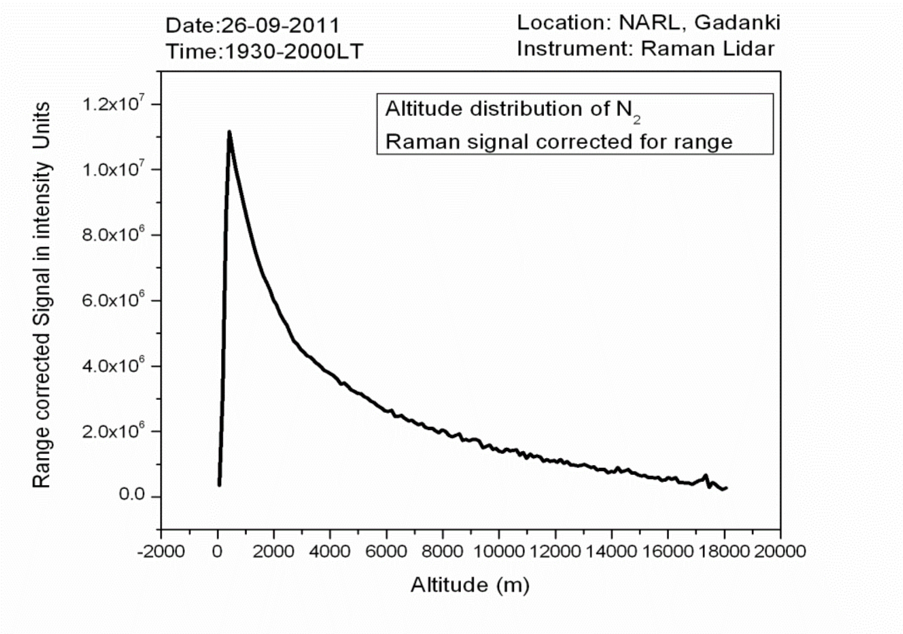

Figure 6: Altitude distribution of Nitrogen Raman signal measured on 26 September 2011

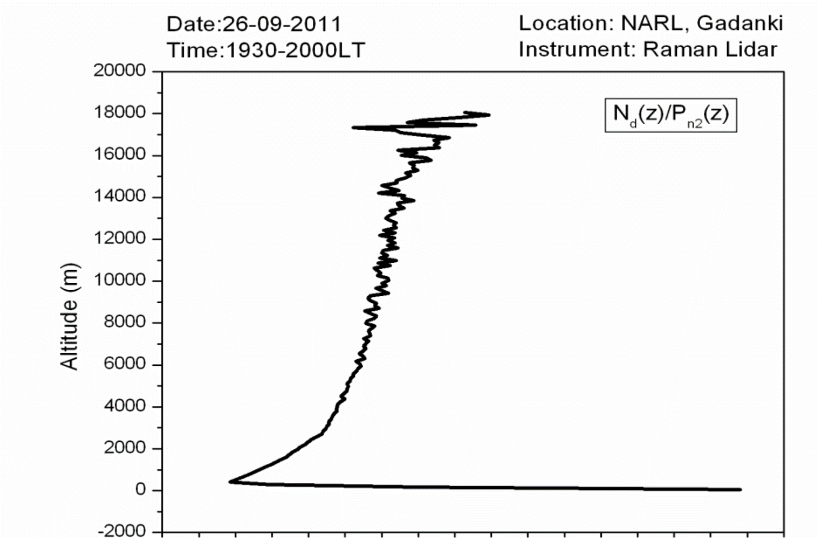

Figure 7: Height profile of computed signal using the Nitrogen number density and Range corrected Raman Lidarsignal

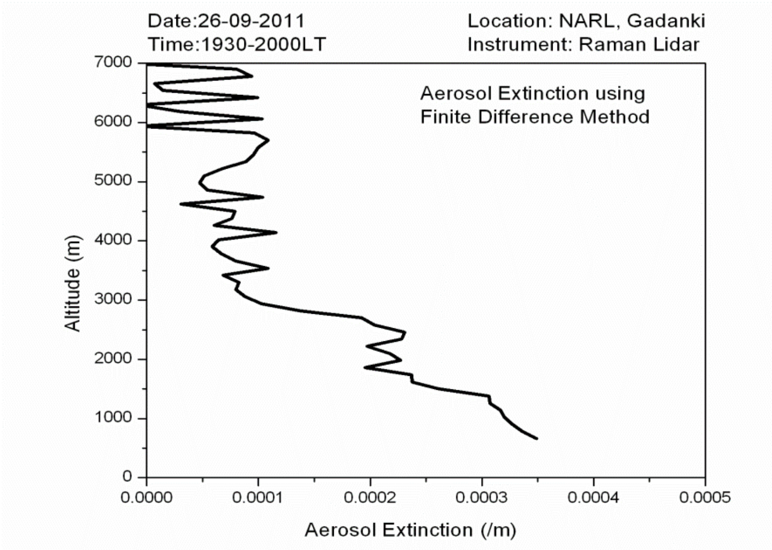

Figure 8: Aerosol extinction profile derived using the new method employing Finite Difference Technique

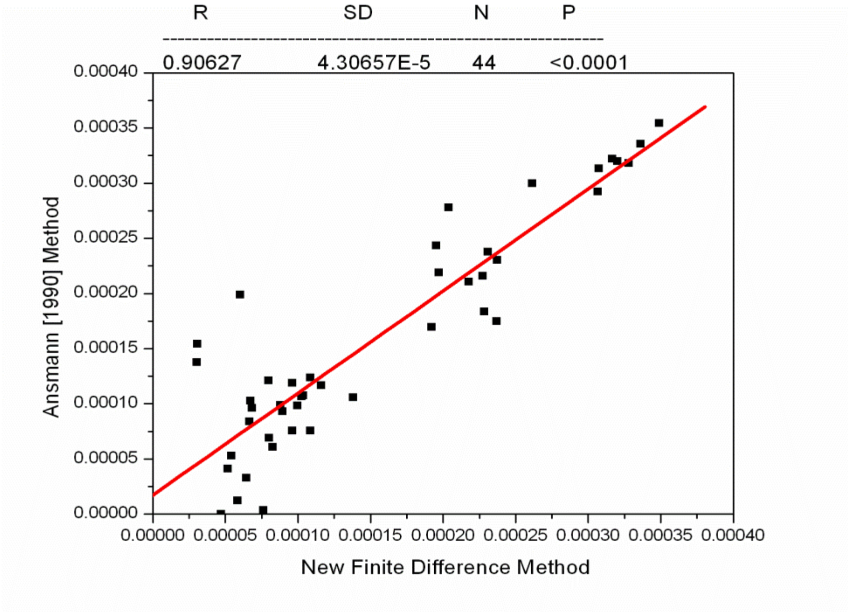

Figure 9: Correlation graph drawn between Ansmann [5] and the new Finite Difference method presented in this work.

Figure 9 shows a correlation between the convectional gradient method reported by Ansmann [5] and the Finite Difference Method described in this Report.The Y axis represents the gradient method given by Ansmann[5]. The X-axisrepresents the novel finite difference method presented in this report. From the above figure one can observe a clear and excellentcorrelation [0.9062] between old and new methods. However, the old methodology requires heavy smoothing to avoid the breaks in the altitude profiles. The new novel method eliminates this limitation and provides a smooth curve of atmospheric extinction, which can be readily used with backscattering coefficient data for computation of altitude distribution of lidarratio (LR), a vital parameter for identification type of aerosols in the atmosphere [20].

VIII. SUMMARY

This paper presented a new and novel method of computation of aerosol extinction coefficient from Raman lidar data. The new method utilizes the finite difference technique and provides a smooth altitude profile of atmospheric extinction. The new method uses the altitude profiles of range corrected Nitrogen Raman signal and Nitrogen number density derived from the data of NOAA-READY website. The new method of computation of aerosol extinction was successfully implemented in MATLAB code and compared with the existing methodology given by Ansmann [5]. The comparison of results provides a correlation coefficient of 0.9 which indicates excellentcomparison. The output of novel method is smooth than compared to the old method given by Ansmann [5]. The Raman lidar data utilized in this report was obtained from NARL site Gadanki.

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