ECE Senior Capstone Project 2022 Tech Notes

Mahogany

Overview of Doppler Processing

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Introduction

For radars, the purpose of doppler processing is to suppress clutter and be able to detect moving targets. The solution to increase power is not an efficient way to increase signal to clutter ratio. Signal processing techniques are used for clutter suppression. Clutter consists of unwanted echoes returning to the radar that could result from the atmosphere (ex. rain), ground and buildings, birds, and more. Doppler processing is useful when the reflected signal from the target has an amplitude greater than that of noise (SNR>1) and smaller than the amplitude of the clutter return. In this case, the goal is to filter out the clutter bands in the frequency domain and leave the reflected signals from the moving targets. There are two common techniques for doppler processing: Moving Target Indicator (MTI) techniques and Pulse Doppler (PD) techniques. MTI filtering separates moving targets from clutter using high-pass filtering. It uses short waveforms that consist of 2-3 pulses and as a result do not provide velocity estimation. MTI implements all the processing in the time domain and uses less computations but produces limited information. PD techniques on the other hand are frequency domain techniques that separate targets into different velocity bands and estimates radial velocities of desired targets by using long waveforms (up to thousands of pulses).

Background

Doppler Frequency

Doppler frequency is the change in frequency (Δf) that is perceived by the radar transreceiver due to a target moving radially towards or away from the radar. Doppler frequency is calculated by $\Delta f = \frac{2V}{\lambda}$. As seen in figure 1, clutter of various sources are shown, with ground ("stationary") clutter having the highest power level. Range estimation from echo time-delay cannot be used in this case since the target and the clutter sources could be in the same range.

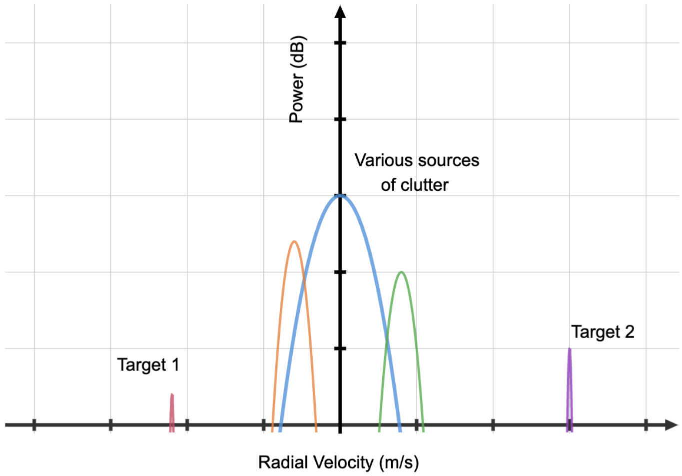

Figure 1 Sample Power vs Doppler Velocity plot (based on [1])

Terminology

There is various terminology used in this field that are relevant. The time between individual transmitted pulses is called *pulse repetition interval* (PRI). The pulse repetition frequency (PRF) is the inverse of the PRI (i.e., 1/PRI). The ratio between the pulse length to the pulse repetition interval is called the *duty factor*. The time interval that includes all the pulses transmitted before processing is done is called the *coherent processing interval* (CPI). For MTI filtering, the CPI contains few pulses, and for PD filtering, the CPI contains potentially thousands of pulses.

Data Collection

Next, data collection by the receiver should be addressed. The radar transmits pulses and there is "dead time" in between pulses. During this time, the receiver (another or same antenna) is listening for incoming signal which is the sum of many echoes. The analog signal received during this time is digitized and stored in memory. Each sample number corresponds to a particular range (“range bin”). The initial samples would correspond to very close ranges to the receiver and the final samples correspond to further ranges. Then, the radar switches from listening to transmitting and another pulse is sent. This process is repeated for the whole CPI. The data collected can be organized in a 2D matrix as shown below before they processed. As a extra detail, each digital sample obtained from the received analog signal consists of both a real and an “imaginary” component (in-phase and quadrature sampling) in order to keep track of the amplitude and phase of the signal.

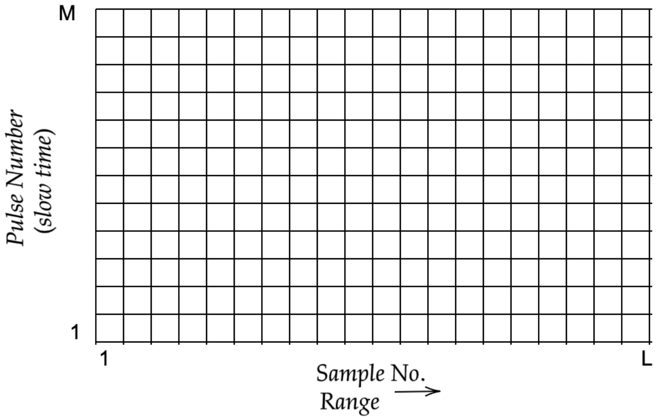

Figure 2 Received Data Matrix (based on [1])

Moving Target Indication (MTI):

MTI filtering is a high-pass notch or a matched filter. It significantly attenuates doppler frequencies close to zero (stationary and slow objects) and passes all other frequencies. The information provided is quite limited: MTI only indicates whether a target is present in a particular range bin or not. It does not indicate the number of targets in a particular range, their moving direction, or their velocities.

For MTI filtering, common digital high-pass filters can be used. High-pass filters significantly attenuate frequencies below a chosen cutoff frequency f_{cutoff}. One such filter is the two-pulse canceller in which two consecutive pulses are subtracted from each other. The stationary clutter component should be removed in this subtraction operation since they are (hopefully) identical between the pulses, but the phase of the moving target is changing. The transfer function and the frequency response of this filter can be derived as follows:

$$\begin{aligned} H(F) &= (1 - z^{-1})\Big|_{z=e^{j2\pi Ft}} \\ &= 1 - e^{-j2\pi Ft} \\ &= e^{-j\pi FT}(e^{+j\pi FT} - e^{-j\pi FT}) \\ &= 2je^{-j\pi FT}\sin(\pi FT) \end{aligned}$$

A three-pulse canceller consists of a cascaded two-pulse cancellers and has a smoother transition from low to high frequencies. An N-point canceller will have the frequency response and time-domain impulse response as follows:

$$\mathbf{H_N(Z) = (1 - z^{-1})^{N-1}}$$

$$\mathbf{h_N[m]} = (-1)^{\mathbf{m}} \binom{N-1}{m} = (-1)^{\mathbf{m}} \frac{\mathbf{(N-1)!}}{\mathbf{m!(N-1-m)!}}, \quad \mathbf{m = 0, ..., N-1}$$

Many other finite-impulse response (FIR) high-pass filters can designed to meet desired specifications using variety of techniques. An infinite-impulse response (IIR) digital filter can be designed as well for superior performance.

Moreover, optimal MTI filters involve designing matched filters. Matched filters work by correlating the “expected” target echo signal with the received signal (presumably containing clutter and noise). The goal of optimal MTI filtering is to find filter coefficients that will maximize the signal-to-interference (SIR) ratio of the filtered data. The result of the derivation of the optimum filter coefficients is presented below:

$$\mathbf{h} \equiv \begin{bmatrix} h[0] \\ \vdots \\ h[N-1] \end{bmatrix} = \mathbf{S_I^{-1} t}^*$$

- $\mathbf{h}$ = $N \times 1$ column vector of filter coefficients
- $\mathbf{S_I}$ = $N \times N$ covariance matrix of the interference
- $\mathbf{t}$ = $N \times 1$ column vector representing the desired target signal to which the filter is matched

To evaluate the effectiveness of MTI filtering, the *MTI Improvement Factor* is calculated as follows: $\frac{(signal/clutter)_{out}}{(signal/clutter)_{in}}$. It is the signal to clutter ratio after processing, divided by the signal to clutter ratio of an individual pulse. As an additional detail, it is difficult to find targets with doppler frequencies at a multiple of the sampling frequency (PRF). One solution is to use *staggered* PRFs which involves changing the PRI between pulses; however, this also suffers its own problems.

Pulse Doppler Processing (PD):

PD processing passes the M pulse returns saved in memory through a bank of digital filters as depicted in figure 3. These filters are designed such that each one passes a certain doppler frequency (corresponding to a velocity) and suppresses all the rest. The velocity *resolution* is a measure of the range of velocities that are also passed through a single filter around its *center velocity*. For example, a filter could be centered at 20 m/s but passes velocities from 17 m/s to 23 m/s. An important topic for PD processing is the notion of *Doppler Ambiguities*. This is equivalent to *aliasing* in digital signal processing (DSP). The maximum velocity that can unambiguously be detected is $V_{max} = \frac{\lambda(PRF)}{2}$. Velocities higher than this value will falsely appear within the desired velocity range. For example, if the PRF corresponds to 150 m/s, a target moving at 160 m/s could be detected by the radar as moving at 10 m/s. Similarly, the maximum unambiguous range is given by $R_{max} = \frac{c(PRI)}{2}$ where c is the speed of light. In other words, if the round-trip time for a pulse hitting a target is greater than the PRI, it will be detected by future pulse returns, giving a false impression that a target appeared within the desired range. As noted before, a trick to detect velocities higher than the maximum unambiguous velocity is to send out multiple CPIs with different PRFs, and use math tricks (such as the Chinese Remainder Theorem) to detect and undo the aliasing.

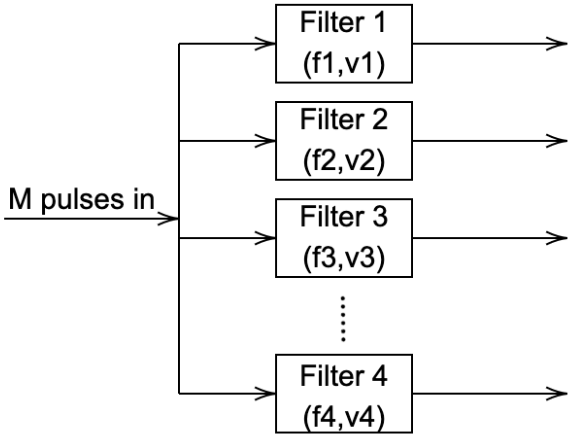

Figure 3 Pulse doppler processing seen as filter bank (based on [2])

Summary

Two signal processing techniques are used for clutter suppression: Moving Target Indicator (MTI) and Pulse Doppler (PD) processing. MTI involves doppler filtering that removes stationary clutter. It only allows for the detection of moving targets but does not estimate velocities. PD techniques can reject different sources of clutter and additionally provide estimates for the target velocities. One solution to resolve ambiguities in velocities and range is alternating the pule repetition frequency (PRF) and using further processing to undo aliasing.

References

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