Clutter Mitigation Techniques For Doppler Weather Radar For Fine Grain Velocity Estimation

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***Abstract**:*

Weather Radars provide valuable information on various weather phenomenon such as rain, hail, storm, etc that are increasingly become important in today's scenario where disaster management has got a wider role to play. But due to the way a radar works, not only precipitation but also unwanted echoes ,that we broadly classify as clutter , which includes returns from land, sea waves, birds, insects, buildings, etc, is observed by the radar. Such cluttered returns interfere with weather products estimation. Clutter detection and mitigation play a massive role in ensuring accurate weather estimation. In this paper we present two different clutter filtering approaches viz, 1) Time domain- IIR Filtering Approach and 2)Frequency Domain- FFT spectral processing Approach. Their feasibility in fine grain velocity estimation is discussed and a novel technique for further improvements in Clutter Filtering Approach is suggested. We shall also discuss the loss of velocity information in certain Doppler bands experienced by other clutter filtering techniques and a solution is proposed for the same.

key words: doppler weather radar,clutter,FFT,IIR

I INTRODUCTION:

A Radar clutter is any unwanted return(s) from targets that are undesirable from the point of view of the specific application of the Radar. What is clutter for one application of a given radar may be the target for another radar application. For example, returns from ships, enemy planes, etc, are targets for a Surface Surveillance Radar but for a Weather Radar these returns are clutter. Similarly, returns from clouds are targets for Weather Radar but undesirable returns for Surface Surveillance Radar.From the point of view of Weather Radars, echo returns due to ground, sea, and other obstacles such as buildings, mountains, etc and other stationary targets represent sources of error in quantitative radar rainfall estimation. These returns are undesirable and ideally we would like to remove them before any quantitative estimation. From the above discussion it is evident that we need to remove or lessen the effects of the static or slow moving targets, so that they may not impede the accurate estimation of the targets of interest. In this paper, we shall discuss the time-domain and frequency domain approach to mitigate the effects of clutter.

II. CLASSICAL CLUTTER FILTERING APPROACH

The traditional approach to time domain clutter filtering involves the use of High Pass IIR filter. High Pass IIR filter is designed such that it suppress clutter falling in stop band sufficiently without affecting pass band targets. The basic equation of a n-tap IIR filter is as follows:

$$Y[n] = a_0X[n] + a_1X[n-1] + a_2X[n-2] + a_3X[n-3] + \ldots + b_1Y[n-1] + b_2Y[n-2] + b_3Y[n-3] + \ldots \quad (1)$$

Where a, b are coefficients, X is input signal and Y is output signal.
Coefficients value depends on IIR specifications such as filter type, pass band attenuation, stop band attenuation, and order of filter. Filter response of four basic IIR filters types are as shown below.

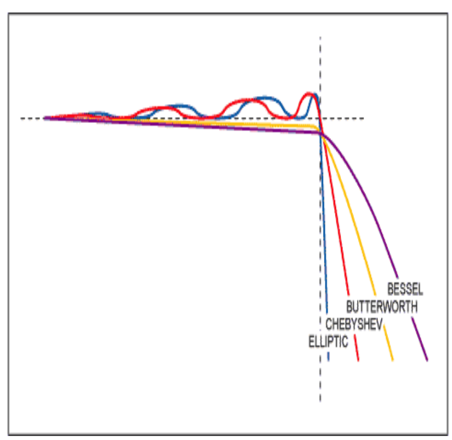


Figure 1. Four basic filter types.

For weather applications order of filter may be in the order of 5,stop band attenuation should be greater than 30 dB, and pass band ripple and roll-off should be minimum. Keeping all these requirements into consideration CHEBYSHEV filter is our obvious choice. So, specifications of IIR filter proposed in this paper are as below.

Response Type : High Pass.
Filter Type : Chebyshev Type II.
Order : 5.
Stop band Attenuation : 50 dB.
Stop band frequency : 60Hz.

Magnitude and phase response of proposed clutter filter are as shown below:

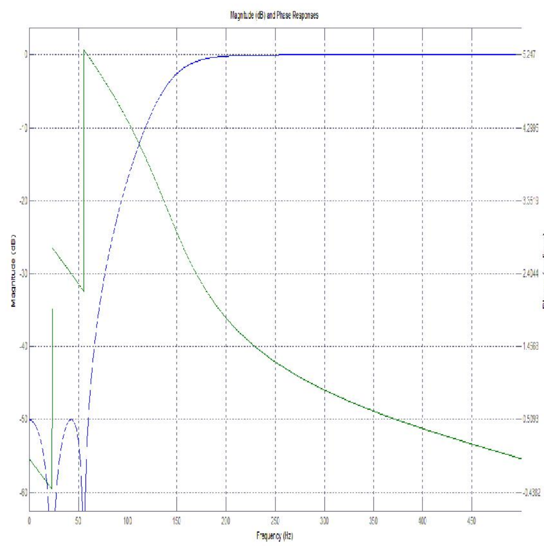
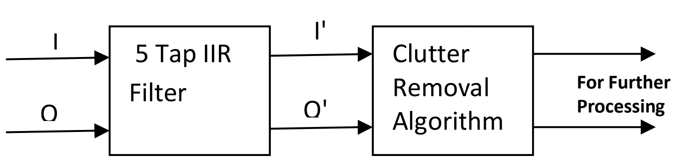


Figure 2. Magnitude and Phase Response.

1. Implementation Of IIR Approach:



The steps used to implement this approach are summarized as follows

Step1: The incoming In phase(I) and Quadrature phase(Q) samples from digital down converter are passed through an appropriate IIR Filter.

Step2: Cluttered return power is calculated using pulse pair algorithm using filtered In phase(I) and Quadrature phase(Q) samples.

Step3: Uncluttered return power is calculated using pulse pair algorithm using unfiltered In phase(I) and Quadrature phase(Q) samples.

Step4:Clutter Suppression Ratio(CSR) is calculated using uncluttered and cluttered power.

Step5: DC and low frequency contents(clutter) are removed using calculated clutter to signal ratio (CSR).

2. Simulation Results: In order to illustrate the effectiveness of IIR filter approach on clutter suppression, we have simulated only target and target plus clutter in MATLAB and results are as shown below.

I. Simulation 1: Only Target

Simulation Characteristics

	Clutter	Weather	Units
power	0	–46	dB
velocity	0	5.3	m/s
PRF	1000 Hz		
Samples	128		
wavelength	0.053m		

Input Plots:

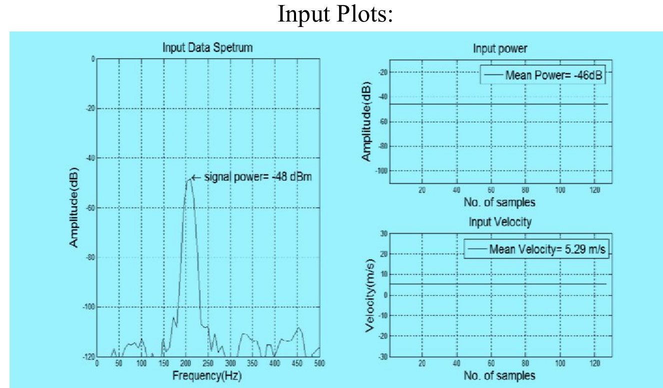


Figure 3

Output Plots:

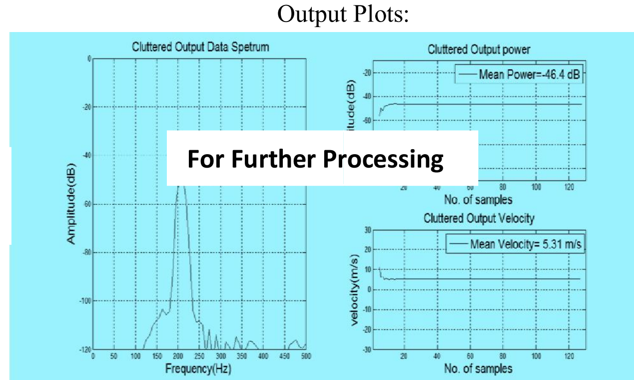


Figure 4

***Simulation 2*: Target and Clutter**

Simulation Characteristics

	Clutter	Weather	Units
power	-26	–46	dB
velocity	0	5.3	m/s
PRF	1000 Hz		
Samples	128		
wavelength	0.053m		

Input Plots:

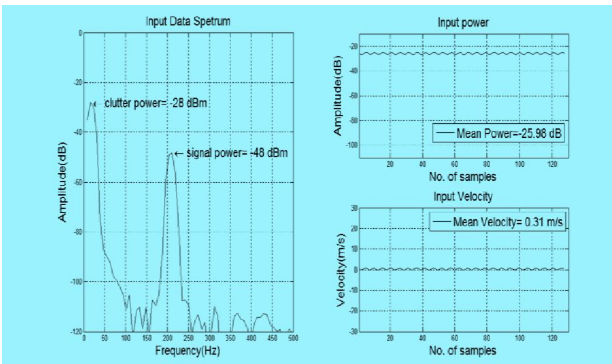


Figure 5

Output Plots:

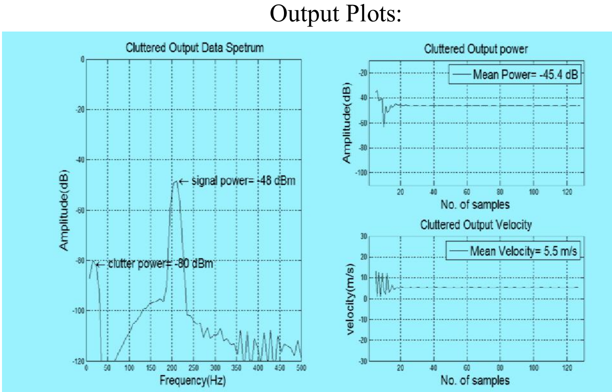


Figure 6

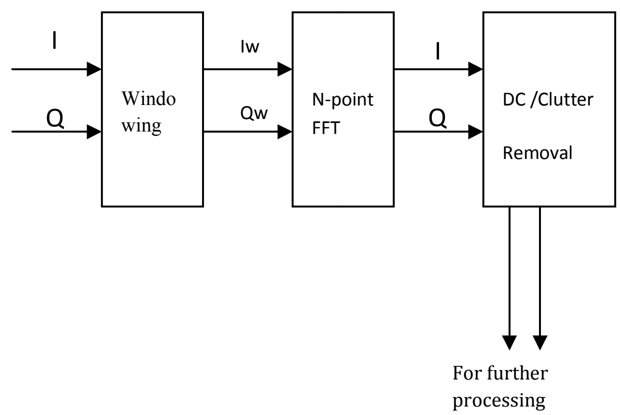
Comment On Results: From the simulation results it is quite obvious that when both clutter and weather returns are present then the rainfall estimations are erroneous, if clutter is not suppressed substantially. So, traditional IIR filtering approach helps in mitigating clutter effects. Although IIR filter has minimal storage and computation requirements but it has some major drawbacks:

- The infinite impulse response requires considerable settling time when a transient occurs such as a PRF change, or a spike in the echo. During the settling time, the transient response degrades the performance of the filter.
- The filter is fixed width in the Nyquist interval. This means that it may be sufficiently wide to remove moderate or weak clutter, but may not be wide enough to remove all of the clutter when the clutter power is very strong and consequently wider in the Nyquist interval. This causes operators to select wider filters than necessary so that strongest clutter is adequately removed.
- The filter does significant damage to overlapped (zero velocity) weather signals.

III. FREQUENCY DOMAIN APPROACH TO CLUTTER FILTERING

The advent of powerful processors and the storage of large amount of data no longer being a constraint, the frequency domain approach to radar signal processing has become attractive. Clutter filters based on this approach can be accomplished using FFT on the incoming digital I and Q samples. The transformed output can be further used for calculation of moments for the estimation of target's characteristics.

1. Implementation Of Frequency Domain Approach:



The steps used to implement this approach are summarized as follows:

Step1: The incoming In phase(I) and Quadrature phase(Q) samples from digital down converter are passed through an appropriate window.
Step2: Using the process of FFT on the windowed output(Iw, Qw) to generate Doppler Spectra(PSD).
Step3: Reorder the spectrum to its correct index of frequency (i.e. -fmax to +fmax).
Step4: Subtract noise level from spectrum.
Step5: Remove the DC and low frequency contents (clutter) from spectrum using clutter standard deviation(CSD) and do interpolation.
Step6:Calculate zeroth moment or Total Power in the Doppler spectrum, first moment or Mean Doppler in Hz

and second moment or Variance using spectrum obtained from Step 5.

2. Simulation Results: In order to illustrate the effectiveness of FFT filtering approach on clutter suppression, we have simulated target plus clutter in MATLAB and results are as shown below.

Simulation: Target and Clutter

Simulation Characteristics

	Clutter	Weather	Units
power	-26	–46	dB
velocity	0	5.3	m/s
PRF	1000 Hz		
Samples 128			
wavelength	0.053m		

Input Plots:

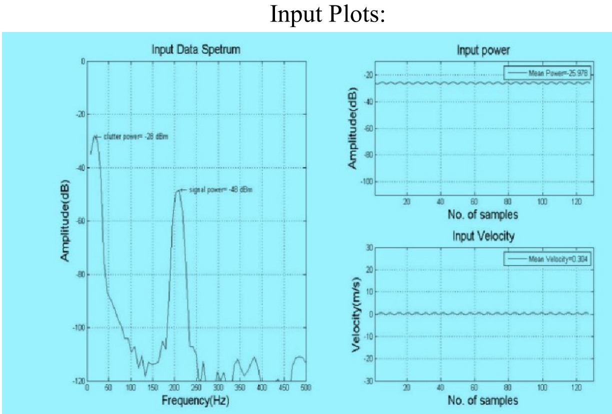


Figure 7

Output Plots:

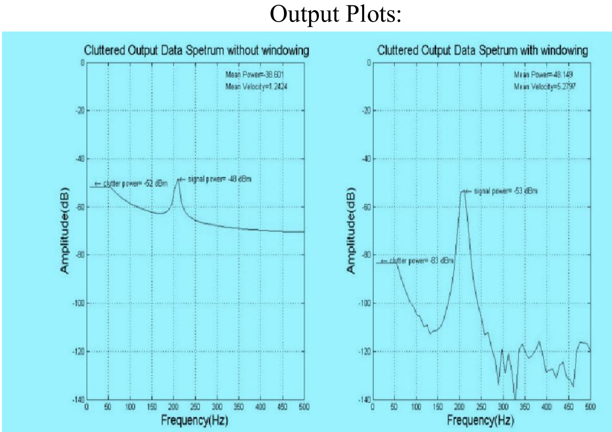


Figure 8

Comment On Results: Using an appropriate window is very important to limit the effects of spectral leakage and picket fence effects arising due to the application of Fourier Transform on a finite data sequence. Side lobes reduction generated in the spectra due to discontinuities at the ends of the signal measurement time will interfere in the accurate estimation of moments after the Fourier Transform. Hence, windowing must be done to reduce such effects. But, one must be careful with the choice of window, as it can be too aggressive or mild. A very aggressive window can suppress signals even in environments where there is little or no clutter whereas a mild filter can prove to be ineffective in reducing side lobes of in the presence of heavy clutter. Also, there is trade-off between a narrow bandwidth window function and side-lobe reductions. Ideally we would want a windowing function that has a very narrow bandwidth and strong side-lobe rejection.

Although FFT filtering approach requires more resources than IIR approach but it shows drastic improvement over some of the drawbacks of IIR approach:

- The FFT filtering allows for better target frequency determination and immunity from clutter as we are only interested in the peaking bin that can be easily discernible once the clutter has been neutralized as mentioned above. This also does not suffer from the phase non-linearity of an IIR filter's transition zone. Also, it is not plagued by the long settling time of the IIR filter response.
- The filtering of clutter represented by a sharp peak on the zero frequency regions is performed by removing the peaks and interpolating across the 0Hz region of the resultant Power Spectra ,due to this overlapped (zero velocity) weather signals don't suffer significant damage.

3. Limitation of FFT approach:

- The most significant limitation arises from the limited number of samples that is available for the spectral analysis. If we regard the FFT as equivalent to a series of filters centered on each spectral sample, the width of each of these filters is limited by the Pulse Repetition Frequency(PRF) and the number of FFT points(N).

$$Fbin=PRF/N$$

The limitation in the resolution of each of the FFT filters results in the maximum absolute error of Fbin/2 in the determination of frequency of the target . Naturally if the PRF is large and the samples are small in number, then substantial error is introduced.

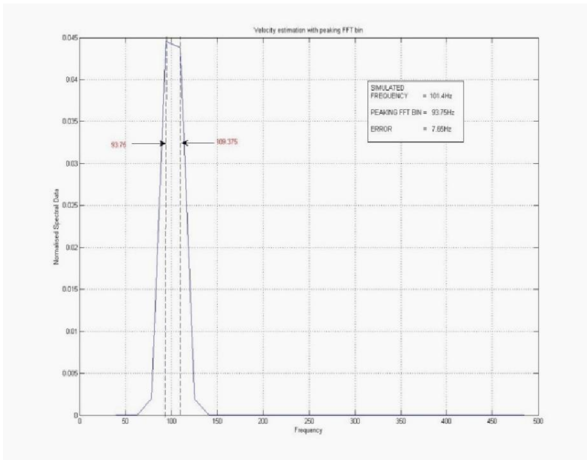


Figure 9

As can be seen in fig (9), an error of 7.65Hz is generated with 64 pulses FFT output. This error can be mitigated to great extent if we calculate the velocity using non-parametric method of moment estimation. The simplest such method is Periodogram Approach. The target's frequency can then be estimated as

$$\mathrm{E}[X] = \frac{x_1 p_1 + x_2 p_2 + \ldots + x_k p_k}{p_1 + p_2 + \ldots + p_k}. \quad (2)$$

Where,
X =frequency of the kth bin of FFT, $0 \le k \le N-1$;
Pk =amplitude of the kth bin, $0 \le k \le N-1$;
E[X] =Expected value of X,

The Frequency estimated using the above method is as good as 101.24Hz, i.e. the error is only 0.16Hz which is a massive improvement over the 7.65Hz,the error obtained using Peaking Filter Method. This method enables a very fine grain velocity estimation and in many ways is superior to other methods of estimation because of its simplicity and accuracy.

- Due to non adaptive nature of window, real time aggressive/mild window selection based on returned clutter/target is not possible.

IV. IMPROVEMENTS OVER THE EXISTING TECHNIQUES FOR CLUTTER SUPPRESSION IN FREQUENCY DOMAIN:

1) GMAP clutter filtering approach: The Gaussian Model Adaptive Processing is essentially a frequency domain filtering approach which requires minimal operator involvement. This technique adjusts the windowing method to the raw data so that the windowing does not increase the variance in moment estimates.

The steps used to implement this approach are summarized as follows:

Step1: Calculate the moments using an aggressive windowing method.

Step2: If the clutter suppression ratio(CSR) is high, we will retain the windowing method and the results of the estimation.

Step3: If the CSR is not as high we shall repeat step1 with a lesser aggressive window ,for example a Hamming Window, then calculate the moments again.

Step4: If the CSR is higher than the acceptable limit we take the results of step3,else we use a rectangular window for our calculation which introduces minimum variance in the estimation.

2) Distance based Adaptive Window (DAW) technique

Although the GMAP offers considerable improvement over the usual Periodogram approach in reducing the variance of the moment's estimates, it significantly increases the processing requirements of the Signal Processor. Also, the method increases considerable time lag between the final values of the estimates and the start of the processing as multiple iterations are involved, which can be difficult for a radar system with high antenna rotation speed as the time for computation is very little.

The DAW technique offers an improvement to the Periodogram Method while reducing the time lag and resources required to obtain similar improvements over the Periodogram Approach. However, the choice of operator involvement is optional. We make use of the inverse relation between range cells and the clutter power. We know that the clutter reduces as the square of the range from the antenna and, more importantly, at higher ranges clutter sources and hence power is not expected for the specifically for a weather radar. Thus the technique uses the varying window approach for a reducing the variance of moments estimated using the FFT approach. The steps used to implement this approach are summarized as follows:

Step1:Calculate the moments using an aggressive window for near target range.

Step2:Calculate the CSR (Xn) for the nth range cell in the near range and compare the value with threshold value for the CSR for the near range cell. For example, if the CSR threshold is 25db and the value for Xn is greater than the threshold then continue with the same window for the next range cell.

Step3:If Xn is less than 25db then we will continue with the same window for the next range cell.

Step4:If the CSR calculated has been less than the threshold CSR for consecutive number of range cells (say for 5 cells), then switch to a moderate windowing method with much lesser variation in moments.

Step5:Repeat steps 2,3 and 4 for the moderate window with consequent transition towards a lesser aggressive window till we arrive at the rectangular window. It must be noted that the choice of threshold can rest with the operator or it can be incorporated in the algorithm as standard values. The number of comparisons before switching the windowing method can once again be operator controlled ,however this ensures a smoother transition of the window and overcome the "one-off" CSR reduction for any range cell

3) Spectrum Edge Effect: The FFT based moments calculation is much simpler than the time domain approach in terms of the ease of clutter filtering and the flexibility involved once the FFT of the I and Q data is obtained. However, the nature of FFT spectra so obtained introduces effects that hinders the accurate calculation of moments. The most notorious of them is what we call as the Spectrum Edge Effect.An observation of the Spectrum of the Weather data reveals that the return target spreads over several FFT bins and if it happens to be of a higher velocity (close to PRF/2), it can spill over to the negative spectrum which gives an unacceptable velocity estimate of the return target. This is particularly severe when the number of pulses are limited which is typical of a sophisticated modern day weather radars. Since, the mean Doppler frequency shift is calculated making use of the entire spectra with the respective power of each range cell acting as the weight for each range bin. So the high velocity estimates are severely compromised because of the greater power spillage towards the negative spectrum when the frequency of the Doppler is closer to the Nyquist frequency for a given PRF.

To overcome this problem we make use of the initial assumption of the radar clutter that the clutter returns are mostly stationary and their effects are concentrated around the DC line of the frequency spectrum. Hence, the effect of clutter at a higher velocity is often negligible.

The method involves the calculation of unfiltered Doppler velocity in the time domain of the incoming radar returns. This velocity may not be correct for lower Doppler frequency shifts but are reasonable accurate for higher dopplers. We compare the frequency estimates after FFT with the unfiltered frequency estimate obtained in the Time domain if the calculated estimate is greater than Nyquist frequency/2 to avoid unnecessary comparisons. If the estimates vary greatly, if throw the estimate of the FFT method and take the frequency value of the unfiltered data. This can effectively solve the problems arising due to the Power spillage and restore the credibility of the values so calculated.

CONCLUSION:

The clutter mitigation techniques have evolved continuously over last decade or two and with the effective employment of techniques like FFT and GMAP and the virtually unlimited processing, storage capacity and speed of the modern day processors, the technology is sure to reach unprecedented heights over the next decade.

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