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STEPPED FREQUENCY WAVEFORM DESIGN WITH APPLICATION TO SMR

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ABSTRACT

In radar systems, the stepped frequency waveform is commonly used for achieving high range resolution capabilities. The waveform and system parameters, such as the pulse length and range gate, must be suitably chosen in order to reconstruct the range profile correctly. In this paper, the authors propose a method for the correct choice of such parameters. Moreover, the application of such method is tested on simulated data in a Surface Movement Radar (SMR) scenario.

1. INTRODUCTION

In radar systems, high range resolution profiles (HRRP) are typically obtained by using wide band transmitted pulses. The use of Wide Instantaneous Bandwidth (WIB) signals often requires complex and expensive radar hardware and software configuration. In the last decade, alternative solutions for high range resolution radar have been proposed that make use of Synthetic Wide Bandwidth (SWB) signals [1]-[6].

The basic idea consists of transmitting narrow band signals at different carrier frequencies for each sweep in order to cover the required bandwidth in N radar sweeps. A well known SWB signal is the stepped frequency waveform [1],[2]. When a stepped frequency waveform is used, long RF pulses are transmitted at adjacent carrier frequencies $f_n = f_0 + n\Delta f$, with $n = 0,1,2,\ldots,N-1$, where Δf is the frequency step and N is the number of frequencies. The complex range profiles are obtained by collecting one sample per sweep and by performing the Discrete Fourier Transform (DFT) of the sample vector. A critical point of such technique is the choice of the pulse length as a function of the other waveform parameters. In fact, an incorrect choice may produce distorted range profiles with scatterer's attenuation, spread and shift from the correct range position.

Although the paper deals with all waveform parameter design, the new contribution concerns the correct choice of the pulse length and range gate size in relation with the other waveform parameters as well as target size and motions. Moreover, the effectiveness of the proposed criterion for the parameter choice is tested by means of an application to a Surface Movement Radar (SMR). The organisation of the paper is as follows. Section 2 is devoted to the definition of the stepped frequency waveform. Section 3 introduces the main steps of the HHRP reconstruction technique. In section 4 the criterion for the correct choice of the pulse length and range gate is introduced. An analysis of Doppler effects is also provided. Ultimately, section 5 shows the application of the proposed method to a SMR.

2. RECEIVED SIGNAL MODEL

In this section, the analytic expression of the stepped frequency signal waveform is provided.

A SWB waveform consists of a sequence of N narrow band pulses centred at increasing frequencies $f_n = f_0 + n\Delta f$, with $n = 0,1,2,\ldots,N-1$. The expression of the analytic signal is:

$$s_T(t) = \sum_{n=0}^{N-1} s_{TP}(t,n) = $$

$$= \sum_{n=0}^{N-1} x(t - nT_R)\exp\left[j2\pi\left(f_0 + n\Delta f\right)\left(t - nT_R\right)\right]$$

where $x(t) = rect(t/T_i)$, with $\mathrm{rect}(x) = 1$ for $|x| \le \frac{1}{2}$, T_i is the pulse length, T_R is the Pulse Repetition Time (PRT), f_0 is the fundamental carrier frequency, Δf is the frequency step and N is the number of transmitted frequencies. The total time length of the SWB is $(N-1)\cdot T_R + T_i$. The time interval $N\,T_R$ is called Ramp Repetition Interval (RRI).

3. RANGE PROFILE RECONSTRUCTION TECHNIQUE

In this section, the range profile reconstruction method when stepped frequency waveforms are used is summarised. Such method consists of transmitting long RF pulses, collecting one sample per sweep and performing the Discrete Fourier Transform (DFT) of the collected samples [2]. The final range resolution δR depends on the total bandwidth $B_T = N\Delta f$, as expressed in eq. (1):

$$\delta R = \frac{c}{2B_T} = \frac{c}{2N\Delta f} \tag{1}$$

where c is the light speed.

The range ambiguity ΔR_{am} is related to the frequency step Δf according to $\Delta R_{am} = \frac{c}{2\Delta f}$.

To avoid range folding of the target scatterers, the range gate ΔR must be smaller than ΔR_{am} , i.e. $\Delta R < \Delta R_{am}$.

The main steps of the range profile reconstruction technique are summarized as follows (steps 3-7 can also be followed in fig. 1).

1) Down converting
2) Matched filtering
3) Collecting one sample per sweep every T_c seconds.
4) Storing the recorded samples in a *N*-element vector
5) Zero padding the *N*-element vector to obtain a vector of length $N_{zp} > N$
6) Data smoothing (e.g. Kaiser windowing)
7) Taking the FFT of the the vector obtained at 6.

By considering an ideal point scatterer with initial position $R_0 = c\tau_0/2 \in [R_m, R_m + \Delta R]$ and radial velocity v_r , the reconstructed range profile can be analytically derived. Avoiding mathematical passages, the analytical form of the range profile is shown in eq. (2).

$$p_r\left(\frac{p}{\Delta f\, N_{zp}}\right) = \left|x_{MF}\left(T_c - \tau_0\right)\right| \cdot \left| \frac{\sin\left(\pi N \Delta f\left(\frac{p}{\Delta f\, N_{zp}} + \left(T_c - \tau_0\right) + \frac{f_d T_R}{\Delta f}\right)\right)}{\sin\left(\pi \Delta f\left(\frac{p}{\Delta f\, N_{zp}} + \left(T_c - \tau_0\right) + \frac{f_d T_R}{\Delta f}\right)\right)} \right| \tag{2}$$

$$-\frac{N_{zp}^{(c)}}{2} \le p \le \frac{N_{zp}^{(c)}}{2} - 1; \quad N_{zp}^{(c)} = \mathrm{int}\left(N_{zp} \cdot \frac{\Delta R}{\Delta R_{am}}\right)$$

where $f_d = -2v_r f_0/c$, $\mathrm{int}(\bullet)$ is the integer part and

$$x_{MF}(t) = T_i \,\mathrm{sinc}\left[f_d T_i\left(1 - \frac{|t|}{T_i}\right)\right]\left(1 - \frac{|t|}{T_i}\right)\mathrm{rect}\left(\frac{t}{2T_i}\right) \tag{3}$$

is the signal at the output of the matched filter. In typical microwave radar systems T_i is of the order of a few μseconds. Moreover, by considering a maximum value of f_d equal to of few tens of KHz, eq.(3) can be approximated by means of eq. (4):

$$x_{MF}(t) = T_i\left(1 - |t|/T_i\right) \cdot rect\left(\frac{t}{2T_i}\right) \tag{4}$$

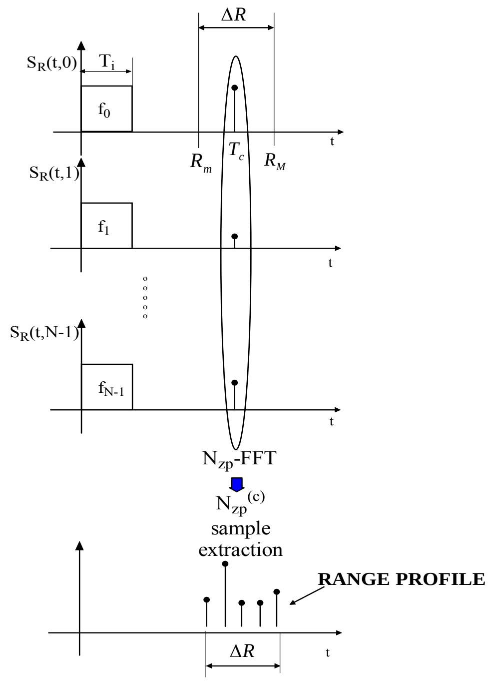

Figure 1 –Range profile reconstruction procedure

The term $\left|\frac{\sin(\bullet)}{\sin(\bullet)}\right|$ determines the shape of the range profile.

The following properties can be highlighted:

P1) The -3dB width of the main lobe is roughly equal to $t_{-3dB} = \frac{1}{N\Delta f}$ corresponds to a range resolution δR equal to $\delta R = \frac{c}{2B_T}$, where $B_T = N\Delta f$ is the total bandwidth of the transmitted signal. It is worth noting that the range resolution is independent of the pulse bandwidth $B \cong 1/T_i$.

P2) When the target is stationary ($f_d = 0$), the peak in the range profile is centered on τ_0 , which corresponds to an initial distance equal to $R_0 = \frac{c}{2}\tau_0$.

P3) The amplitude of the peak is attenuated by the value of $\left|x_{MF}(t)\right|$ calculated in $t = T_c - \tau_0$. Such attenuation depends on the position of the scatterer and produces a range profile distortion when finite dimension targets are considered.

P4) When $f_d \ne 0$, a range shift occurs. Such a range shift can be analytically calculated as in eq. (5):

$$\varepsilon_R = \frac{c f_d T_R}{2\Delta f} = \frac{N\ f_d\ \delta R}{PRF} \qquad (5)$$

where $PRF = \frac{1}{T_R}$. When ε_R is large enough, the target scatterers may move outside the range gate $\left[R_m, R_m + \Delta R\right]$ and disappear from the reconstructed range profile.

By assuming that the sampling time instant T_c is taken within the target echo radial extent $\frac{2}{c}\Delta R_t$ and considering the worst-case situation (as represented in Figure 2), the range gate ΔR must satisfy the following condition

$$2\left(\Delta R_t + \varepsilon_{R_M}\right) < \Delta R < \Delta R_{am} \qquad (6)$$

where ε_{R_M} is the maximum Doppler range shift.

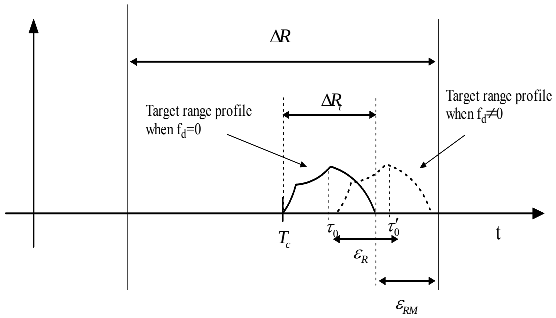

Figure 2 - Range gate setting

4. SIGNAL WAVEFORM PARAMETER DESIGN

In the present section, we describe the reconstructed range profile distortions produced by an incorrect choice of waveform and system parameters. Therefore, to overcome such a problem a criterion for correctly choosing such parameters is proposed.. The theoretical analysis is supported by numerical results obtained by considering an X-band radar whose main characteristics are summarized in Table 1.

f_0	10 GHz
PRF	20 kHz
δR	5 m
ΔR	100 m

Table 1 – Radar parameters

The analysis is performed by considering a parameter at a time. It is worth remarking that the novel contribution concerns the correct choice of the pulse length.

4.1 Frequency step

Given a range gate ΔR and a frequency step Δf such that $\Delta R = \Delta R_{am} \rightarrow \Delta f = \frac{c}{2\Delta R}$, the reconstructed range profile eco of a scatterer at the edge of the range gate is folded because of the periodicity of the DFT.

For example, a stationary single ideal scatterer with $\tau_0 = T_c + \frac{\Delta R}{c} = 32.33\ \mu\text{sec}$ gives the range profile of Figure 3.

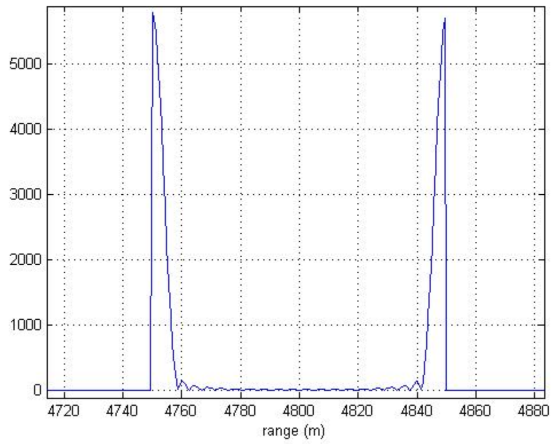

Figure 3 – Range profile of an ideal scatterer with $\tau_0 = T_c + \frac{\Delta R}{c}$ and $\Delta f = \frac{c}{2\Delta R}$

This problem can be overcome if $\Delta R < \Delta R_{am} = \frac{c}{2\Delta f}$. A reasonable rule is to take [2]:

$$\Delta f = \frac{c}{4\Delta R} \qquad (7)$$

Following the example of Table 1, $\Delta f = 750$ kHz.

4.2 Number of frequencies

The number of transmitted frequencies depends on the final resolution δR. From eq.(1) we have:

$$N = \text{int}\left(\frac{c}{2\delta R \Delta f}\right) \qquad (8)$$

According to the parameters already presented in Table 1 and considering $\Delta f = 750$ kHz, we obtain $N = 40$.

4.3 Pulse length

Because of the property at P3, scatterer's echoes that are not centred at T_c suffer an attenuation that depends on the pulse shape at the output of the matched filter.

If a value of the pulse length is chosen such that $T_i = \frac{2\Delta R}{c}$, the target is completely illuminated by the e.m. pulse.

As shown in Figure 4, three stationary ideal scatterers with unitary reflectivity function located in $\tau_{0_1} = T_c - \frac{1}{4}\left(\frac{\Delta R}{c}\right)$, $\tau_{0_2} = T_c$, $\tau_{0_3} = T_c + \frac{1}{2}\left(\frac{\Delta R}{c}\right)$ are weighted in the range profile by the triangular shape of the matched filter output.

By changing the sampling time position T_c within the range gate, the same scatterers have a different weighting (see

Figure 5).The larger is the distance of the target delay from the sweep sample location T_c, the stronger is the attenuation.

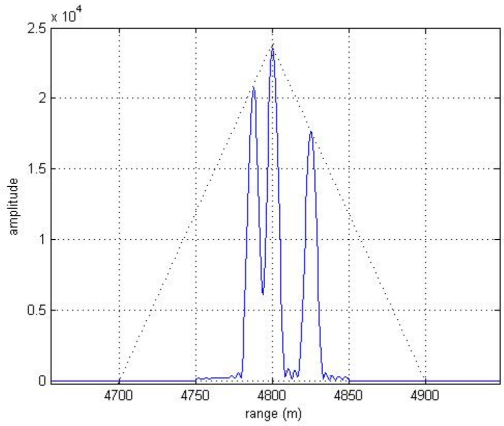

Figure 4 – Range profile of three scatterers with $T_i = \frac{2\Delta R}{c} = 0.666$ µs

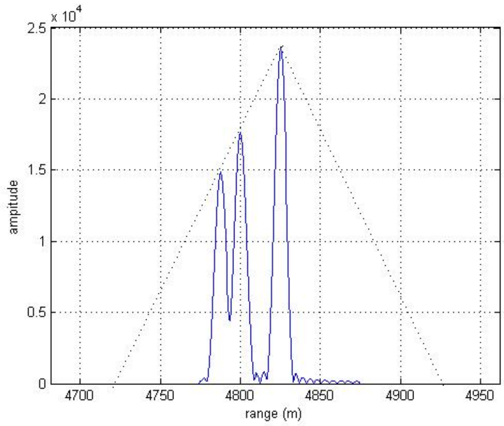

Figure 5 – Range profile of the three scatterers in Figure 4 with a shift of the sampling time T_c

A solution to such a problem can be obtained by choosing the pulse length such that $T_i >> \frac{2\Delta R}{c} = \frac{1}{2}\frac{1}{\Delta f}$. A rule of thumb is provided in eq. (9):

$$T_i = \frac{20\Delta R}{c} = 6.6 \text{ µs} \quad (9)$$

When the pulse length is such that $T_i = \frac{20\Delta R}{c} = 6.6$ µs, the reconstructed range profile appears as in fig. 6. It is worth noting that no attenuation is produced.

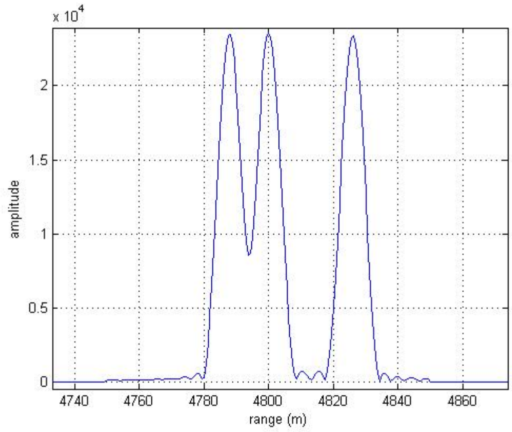

Figure 6 – Range profile of three scatterer of Figure 4 with $T_i = \frac{20\Delta R}{c} = 6.6$ µs

4.4 Doppler effects

Once the target radial extent ΔR_t is set, the maximum acceptable target speed can be obtained from eq.(6) as follows:

$$v_{RM} = \frac{\lambda\, PRF}{4N\delta R}\cdot\left(\Delta R - 2\Delta R_t\right) \quad (10)$$

If eq.(10) is not satisfied, target velocity compensation must be carried out. Some techniques are proposed in [3]-[6].

The Doppler effect is shown in Figure 7. A single ideal scatterer is supposed to be located at an initial distance $R_0 = \frac{c\,\tau_0}{2} = \frac{c\,T_c}{2} = 2.4$ km and moving with a radial velocity $v_R = 50$ m/s. By using eq. (5), the Doppler range shift obtained is equal to be $\varepsilon_R = 33.3$ m.

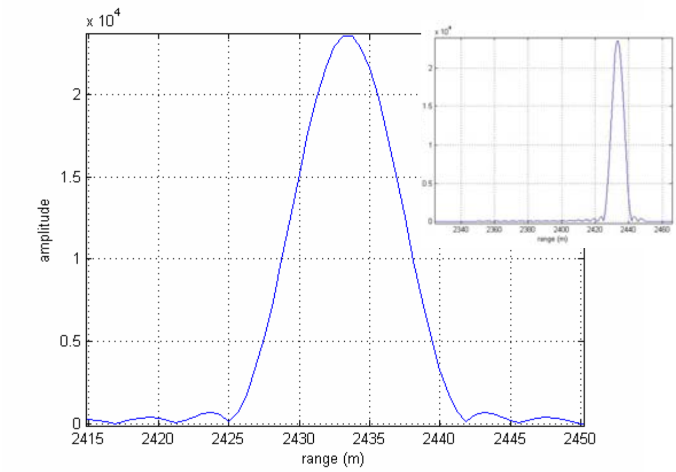

Figure 7 – Reconstructed range profile of an ideal scatterer with initial distance $R_0 = 2000$ m and radial velocity $v_r = 50$ m/s

5. APPLICATION TO SMR RADAR

In this section, a SMR scenario is considered and the proposed method is used for the correct selection of the pulse length and the range gate size. An e.m. model of a Boing 747 is used as a target. In Table 2 a list of the radar parameters used for the simulation is shown, where ϑ_{az} is the -3dB azimuth antenna beamwidth. The aircraft was located at a distance of about 2700m from the radar, oriented orthogonally to the Line of Sight (LOS) and was supposed stationary. The range gate centre was set to 2700 m (in correspondence of the aircraft fuselage).

Figure 8 shows the Real Aperture Radar (RAR) image obtained by using the correct choice of the parameters. The aircraft shape can be easily recognized. In fact, the main scatterer structures, such as the tail and the engine under the left wing are easily recognisable. When an incorrect choice of the parameters is made, an attenuation of the echoes relative to scatterers located away from the range gate centre occurs. In fig. 9, two range profiles are plotted that represent the range profiles (in correspondence of azimuth = 64m) obtained with a correct and an incorrect choice of the parameters. As expected, scatterers located along the fuselage (centre of the range gate) are not affected by the use of shorter pulse length. On the other hand, scatterers located far from the airplane fuselage are attenuated.

Table 2 –Radar parameters

ΔR	100 m
$\Delta f = \dfrac{c}{4\Delta R}$	750 kHz
$T_i = \dfrac{20\Delta R}{c}$	6.66 µs
PRF	20 kHz
f_0	10 GHz
δR	5 m
$N = \dfrac{c}{2\delta R\Delta f}$	40
ϑ_{az}	0.1°

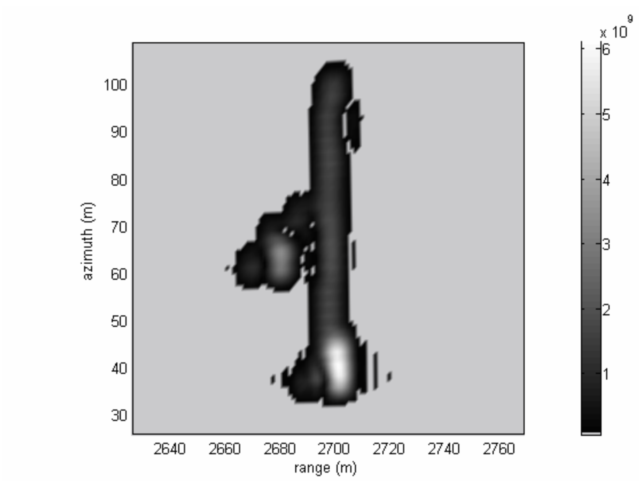

Figure 8 – Simulation result of a Boeing747: correct parameter setting

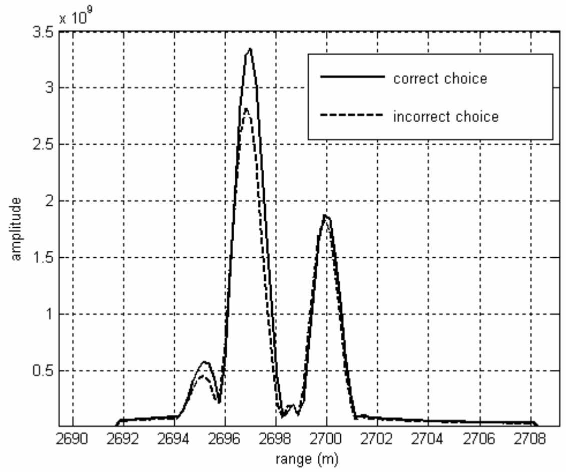

Fig.9 Range profiles (azimuth = 64 m)

6. CONCLUSIONS

In this paper, a criterion for the correct choice of the pulse length and range gate size when using a stepped frequency waveform is proposed. Simulations have shown that an incorrect choice of such parameters may produce distorted range profiles. The effectiveness of the proposed approach has also been proved by means of a simulation of a SMR scenario.

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