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Wavelet-PCA Denoising for LIDAR Signals

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Abstract: Lidar is a remote sensing device used to measure the atmospheric constituents like molecular density and particle concentration. The Rayleigh backscattered lidar signal is a non linear and non stationary signal affected by different noises at higher altitudes. In this paper, a combination of wavelet-PCA method is proposed to improve the signal to noise ratio at higher altitudes. By comparing the experimental results, the proposed method not only removes the noise, but also useful information in the lidar signal is maintained.
Keywords: Rayleigh lidar, Multivariate PCA, Temperature

I. LIDAR SYSTEM DESCRIPTION

Many devices like radar and balloons are used to study the wind fluctuations in troposphere up to 30km.Rocket sounding device is used to measure the temperature in the middle atmosphere, but it is not used for continuous measurements and also expensive. Rayleigh lidar is the only inexpensive device compared to rocket sounding used to measure the density and temperature profiles of the atmosphere in the height range from 30 to 80 km on a continuous basis. Lidar transmits a laser pulse into the atmosphere. The laser light interacts with particles and molecules and backscattered towards the receiver. The intensity of light backscattered is measured in terms of photon count[1]. Above 30 km, the atmosphere contains only air molecular species. Therefore the Rayleigh backscattered photon count is proportional to molecular density. The noise in backscattered lidar signal is due to statistical fluctuations of signal and background radiation. The dark current noise also occurs due to generation of current in the absence of optical signal. The different noises present in lidar signal can be removed by applying denoising techniques .several existing denoising techniques like wavelet transform[2] applied to lidar signal and least squares support vector also mentioned the noises in lidar signal[3]
A Rayleigh scatter lidar system has been established at NARL (National Atmospheric Research Laboratory), Gadanki (13.8^{0}N,79.2^{0}E),India in joint collaboration with National Institute of Information and communication Technology(NICT), Japan for regular observation of middle atmosphere and is operated from March 1998.The block diagram of lidar system is shown in Figure 1[4].The transmitter in lidar system consists of Nd:YAG laser operating at 1064nm[5].The second harmonic generator generates the light signal of 532nm.The beam expander expands the generated laser beam by a factor of 10 and steering mirror reflects the laser beam upward into the sky. The backscattered light is collected by Newtonian telescope at receiver end.

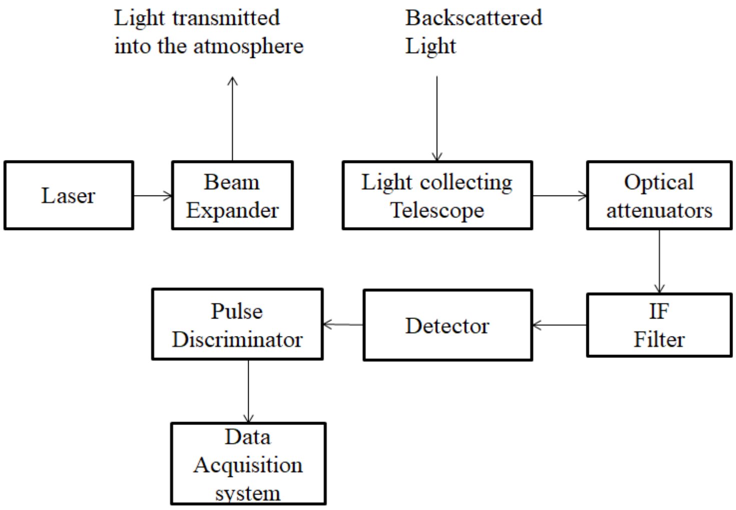

Fig. 1.Block diagram of the LIDAR system

The field of view (FoV) of the telescope allows the background sky noise with addition to backscattered light from air molecules.. The light passes through a narrow band filter with a FWHM bandwidth of 1.07nm and detector. The detector consists of Photo Multiplier Tubes(PMT) split the laser beam into two similar PMT of different gains. The 10% low sensitive channel called as U-channel used to collect signals from lower altitudes (25 to 50 km) and 90% high sensitive channel called as R-channel (Rayleigh channel) collects lidar returns from higher altitudes (35 to 80 km).The backscattered light from the R-Channel is measured in terms of photon counts[6]. The signal from the R-Channel is amplified by pre-amplifier and transmitted to Multichannel scalar (MCS) unit. MCS counts the number of incoming PMT pulses in a given time at a rate of 150 MHz. The successive counting of pulses in a sequence of time, MCS forms a profile in time. The time is converted into altitude R using the equation (1)

$$R = \frac{c\tau}{2} \tag{1}$$

The single raw data profile is obtained by adding 5000 laser echo from the MCS. The data profile is transferred to a personal computer (PC). The PC stores the profiles and initializes MCS unit to start a new profile on the next laser pulse. The accumulation of data for 250 Sec duration corresponds to 5000 laser shots constitute the basic lidar signal[7]. The signal profiles form R & U channels of Rayleigh scatter receiver cover height range of 150 km. For each measurement, background noise is estimated and subtracted from the signal for range correction. These noises corrected signal still has some noise present in it and it can be corrected through some denoising techniques. The raw lidar signal on 05/02/011 and the range corrected signal from 60 to 90 km is shown in Figures 2 and 3.The lidar signal on 05/02/11 from 30 to 90 km is graphically represented in Figure 4.

The noise in any given signal can be reduced by

1. Removing noise in the signal and preserve useful information
2. Eliminate non informative components of signals through dimension reduction

Wavelet Transform-

Through wavelet decomposition, the random noise in the signal can be reduced by equating the detail coefficients to zero and the process of the wavelet transform is described in the following steps[8]

1. Compute wavelet decomposition of the signal up to level J into approximation and detail coefficients
2. Thresholding the detail coefficients below a defined threshold δ
3. Reconstruct the denoised lidar signal using inverse wavelet transform

In general, universal threshold $\delta = \hat{\sigma}\sqrt{2\log(n)}$ is selected for detail coefficients and equate the signal detail coefficients to zero,the noise in the signal is reduced and useful information is maintained through approximation coefficients.Where n is the length of the signal and $\hat{\sigma}$ is the noise standard deviation.

Principal Component Analysis-

Principal component analysis (PCA) in generally used to reduce multidimensional data consists of large data into lower dimensions having most important data and discarding unnecessary data. PCA is calculated on the covariance matrices and the method is based on the Karhunen-Loeve Transform (KLT).The multivariate wavelet denoising using PCA is to use the principal component analysis[9] and kill the unnecessary principal components to obtain additional denoising of LIDAR signal.

The general steps involved in multivariate wavelet denoising are

1. Apply the wavelet transform with J levels for input signal Y
2. Select the number of retained principal components using heur's rule.
3. Define the estimator of the noise co-variance matrix $\hat{\sum}_{\varepsilon} = MCD(D_1)$ and calc.te B such that $\hat{\sum}_{\varepsilon} = BAB^T$ where $B = diag(\lambda_i, 1 \le i \le p)$ .Apply to every detail after modification of basis (namely $D_j B$, $1 \le j \le J$),the p variant thresholding strategies using the threshold $t_i = \sqrt{2\lambda_j \log(n)}$ for jth column of $D_j B$
4. Perform PCA of matrix B_J and select an appropriate number of P_{J+1} of useful principal components
5. Reconstruct denoised signal matrix $\hat{Y}$ from the obtained approximation and detail coefficients by changing of basis using B^T and inverting the wavelet transform

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The denoised signals using multivariate wavelet PCA on 05/02/11 are shown in Figure 5 and comparison of denoising techniques with median filter and wavelets is shown in Figure 6.The comparison of signal to noise ratio at different altitudes is shown in Figure 7 and Table 1.

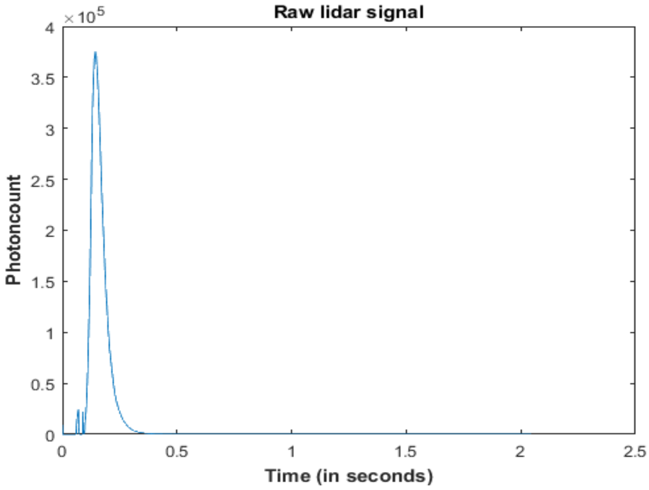

Fig 2: Raw lidar signal on 05/02/11

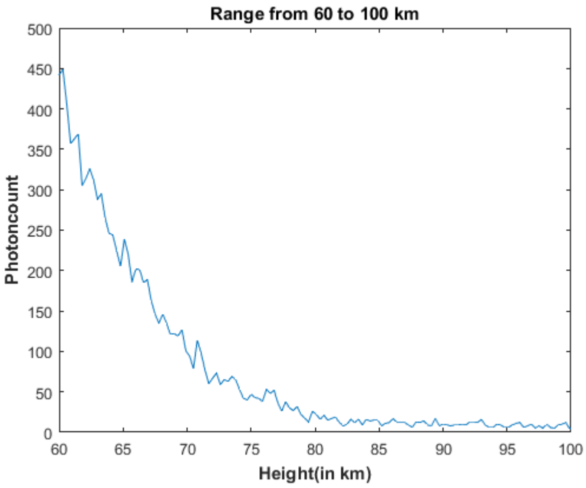

Fig 3:Range corrected signal from 60 to 100km on 05/02/11

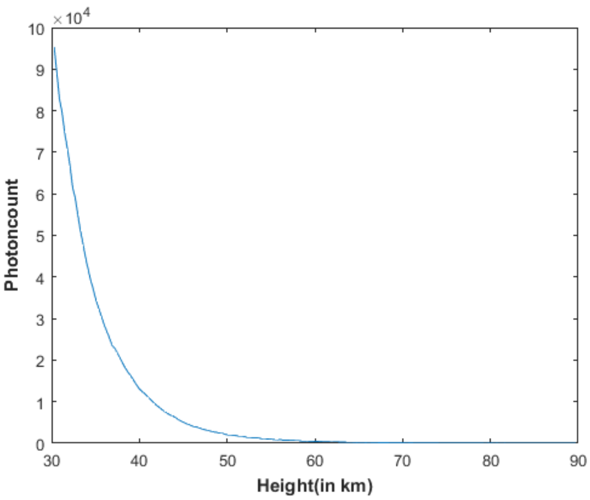

Fig 4: Range corrected signalfrom 30 to 90 km on 05/2/2011

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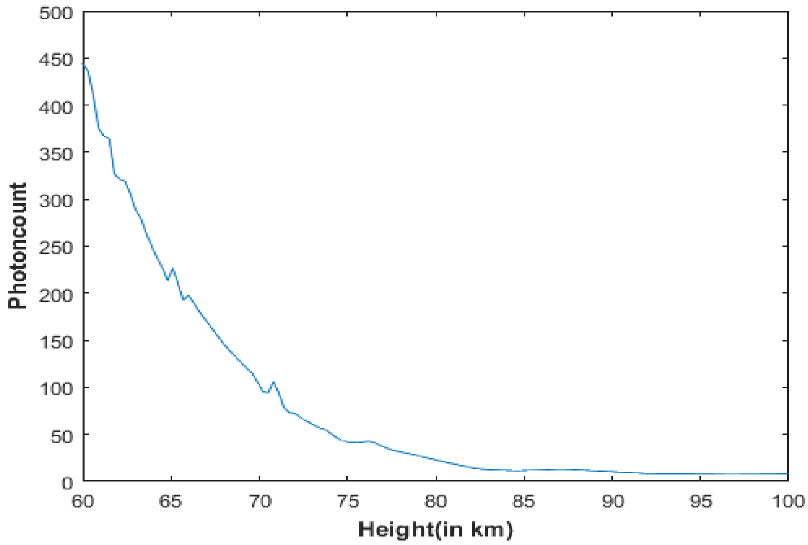

Fig 5- Denoised lidar signal using multivariate pca on 05/02/11

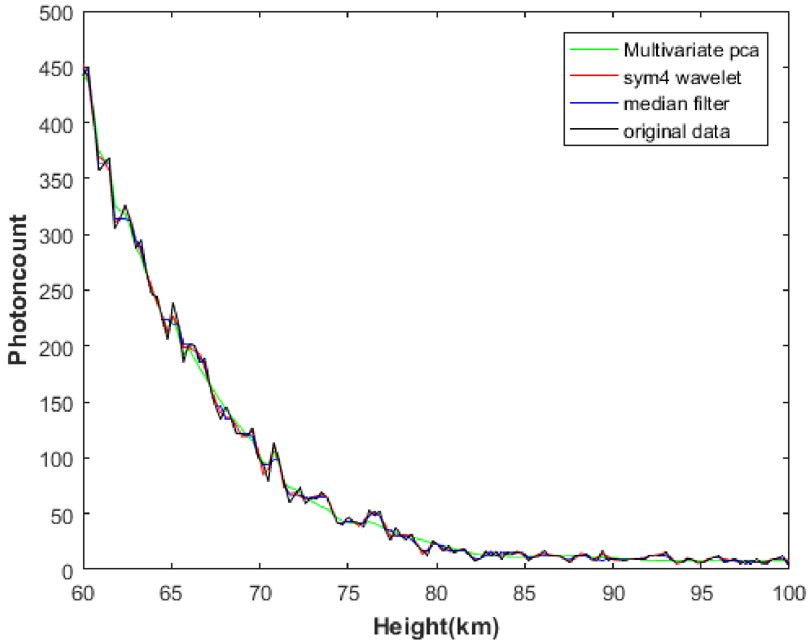

Fig 6:Comparison of denoising techniques on 05/02/11

Table 1 -signal to noise ratio of single profile on 05/02/2011 at different altitudes using different methods

Method	Signal to noise ratio(dB)				
	30Km	40Km	50 Km	60 Km	70 Km	80 Km
Multivariate PCA	56.85	48.91	39.82	33.25	26.52	20.22
Sym 4 Wavelet	43.95	36.01	26.92	20.35	13.63	7.32
Median Filter	44.48	36.55	27.46	20.89	14.16	7.86
Original signal	41.11	33.17	24.08	17.51	10.78	4.48

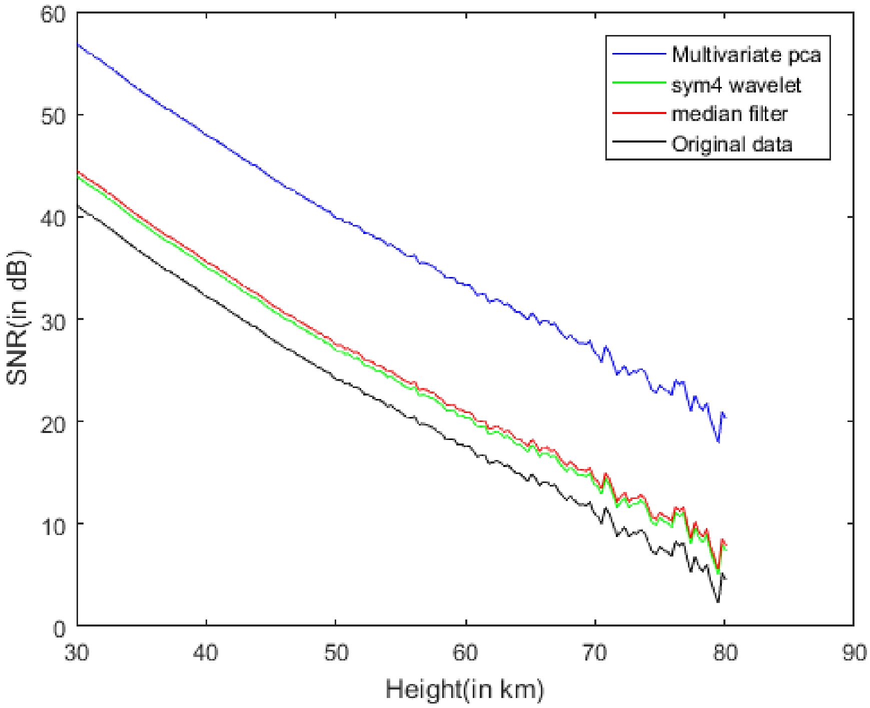

Fig7 :Comparison of signal to noise ratio of different denoising techniques on 05/02/11

The Photon count at a particular altitude is determined by equation(2)

$$N(z_i) = \frac{P_L \Delta t}{hc/\lambda}[o(z)]\left[\frac{c\Delta t}{2}\right][\beta_\pi(z)]\left[\frac{A_R}{(z_i - z_a)^2}\right][T_a^2(z)]\eta_t + N_B \qquad (2)$$

Where

$N(z_i)$ = number of photons received form altitude i[th] layer $(z - \Delta z/2, z + \Delta z/2)$

P_L = Laser power(watts)

Δt = integration time(sec)

H = planck'sconstant(6.634x10^{-34}JS^{-1})

C = velocityoflight(3x10^{8}ms^{-1})

λ = operatingwavelength(532nm)

O(z) = overlapfunction

R = laserpulserate(s^{-1})

A_R = receivertelescopearea(m^{2})

η_t = efficiencyoflidarsystem

z_0 = altitude of lidar site

$\sigma_{\pi m}$ = Miebackscatteringcross-section(m^{2})

$\sigma_{\pi r}$ = Rayleighbackscatteringcross-section(m^{2})

$n_r(z_i)$ = airmoleculesconcentration(m^{-3})

$n_m(z_i)$ = aerosol particleconcentration(m^{-3})

Δz = $c\Delta t/2$ = Receiverrangelength(m)

$T_a(z_o, z_i)$ = onewaytransmissionofatmosphere

N_B = $B_N R \Delta t$ =Backgroundnoise

$\beta_\pi(z) = n_r(z_i)\sigma_{\pi r} + n_m(z_i)\sigma_{\pi m}$ = Totalbackscatteringcoefficient($m^{-1}sr^{-1}$)

The background noise corrected signal becomes

$$N(z_i)-N_B=\frac{P_L\Delta t}{hc/\lambda}[o(z)]\left[\frac{c\Delta t}{2}\right][\beta_\pi(z)]\left[\frac{A_R}{(z_i-z_a)^2}\right][T_a^2(z)]\eta_t \quad (3)$$

Aerosol scattering ratio R(z) defined as is used to estimate the contribution of Mie diffusion in backscattered signal.N(z_i).

$$R(z_i)=\frac{\beta_\pi(z)}{n_r(z_i)\sigma_{\pi r}}=\frac{n_r(z_i)\sigma_{\pi r}+n_m(z_i)\sigma_{\pi m}}{n_r(z_i)\sigma_{\pi r}} \quad (4)$$

At λ=532nm,scattering ratio tends towards unity at 35km.The same wavelength chosen for the detection of Rayleigh backscattered returns from atmospheric molecules above 30km.scattering ratio is unity from 35 to 80 km and scattering ratio due to aerosol is negligible in the height region,$T^2(z_0,z_i)$ is constant between 35 and 80km.

Eq(3)becomes

$$N(z_i)-N_B=[\sigma_{r\pi}n_r(z_i)]\left[\frac{c}{(z_i-z_a)^2}\right] \quad (5)$$

where c is a constant evolved from several constants such as $A_R,\eta_t,P_t,\lambda,\Delta t \; and \; T_a$ .From eq(2),measured signal is proportional to atmospheric density[10].

The relative atmospheric density from lidar signal is given by

$$[\rho_{ref}(z)]=\frac{(N(z_i)-N_B)(z_i-z_a)^2}{k} \quad (6)$$

The air pressure P(z),density(z) and temperature T(z) are related by

$$P(z)=\frac{R\rho(z)T(z)}{M} \quad (7)$$

$$dP(z)=-\rho(z)g(z)dz \quad (8)$$

where R is the universal gas constant and g(z) is the acceleration due to gravity. By using total equations(7)and (8).The pressure with respect to altitude is shown in Equation (9)

$$\frac{dP(z)}{P(z)}=\frac{Mg(z_i)}{RT(z_i)}dz=d[\log(P(z))] \quad (9)$$

If the acceleration due to gravity and temperature is assumed to be constant in the i^{th} layer, the pressure at the top and bottom of the layer related by

$$\frac{P\left(z_i-\frac{\Delta z}{2}\right)}{P\left(z_i+\frac{\Delta z}{2}\right)}=\exp\frac{Mg(z_i)}{RT(z_i)}\Delta z \quad (10)$$

and the temperature is expressed as T(Z_i)using Chanin method and temperature at an altitude is

$$T(z_i)=\frac{Mg(z_i)\Delta z}{R\log\left[\frac{P(z_i-\frac{\Delta z}{2})}{P(z_i+\frac{\Delta z}{2})}\right]} \quad . \quad (11)$$

The presses at the top and bottom of the layer of i^{th} layer are expressed in following equations 12 and 13.

$$P\left(z_i+\frac{\Delta z}{2}\right)=\sum_{j=i+1}^{a}\rho(z_i)g(z_i)\Delta z+P_m(z_a+\frac{\Delta z}{2})$$

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(12)

$$P\left(z_i - \frac{\Delta z}{2}\right) = P\left(z_i + \frac{\Delta z}{2}\right) + \rho(z_i)g(z_i)\Delta z \quad (13)$$

Let $X = \dfrac{\rho(z)g(z)\Delta z}{P\left(z_i + \frac{\Delta z}{2}\right)}$.

(14) The atmospheric temperature is expressed as

$$T(z_i) = \frac{Mg(z)dz}{R\log(1+X)} \quad (15)$$

The statistical standard error on the temperature is

$$\frac{\delta T(z)}{T(z)} = \frac{\delta \log(1+X)}{\log(1+X)} = \frac{\delta X}{(1+X)\log(1+X)} \quad (16)$$

SABER(Sounding of Atmosphere using Broadband Emission Radiometry) is one of the instrument in NASA's TIMED (Thermosphere Ionosphere Mesosphere Energetics Dynamics) satellite.The primary goal of the SABER is to provide the data needed to advance our understanding of the processes directing the chemistry,dynamics,energetics and transport in the in mesosphere and lower thermosphere [11]. SABER achieve this with global measurements of the atmosphere using a 10-channel broadband limbscanning infrared radiometer covers the spectral range from 1.27 µm to 17 µm.These measurements provide vertical profiles of pressure,kinetictemperature.height,volume mixing ratios of co_2,o_3 and H_2o. NRLMSISE-00 is an global atmospheric reference model of Earth from ground to space.It models temperatures and densities of atmospheric components[12].This model is also used by astronomers to calculate the mass of air between telescopes and laser beams in order to assess the impact of laser guide stars on the non lasing telescopes.The comparison of denoised signal and orginal lidar signal temperature profile retrieval using equation 15 with saber data and NRLMSISE-00 data is shown in Figure 8.

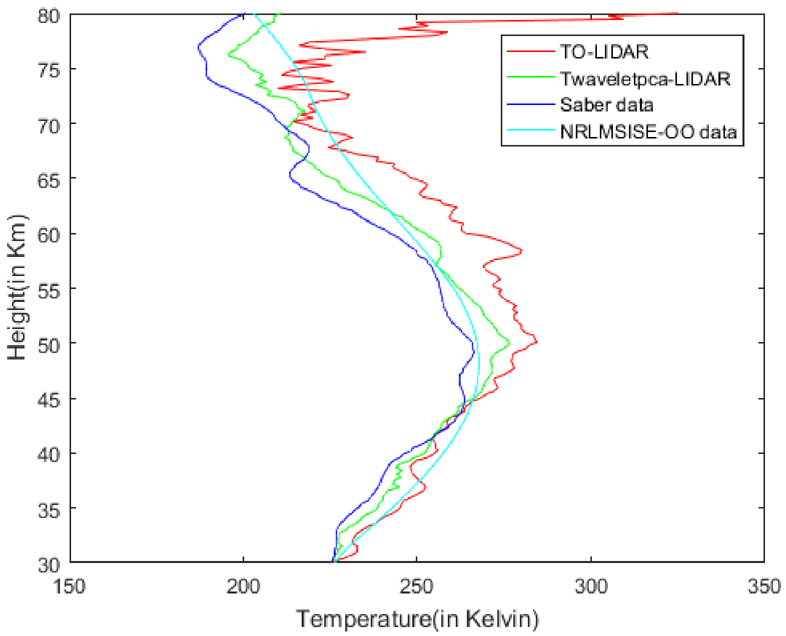

Fig 8 :Comparison of temperature profiles on 05/02/2011

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Conclusion:
The proposed PCA-wavelet transform reduces the noise and improves signal to noise ratio at higher altitudes compared with median filter and sym4 wavelet transform. The denoised lidar signal temperature profile is matches more equally with saber and NRMSISE-00 model data at different altitudes compared with original signal temperature profile.

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