Step Frequency Waveform Design and Processing for Detection of Moving Targets in Clutter

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Abstract

Step frequency waveforms have been used in measurement radars in anechoic chambers for high resolution imaging of stationary or rotating targets in one or two dimensions. However in operational scenarios such as detection of moving targets, frequency step waveform spreads the target return and shifts the target range resulting in a loss of target magnitude, range accuracy and range resolution. This paper models target return, brings out the problems associated with step frequency waveform and then describes a method for detection of moving target in the presence of clutter. Also discussed are step frequency waveform design considerations.

1 Introduction

Reliable detection of moving target in presence of large clutter requires a significant improvement in signal to clutter (S/C) ratio. This can be done by minimizing the clutter entering the radar receiver, followed by clutter cancellation to further enhance the S/C ratio. Amount of clutter entering the radar receiver can be reduced by decreasing the effective pulse width. Short effective pulse width is normally achieved by employing pulse compression which compresses long coded transmit pulses required for adequate average power. However pulse compression increases the instantaneous bandwidth which requires wider bandwidth components and higher A/D sampling rates. Thus hardware and bandwidth requirements will increase significantly for conventional pulse compression for very high range resolution systems which are required for very low clutter.

However, with the step frequency waveform, it is possible to achieve a narrow pulse width (or high range resolution) with a lower instantaneous receiver bandwidth and lower A/D sampling rates. Irrespective of the waveform and the compression method used, short effective pulse width (or narrow range resolution) does require larger bandwidth. For step frequency waveform large bandwidth is obtained sequentially by changing the carrier frequency in steps over several pulses instead of within a single pulse. Each individual pulse can be relatively of longer time duration resulting in a lower instantaneous bandwidth which allows the use of a narrowband receiver as well as a lower A/D sampling rate.

The disadvantages of this waveform are the complications caused by range-Doppler coupling, due to target motion, which result in a target range shift, as well as in the spreading of the target return [1]. Furthermore, the step frequency waveform does not provide a direct target velocity measurement.

The waveform design is not as obvious and clear-cut as for traditional pulse Doppler waveforms. This paper describes the step frequency radar briefly, models the target return mathematically, outlines the difficulties associated with the processing of step frequency waveform and then describes a processing scheme for detection of moving targets in the presence of clutter. Also outlined are constraints to be satisfied in the design of step frequency waveform to detect moving targets.

2 Waveform Modeling

In contrast to conventional coherent radars, the frequency of the step waveform changes from pulse to pulse, however, it stays constant within an individual pulse. The increase in interpulse frequency is linear as shown in Fig. 1 where \( \Delta f \) is the frequency change from pulse to pulse. A block diagram of a radar using the step frequency waveform is shown in Fig. 2. This block diagram is similar to that of a typical coherent radar except for addition of a step frequency synthesizer which is programmed to generate frequency in increasingly larger steps. Step frequency is added onto stalo and coho frequencies to generate RF sig-
nal. Like stalo and coho frequencies, frequency steps are taken out from the received signal to extract the baseband signal.

After a pulse is transmitted, the output of the phase detector (PD) is sampled and stored. Each sample is termed a range bin as it represents the signal from a range window of cr/2 (where r is the pulse width). The phase detector output for all range bins of interest due to all N pulses in a burst are collected prior to performing any processing.

If transmit signal for the kth pulse is $A_1 \cos 2\pi (f_0 + k\Delta f)$, the corresponding phase detector output for a scatterer or a target at range R can be modeled as $A_2 e^{-j\phi_k}$ where

$$\phi_k = 2\pi (f_0 + k\Delta f) \frac{2R_k}{c}$$

where $R_k$ is the range to the scatterer or the target, $f_0$ is the RF frequency of the first transmitted pulse which is the sum of stalo and coho frequencies.

If the target is stationary, it has been shown that the IDFT of N samples (from N pulses) corresponding to a range bin divides the range bin into finer subdivisions resulting in improved range resolution [2]. To explore what happens if the target is in motion, consider a target moving at a constant velocity, v. The target range changes with each pulse as

$$R_k = R_0 + vkT$$

where T is the pulse repetition interval and k is pulse index which varies from 0 to N – 1. From (1) and (2), the phase of the detector output for kth pulse becomes

$$\phi_k = 2\pi (f_0 + k\Delta f) \frac{2}{c}(R_0 + vkT)$$

The above equation can be rewritten to identify the frequency components in each term as:

$$\phi_k = \frac{4\pi f_0 R_0}{c} + 2\pi \frac{\Delta f}{T} \frac{2R_k}{c}kT$$

$$+ 2\pi \frac{2v}{c}f_0kT + 2\pi \frac{\Delta f}{T} \frac{2vkT}{c}$$

The examination of above equation reveals the problems as well as the special properties of step frequency waveform. For stationary targets only the first two terms are applicable. The first component represents a constant phase shift which is not of any practical significance. The frequency shift in the second term is given by the product of frequency rate of change $\frac{\Delta f}{T}$ with the round trip time $2R_0/c$. Thus the range is converted into the frequency shift. Therefore, it is possible to resolve the range by resolving the frequency shift. Frequency shift is resolved by discrete Fourier transform (DFT). Therefore the range resolution $\Delta R$ and unambiguous range $R_u$ are dependent respectively on frequency resolution and maximum unambiguous frequency measurement of DFT process. The expression for these quantities are given below

$$\Delta R = \frac{c}{2N\Delta f}$$

$$R_u = \frac{c}{2\Delta f}$$

Thus, it is the second component in (4) which gives the fine range resolution in the step frequency radars. Equations (5) and (6) can be rewritten as

$$\Delta R = \frac{c}{2N\Delta f} = \frac{cr/2}{N\tau\Delta f} = \frac{R_u}{N}$$

Above equation implies that the unambiguous range $R_u$ is divided into N equal parts and the original range bin of width $cr/2$ is divided into $N\tau\Delta f$ equal parts as shown in Fig. 3. The relative magnitudes of $R_u$ and $cr/2$ depends upon the magnitude of $\tau\Delta f$. If $\tau\Delta f$ is unity, the original range bin of width $cr/2$ occupies the entire $R_u$, that is, both the quantities are equal. In this case the pulse compression ratio and the resulting processed range resolution is maximum and is given by $cr/2N$. However, if $\tau\Delta f$ is less than unity, the original range bin occupies less range than $R_u$. The original range bin is now divided into $N\tau\Delta f$ parts instead of N parts. The range resolution has suffered. However, in this case there is clear space available in the range domain for a nonstationary target to move out as shown in Fig. 3. The third possibility of $\tau\Delta f > 1$ is not of any practical value as the original range bin will wrap around itself in the range domain after the processing, resulting in the distortion of range profile.

The third term in (4) represents the Doppler frequency shift due to target motion and it adds to the frequency shift of the second term. The range resolution process mistakes the Doppler frequency as a frequency shift due to range and thus results in shifting of target range from its true range. This range shift can be easily calculated as $\nu T_f c/\Delta f$ where $f_c$ is the center frequency of the step frequency waveform. Target motion related range shift in terms of processed range bins (of width $c/2N\Delta f$) is given by,

$$L = \frac{2\nu T_f c}{cN}$$

The fourth term in (4) is due to the interaction of changing frequency of step waveform with target motion. Frequency term $\Delta f 2vk/c$ is changing with each pulse (as represented by k) and thus causing the frequency spread over the dwell. When processed, this
would disperse target energy into several range bins with several negative effects including loss of range resolution, range accuracy and loss of signal to noise ratio. Target spread in range is \( vNT \) and the corresponding spread in the frequency domain is given by \( \Delta f 2vN/c \).

### 3 Signal Processing for Detection of Moving Target

The first step in the signal processing of step frequency signals is the transformation of data domain (sometimes also called frequency domain) into range domain by taking IFFT. If the waveform is designed properly, the non-stationary target will move out of the clutter region after the transformation. However, during the transformation the moving target has spread as well as shifted in range by an unknown amount, resulting in the loss of signal-to-noise ratio, range resolution, and range accuracy. These problems can be resolved if the frequency shift caused by the target motion (i.e., the last two terms in (4)) is eliminated. Since the target velocity is generally unknown, compensation may be applied at all velocities uniformly spaced between minimum and maximum expected target velocities. The compensation technique discussed so far will increase the magnitude of the target by counteracting the range spread. However, it will put the target peak back into clutter and also spread the clutter beyond its domain. Thus, clutter must be canceled prior to applying the velocity compensation so that the target can be detected while still maintaining accurate target range and fine range resolution. Following steps are performed in the signal processor:

1. Convert the phase detector output data into the range domain by performing IFFT. This data consists of \( N \) samples from \( N \) frequency stepped pulses for one range bin (of width \( cT/\Delta f \)) at a time.

2. Apply clutter cancellation by zeroing out points corresponding to the clutter extent in the range domain obtained in the first step. Also apply weighting to the rest of data to reduce sidelobes to be encountered later in the reverse transformation.

3. Convert the modified range domain data back into the data domain by taking FFT.

4. Apply velocity compensation to data in step 3 by multiplying with terms 3 and 4 in (4). Estimate the target velocity or use several velocities between the minimum and maximum expected target velocities.

5. Convert the compensated data back into range domain via IFFT. If there are more than one range domain data sets, choose the one with the highest and sharpest output in the clutter free area. The compensation velocity corresponding to the chosen set is the correct target velocity and that set shows the true target range position and its detailed range profile. The range resolution is restored to theoretical \( c/2N\Delta f \).

Computation may be significantly reduced if the velocity compensation is directly applied in the range domain. This would require only one Fourier transform operation. However, one would need transformed compensation term and also the multiplication in the compensation process will be replaced by a convolution.

Ideas presented in this paper were verified using simulation. Some of the relevant parameters used in the simulation are: \( PRF = 4 \) KHz, \( \Delta f = 1 \) MHz, \( N = 500 \), \( \tau = 0.1 \) sec, S/C ratio= 0 db, target velocity = 150 m/sec, \( f_0 = 5 \) GHz. From the above parameters one obtains \( \tau\Delta f = 0.1(\leq 1) \); original range bin width (\( c\tau/2 \)) = 15 m, processed range resolution \( = 0.3 \) m, \( R_0 = 150 \) m.

Raw data contains 500 samples of signal and clutter of equal magnitude. Figure 4 shows the IFFT of the data in which target has moved out of clutter (note clutter occupies first 50 points), however, the target is spread out and is of low magnitude. Figure 5 shows the results after applying the processing discussed in the paper. The target magnitude has gone up, clutter is canceled, target range is correct with expected resolution. This gain in performance has come at the expense of increased signal processing.

### 4 Waveform Design

#### Considerations for Detection of Moving Target

Waveform design involves the selection of parameters such as pulse width, frequency step size, pulse repetition frequency, number of frequency stepped pulses (\( N \)) in coherent interval and RF frequency to satisfy performance requirements such as range resolution, minimum and maximum target velocities, maximum target extent, unambiguous range, probability of detection, etc. This section will give the equations which relate the parameters of step frequency waveform with these performance related parameters.
These equations, along with conventional radar equations, can be used to satisfy the performance requirements. The order and manner in which these equations are used for waveform design may vary with an application.

1. Sequential (or effective) bandwidth $N\Delta f$ determines the range resolution as given by

$$\Delta R = \frac{c}{2N\Delta f}$$

2. The amount of clutter free space in the range domain will depend on the product $\tau \Delta f$ as the fraction of range domain containing clutter is specified by the following equation

$$\frac{c\tau/2}{R_u} = \tau \Delta f$$

Choosing low value for the product $\tau \Delta f$ will increase the clutter free space.

3. There are two constraints related to the maximum target extent $L_t$. To avoid aliasing or wrap around

$$L_t < R_u$$

Also, the pulse width should be large enough that it encompasses the entire target length for good target detectability, that is, $c\tau/2 > L_t$ or

$$L_t < \frac{c\tau}{2}$$

Since $R_u$ will always be greater than $c\tau/2$ for the waveforms used for the detection of moving targets, therefore the latter constraint in (11) related with the pulse width is a tighter constraint and will always satisfy the former constraint. It should be noted that the pulse width effects the signal power as well as the amount of clutter intercepted. These factors will also be considered in the selection of pulse width $\tau$.

4. This constraint derives from the requirement that a moving target must migrate from the clutter region to the clutter free region. The worst case is for a slowest moving target or scatterer at the beginning of the clutter region. The worst case requirement for a target to be out of clutter is that the range shift $L$ should be greater than the clutter extent $N\tau \Delta f$, that is,

$$\frac{2v_{min} N}{\lambda f_{PRF}} > N\tau \Delta f$$

or

$$f_{PRF} < \frac{2v_{min}}{\lambda \tau \Delta f}$$

or

$$\tau \Delta f < \frac{2v_{min}}{\lambda f_{PRF}}$$

5. Doppler induced range shift is necessary for a target to move out of the clutter region. However, it should not be so large that it exceeds $R_u$, in which case the target aliases or wraps around in the range domain. The worst case for this situation is the maximum velocity target at the end of the clutter region. To avoid aliasing the range shift for this target must be less than $R_u$, that is,

$$\frac{2v_{max} N}{\lambda f_{PRF}} < N(1 - \tau \Delta f)$$

or

$$f_{PRF} > \frac{2v_{max}}{\lambda(1 - \tau \Delta f)}$$

or

$$\tau \Delta f < 1 - \frac{2v_{max}}{\lambda f_{PRF}}$$

Along with the standard radar equations these special constraints for the step frequency can be used for the design of step frequency waveform.

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References

Figure 1: Step frequency waveform.

Figure 2: Block diagram of step frequency radar.
Figure 3: Range domain when $\tau \Delta f < 1$.

Figure 4: IFFT of radar (detector) data showing separation of clutter and target.

Figure 5: Signal processor output after clutter cancellation and velocity compensation showing build up of target magnitude and improvement of range resolution.