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BINOMIAL FILTERING TO IMPROVE BACKSCATTERED LIDAR SIGNAL CONTENT

Aimé Lay-Ekuakille, Amerigo Trotta

Dipartimento d'Ingegneria dell'Innovazione, Università di Lecce, Lecce, Italy

Abstract − Binomial filter may be applied wherever easily predictable smoothing is required. That is possible in lidar signal processing. Digital filtering is a way of extracting noise from signal [1] beside poissonian averaging. Binomial filtering is useful in making data easier to interpret provided that proper perspective relative to measurement errors is maintained. Kaiser algorithm has been used to improve recovered data.

Keywords: Lidar, Remote sensing, Kaiser algorithm

1. WATER VAPOR DIGITAL FILTERING

In the laser detection [2] by means of lidar, there are five types of noise that can be treated with: *backscattering noise, quantum noise, statistical noise, dark current noise and noise due to optical elements.*

To discriminate noises [4] from the main signal that is backscattered from sky, we are investigating on the use of appropriate digital filtering to be utilized in order to retrieve a noiseless signal [5]. This approach is different from the current one that uses a poissonian averaging of collected data. In the first level of our investigation, we prefered to employ filters that preserve either amplitude information and phase one. We used various filtering technique to improve data retrieval from backscatterd signal [6]; that is, Finite-Impulse Response (FIR) or nonrecursive filters, least-squares filters, adaptative filters and ARMA (Auto Regressive Moving Average), etc. We have chosen to use normal FIR (Fig.1) and least-squares filters so that phase and amplitude information contained in the lidar signal must be preserved.

To design the filter, the following steps have been performed:

-*specifications for digital filter*: low-pass filter with sampling frequency f_s=10GHz, cutoff frequency f_c=400 kHz and passband ripple of 1 dB or less as specified in Fig.3;

-*the approximation problem*: obtain an input-output characterization of the filter (such as transfer function) that satisfies the specifications;

-*the realization problem*: obtain a realization that defines the internal structure of filter that has transfer function *H(z)*. The realization is chosen to optimize criteria associated with the actual computation. The resulting vector of filtering must be put in the following equation in order to obtain aerosol extinction profile that is correlated to water vapor, that is:

$$\alpha^{aer}(z) = \frac{\frac{d}{dz}\ln\left(\frac{z^2 s}{\rho}\right) - \alpha_{\lambda_L}^{ray}(z)\left(1-(\frac{\lambda_L}{\lambda_R})^4\right)}{1+(\frac{\lambda_L}{\lambda_R})^k} \quad (1)$$

where α is extinction coefficient (aerosol and rayleigh ones), ρ stands for air density, z^2s is the filtered signal, λ_L and λ_R are respectively lidar wavelength and Raman one. Figure 2 illustrates the application of equation (1) after filtering as shown in figure 1.

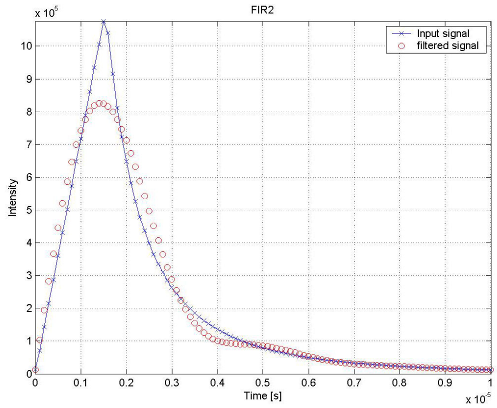

Fig. 1. Digital filtering with FIR filters

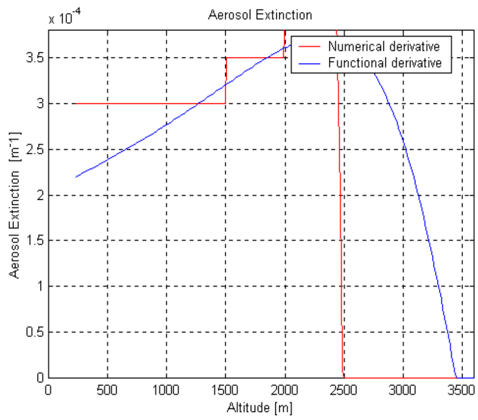

Fig. 2. Aerosol extinction obtained by FIR filtering

2. BYNOMIAL FILTERING AND DATA SMOOTHING

The “lidarist” frequently wishes to process his experimental data to obtain as accurate and clean a representation of water vapor as is consistent with his measurement accuracies [7]. In measurements contaminated by high-frequency noise this usually means smoothing the experimental data by some method (which is equivalent to smoothing with a low-pass filter) to eliminate or greatly reduce the amount of high frequency noise without distorting the desired signal. For data which are continuous in time (analog data) this is commonly accomplished using low-pass RC filters. However, with the increasing use of computer-controlled data acquisition systems which record data in digital form, there has developed a need for techniques which perform the same filtering process on the digitized data [8]. Filtering or smoothing process should be as simple and efficient as is consistent with experimental situation.

In the general case, a smoothing formula should have the following properties:

(1) Zero phase shift at all frequencies unless the transfer function is negligible at frequencies where there is some phase shift.

(2) The sequence of smoothing coefficients should be such that smoothing introduces no undesirable side effects such as multiple peaks when only one is present in the original data, or overshoots and undershoots in the response to an impulse or to a step function.

(3) Nowhere should the transfer function become > 1, especially if repeated used of the formula on the same data have to be performed, since some frequency components would thereby be unduly enhanced.

Note that these are general criteria that are sufficient but not necessary in all possible cases. There may indeed be particular experimental cases where they may not apply to the smoothing algorithm which optimizes the measurement error of the desired parameters. Still, they are applicable in a wide range of situation and, therefore, useful [9].

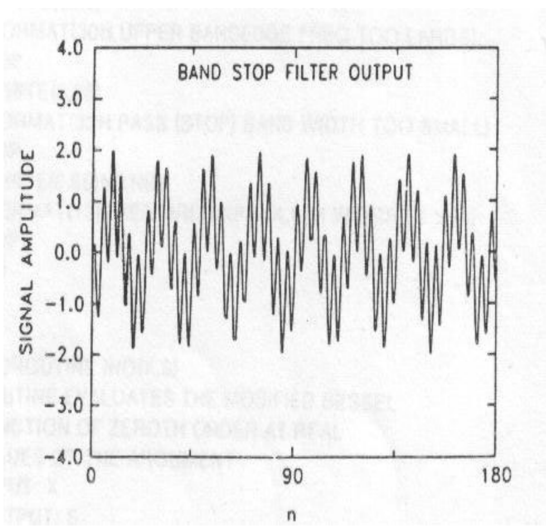

Fig. 3. Data after bandstop filter

To be coherent with previous experimentation with FIR filter and in order to make a best comparison, low-pass filter with Kaiser algorithm has been implemented as second level of our investigations. For the first step, a bandpass filter has been designed (Fig. 3) by summing three cosine functions. But for lidar signal content evaluation, it is appropriated to use a low-pass filter that will give a similar result of figure 3 but with a signal amplitude between –3.0 and 3.0.

The adopted window of FIR filter design started with the design of a least-squared-error approximation. If the desired filter has a basic-pass response, the impulse response of the optimal filter is

$$\hat{h}_d[n] = \frac{\sin(\omega_0 n)}{\pi n} \tag{2}$$

the shifted and truncated version is

$$h(n) = \begin{cases} \dfrac{\sin(\omega_0 (n-M))}{\pi(n-M)} \\ 0 \end{cases} \tag{3}$$

Relationship (3) is valid for 0≤n≤L-1 otherwise *h(n)* is zero for *M=(L-1)/2*.The truncation was obtained by multiplying Eq.(1) by a rectangle function. Multiplication in the same domain by a rectangle is convolution in the frequency domain by a sinc function. Since that is what causes the Gibbs effect, we will multiply by a window function that has a smoother Fourier transform with lower sidelobes. One method of smoothing the ripples caused by the sinc function is to square it. This results in the window being a triangle function, also called the Barlett window. The four generalized cosine windows, used in our experimentations, are given by

$$W[n] = \begin{cases} a - b\cos\left(\dfrac{2\pi n}{L-1}\right) + c\cos\left(\dfrac{4\pi n}{L-1}\right) \\ 0 \end{cases} \tag{4}$$

Relationship (4) is valid for 0≤n ≤L-1 otherwise 0. The names of the used windows and their parameters are:

TABLE 1: Window specifications

Window	**a**	**b**	**c**
Rectangular	1	0	0
Hann	0.5	-0.5	0
Hamming	0.54	-0.46	0
Blackman	0.42	-0.5	0.08

A more flexible and general window, used in this paper, is the Kaiser window given by

$$W[n] = \begin{cases} \dfrac{I_0(\beta\sqrt{1-[2(n-M)/(L-1)]^2})}{I_0(\beta)} \\ 0 \end{cases} \tag{5}$$

Relationship (4) is valid for *0≤n≤L-1* otherwise zero where *M=(L-1)/2*, $I_0(x)$ is the zeroth-order modified Bessel function of the first kind and β is a parameter to adjust the width and shape of the window. The generalized cosine windows have no ability to adjust the trade-off between transition bandwidth and overshoot and therefore are not very flexible filter design tools. The Kaiser window, however, has a parameter β which does allow a trade-off and is known to be an approximation to an optimal window. An empirical formula for β that minimizes the Gibbs overshoot is

$$\beta = \begin{cases} 0.1102(A-8.7) \\ 0.5842(A-21)^{0.4} + 0.07886(A-21) \\ 0 \end{cases} \qquad (6)$$

the first line of the relationship is valid for $50 < A$, the second one is valid for $21<A<50$ and the third one for $A<21$, where

$$A = -20\log_{10}\delta \qquad (7)$$

$$\Delta = \omega_s - \omega_p \qquad (8)$$

$$L-1 = \frac{A-8}{2.285\Delta} \qquad (9)$$

with δ being the maximun ripple in the passband and the stopband. Because the Bartlett, Hanning, and Blackman windows are zero at their endpoints, multiplication by them reduces the length of the filter by 2. To prevent this shortening, these windows are often made $L+2$ in length. This is not necessary for the Hamming or Kaiser windows. These windows not only can be used on the classical ideal low-pass filter given in Eq.(2) and Eq.(3) but can be used on any ideal response to smooth out a discontinuity.

Fig.4 illustrates the application of Kaiser's algorithm together with normal filtering as shown in Fig. 1. It is clear that

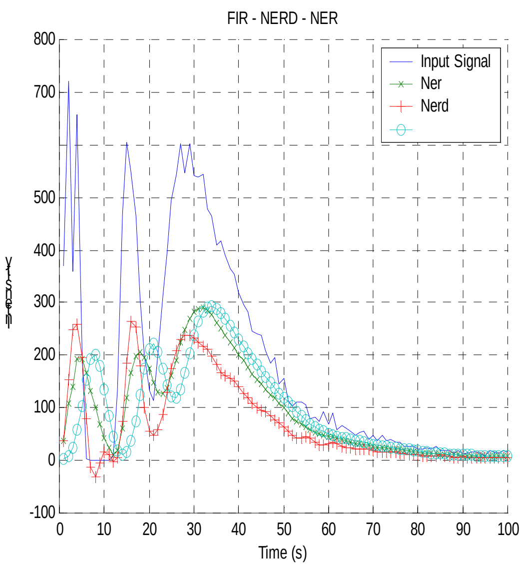

Fig.4. Comparison for different techniques

the Nerd approach is the best one for the present lidar signal since it allows a maximum reduction of noise. That is one of the advantages of adjustable windows. Fig.5 and Fig 6 illustrate profiles of extinction and number of countings respectively; they have been recovered from Fig. 1, and Fig. 3 after having used relationship (1).

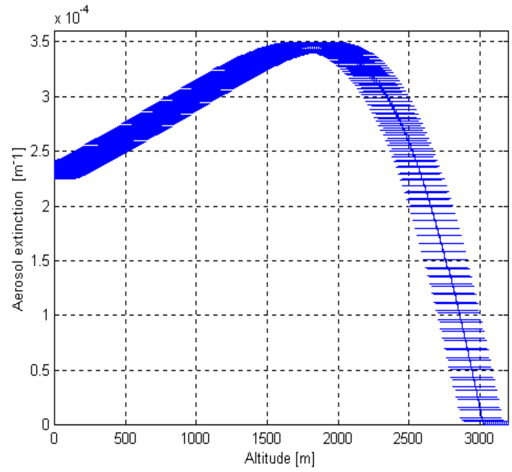

Fig. 5. Spatial – domain aerosol extinction with error band

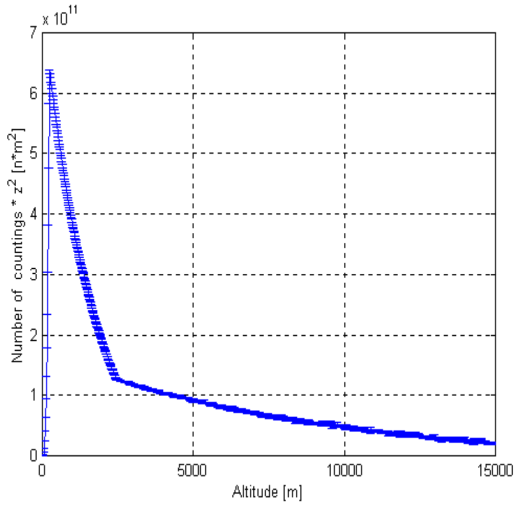

Fig. 6. Number of countings in spatial – domain

3. SUMMARY AND CONCLUSION

Poissonian averaging has been using for filtering lidar signal data. In previous work we showed the opportunity of using digital filtering in order to overcome problems created by poissonian averaging. To introduce further improvement in filtering we have used binomial filters; some scientists also use differentiating smoothing in an attempt to compensate for the fact that differentiation reduces the signal-to-noise ratio. This can easily be performed with the binomial filter by convolving either the filter coefficients or the data by sequences [1,0, -1]/2. This may be repeated any number of times to obtain the second-third-,and higher-order derivatives, after which the data are low-pass filtered in usual manner [10]. The advantages of the above adjustable windows compared to the fixed windows are their optimality and flexibility. Given ω_p, ω_s and the minimum stopband attenuation A_s of the filter, the adjustable parameter can be dtermined to give the desired A_s, whereas M can be determined to give the desired value for the transition bandwith $\Delta\omega=\omega_s-\omega_p$ of the filter.

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Authors: Aimé Lay-Ekuakille, Amerigo Trotta, Dipartimento di Ingegneria dell'Innovazione; Facoltà d'Ingegneria, Via Arnesano-Monteroni, 73100 Lecce, Fax +39.0832.325004, Phone +39.0832.297226, aime.lay.ekuakille@unile.it