High Resolution SAR Processing Using Stepped-Frequencies

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Abstract—This paper demonstrates a method to produce high resolution SAR images using stepped-frequencies. An advantage of the stepped-frequency approach is the reduction of the instantaneous bandwidth and sampling rate requirements of the radar system, as well as the possibility of skipping frequencies that might be corrupted due to external interfering frequency sources. The technique described in this paper involves the construction of a wide-bandwidth chirp pulse produced from a burst of narrow-bandwidth chirp pulses transmitted at stepped-frequency intervals. A description of this technique is given and simulation results are shown.

INTRODUCTION

The use of stepped-frequency waveforms to obtain high range resolution is well documented [6]. Synthetic range profile (SRP) processing is a very effective method to obtain high downrange profiles of targets such as aircraft [5]. However this method has the unfortunate drawback that target energy spills over into consecutive coarse range bins due to the matched filter operation, causing "ghost images" in the resulting range profile [4]. This is the main reason why it is not regarded as a suitable method to process SAR images. In the following section another method is described which does not cause any "ghost images". This is demonstrated in Fig. 1, which shows a processed SAR image consisting of point targets in the shape of an "R", having been obtained using eight frequency steps.

This paper focuses mainly on the production of high range resolution. To obtain high resolution images, motion compensation and range curvature would also have to be addressed.

WAVEFORM MODELLING

The essence of the method described below is the construction of a fictitious wide-bandwidth chirp signal (with centre frequency f_c, bandwidth B, chirp rate γ and pulse length T_p) from a group or *burst* of n narrow-bandwidth chirp signals (with bandwidth B_n and pulse length T_{pn}). It is important that the narrow-bandwidth chirp pulses have the same chirp rate γ as the fictitious wide-bandwidth chirp signal. Therefore the narrow bandwidth B_n is obtained by reducing the pulse length T_p by a factor of n, where n is the number of pulses used to synthesize the total radar bandwidth B. The centre frequency of the narrow-bandwidth pulses, which are stepped in frequency to cover the whole synthesized bandwidth, is given by

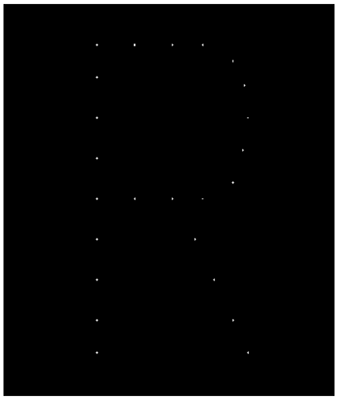

Figure 1: Synthetic SAR image processed using stepped-frequency waveforms

$$f_c(k) = f_c + \left(k + \frac{1}{2} - \frac{n}{2}\right)\frac{B}{n} \quad (1)$$

where $k = 0\ldots(n-1)$. The phase of the transmitted pulses belonging to one burst can be described by

$$s_x(t,k) = \mathrm{rect}\left(\frac{tn}{T_p}\right)\exp\left[j2\pi f_c(k)\,t\right]\cdot\exp\left[j\pi\gamma t^2\right] \quad (2)$$

The signal phase received by the SAR system from a single scatterer at a distance r_t is therefore given by

$$\begin{aligned} s_r(t,k) &= \mathrm{rect}\left(\frac{tn - \frac{2r_t}{c}n}{T_p}\right)\exp\left[j2\pi f_c(k)\left(t - \frac{2r_t}{c}\right)\right] \\ &\quad \cdot\exp\left[j\pi\gamma\left(t - \frac{2r_t}{c}\right)^2\right] \end{aligned} \quad (3)$$

The appropriate reference function for demodulating and motion compensating the received signal is

$$s_{ref}(t,k) = \exp\left[j2\pi f_c(k)\left(t - \frac{2r_s}{c}\right)\right] \tag{4}$$

where r_s is the distance from the radar to scene centre. The presence of the constant r_s in this reference function introduces a phase term in the demodulated signal which varies from pulse to pulse and therefore has to be cancelled. This cancellation is achieved by including another term involving r_s in the frequency-shift operation given by (6).

The signal that results from mixing the received signal of (3) and the complex conjugate of the reference function of (4) is

$$\begin{aligned} s(t,k) \quad &= \quad \operatorname{rect}\left(\frac{tn - \frac{2r_t}{c}n}{T_p}\right)\exp\left[j4\pi f_c(k)\left(\frac{r_s - r_t}{c}\right)\right] \\ &\quad \cdot \exp\left[j\pi\gamma\left(t - \frac{2r_t}{c}\right)^2\right] \end{aligned} \tag{5}$$

Fig. 2 gives an overview of the signal processing steps involved to reconstruct the wide-bandwidth chirp pulse from (5). In the figure, two narrow-bandwidth pulses at baseband are shown. These two pulses have to be upsampled and shifted in frequency, and a constant phase term has to be added to each of them, before they can be combined to yield the wide-bandwidth signal. These operations are described in the following subsections.

Upsampling

The narrow-bandwidth pulses are naturally sampled at a lower rate than the corresponding wide-bandwidth pulse. Before recombining the narrow-bandwidth pulses to obtain the wide-bandwidth pulse, they have to be upsampled, usually by a factor of n, where n is the number of pulses used to synthesize the wide bandwidth. This has been accomplished using a straightforward digital FIR filter. The upsampling operation, which is effectively an interpolation, is the only step in the procedure which introduces a certain amount of error in the reconstructed chirp pulse. However it has been found that this effect is negligible and hardly affects the final image resolution.

Frequency-Shift

Since all n narrow-bandwidth pulses described by (5) are at baseband, they need to be shifted in frequency before being combined. A frequency shift in the frequency domain corresponds to a multiplication with a phase ramp in the time domain. Therefore the received signal has to be multiplied by

$$\phi_1(t,k) = \exp\left[j2\pi\left[\left(k + \frac{1}{2} - \frac{n}{2}\right)\frac{B}{n}\right]\left(t - \frac{2r_s}{c}\right)\right] \tag{6}$$

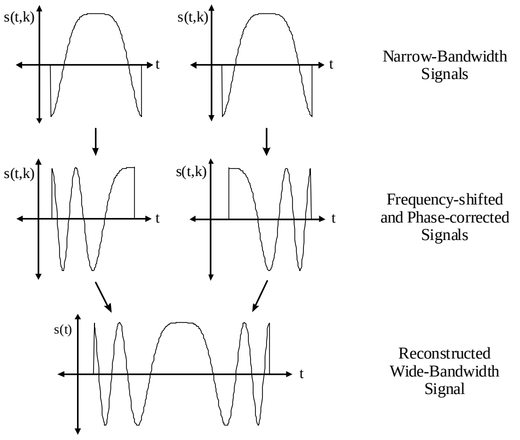

Figure 2: Construction of wide-bandwidth chirp pulse

Phase Correction

In order for the phase of the wide-bandwidth pulse to be continuous at the narrow-bandwidth pulse boundaries, the following phase-correcting term $\phi_2(k)$ has to be added to each pulse:

$$\phi_2(k) = \exp\left[\pi\gamma T_p^2\left(\frac{1}{4} - \frac{k + \frac{1}{2}}{n} + \frac{k^2 + k + \frac{1}{4}}{n^2}\right)\right] \tag{7}$$

Note that the frequency-shift and phase-correcting terms can be applied simultaneously. In fact the phase-correcting terms can be applied before upsampling the signals, resulting in a faster implementation of the whole procedure.

Time-Shift

Before adding the individual pulses together, they have to be shifted in the time domain. The necessary time-shift is given by

$$\Delta t(k) = \left(k - \frac{n}{2} + \frac{1}{2}\right)\frac{T_p}{n} \tag{8}$$

In order for the individual chirp pulses to align next to each other without discontinuity, care has to be taken to ensure that the time-shift is an integer number of discrete sample spacings. This can be achieved by either adjusting the pulse length T_{pn} or the A/D sampling rate f_{ad}.

The raw image is now ready to be processed by a conventional SAR processor such as the Chirp Scaling algorithm, which also applies accurate range curvature correction.

SIMULATION RESULTS

Fig. 3 shows a surface plot of two point targets separated in range by a distance of 3 m. The radar parameters that were used to create the raw data are given in Table 1.

Every individual transmitted chirp pulse has a bandwidth of 15 MHz giving a slant-range resolution of 10 m. However the total synthesized bandwidth is 120 MHz, thereby making a slant-range resolution of 1.25 m possible. The Chirp Scaling algorithm, which was used to process the data, made use of the Taylor weighting function to reduce sidelobes, thereby broadening the mainlobe and reducing the range and azimuth resolution by a factor of 1.34. Nevertheless the two point targets shown in Fig. 3 are clearly distinguishable. It is important to note that there are no "ghost images" in the processed image. Furthermore, it was possible to reduce the minimum A/D sample rate from 120 MHz to 15 MHz (in the simulation 17.5 MHz was used), thereby alleviating the instantaneous sample rate requirements of the radar.

A disadvantage of stepped-frequency systems is the increase in PRF. If the increase in PRF becomes intolerable, one might have to resort to methods such as multiple PRF ranging [2 pg. 116].

INTERPOLATING MISSING FREQUENCIES

Recent advances in analogue-to-digital technology have made it increasingly more feasible to achieve high instantaneous bandwidths, thereby reducing the need to resort to stepped-frequency waveforms to obtain high range resolution. However the capability to omit frequencies in a transmit-burst that are corrupted due to external interference remains an important advantage, especially for high-resolution VHF systems that operate in a frequency band contaminated with broadcast FM and mobile radio. It is desirable to interpolate the missing data in order to obtain the highest possible range resolution. Suitable interpolation techniques are currently under investigation.

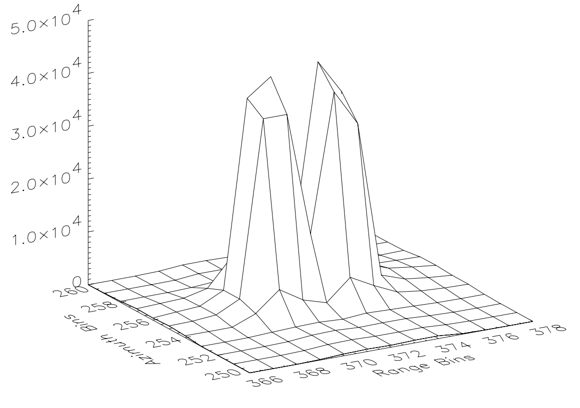

Figure 3: Surface plot of two point targets

Table 1: Radar Parameters

start centre frequency	f_0	347.5 MHz
frequency step size	Δf	15 MHz
number of steps	n	8
total radar bandwidth	B	120 MHz
slant-range resolution	$\rho_r = \frac{c}{2B}$	1.25 m
pulse length	T_{pn}	571.43 ns
chirp bandwidth	B_n	15 MHz
A/D (complex) sample rate	f_{ad}	17.5 MHz
PRF	f_{prf}	1.6 kHz

CONCLUSIONS

The method proposed in this paper to recombine a number of narrow-bandwidth chirp pulses to construct a wide-bandwidth chirp pulse has been shown to be feasible with the aid of simulated SAR data. It does not suffer from the "ghost image" effect as the SRP method, and it is fairly straightforward to implement. Further work will still have to be carried out to determine the optimal method to interpolate missing frequencies.

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