High Range Resolution Radar using Narrowband Linear Chirps offset in Frequency

Richard T. Lord and **Michael R. Inggs**
Radar Remote Sensing Group, Dept of Electrical Engineering, University of Cape Town
Private Bag, Rondebosch 7700, South Africa
Tel: +27 21 650 3756 Fax: +27 21 650 3465
Email: rlord@eleceng.uct.ac.za

Abstract—This paper introduces a method to combine a number of narrow-bandwidth chirp pulses stepped in frequency in order to achieve high range resolution in SAR images. The limitations of this method are discussed, as well as some of the design constraints appropriate to designing a high-resolution stepped-frequency SAR system. Results obtained from processing simulated and E-SAR data are presented and discussed.

I. INTRODUCTION

The use of stepped-frequency waveforms to obtain high range resolution is well documented [6, 7]. An advantage of the stepped-frequency approach to obtain high range resolution is the reduction of the instantaneous bandwidth and sampling rate requirements of the radar system. Another advantage of using stepped-frequencies is the possibility of skipping frequencies that might be corrupted due to external interfering frequency sources. This is especially true for high-resolution VHF systems that operate in a frequency band contaminated with broadcast FM and mobile radio.

Synthetic range profile (SRP) processing is a very effective method to obtain high-resolution downrange profiles of targets such as aircraft. 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 Section II the theoretical basis of another method is presented which does not cause any "ghost images" [5], and in Section III simulation results are shown which confirm the theory. The paper concludes with a practical demonstration using E-SAR data.

II. COMBINING STEPPED-FREQUENCIES

The total radar bandwidth B is synthesized by combining n narrow-bandwidth pulses which are stepped in frequency, each pulse having a bandwidth $B_n = \frac{B}{n}$, pulse width T_{pn} and chirp rate γ. To avoid gaps and overlaps in the resulting wide-bandwidth frequency spectrum, the frequency stepsize Δf between successive pulses is also B_n. If the centre of the frequency range swept by the n pulses is f_c, the centre frequency of each individual chirp pulse is given by

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

where $k = 0 \ldots (n-1)$. Discarding the amplitude information in the discussion that follows, the transmitted pulses belonging to one burst can be described by

$$s_x(t,k) = \text{rect}\left(\frac{t}{T_{pn}}\right) \exp\left[j2\pi f_c(k)\, t\right] \cdot \exp\left[j\pi\gamma t^2\right] \tag{2}$$

The received signal from a single scatterer at a distance r_t is therefore

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

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 within a burst since it is a function of $f_c(k)$. Ignoring this phase term will cause discontinuities in the phase of the wide-bandwidth signal. It is therefore cancelled 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

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

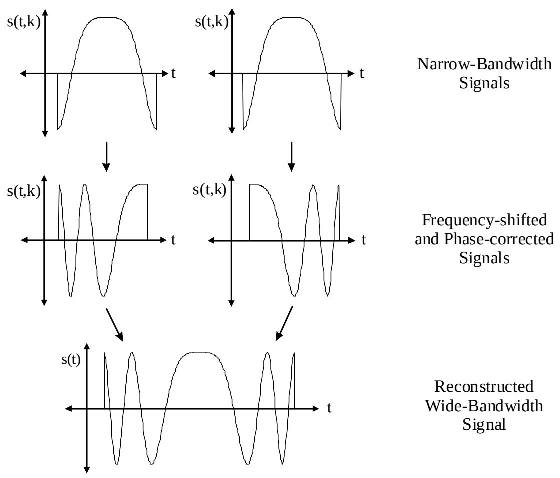

Figure 1: Combination of Narrow-Bandwidth Signals to form Wide-Bandwidth Signal

Fig. 1 gives an overview of the signal processing steps involved in combining the narrow-bandwidth signals given by (5) to form one wide-bandwidth signal. In the figure, two narrow-bandwidth pulses at baseband are shown. These two pulses have to be upsampled and shifted in frequency, and a phase-correction term has to be added to each of them, before they can be combined to form 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 constructing the wide-bandwidth pulse they therefore have to be upsampled, usually by a factor of n, where n is the number of pulses used to synthesize the wide bandwidth. The upsampling operation, which is effectively an interpolation, is the only step in the procedure which introduces an error in the constructed wide-bandwidth signal. However it has been found that this effect hardly affects the final image resolution, as is demonstrated in Section III.

Frequency-Shift

Since all n narrow-bandwidth pulses described by (5) are at baseband, they need to be shifted in frequency before being combined. The necessary phase ramp to shift the signals in the frequency domain is given by

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

Phase Correction

The need to add a phase-correcting term to each narrow-bandwidth pulse can be explained with the aid of Fig. 2. In the figure, the phase versus time plot of the wide-bandwidth signal and of the second narrow-bandwidth signal (from a burst of 4) is shown. The narrow-bandwidth signal has already been shifted in frequency and time, but a constant phase of ϕ_2 has to be added in order for its phase to coincide with the phase of the wide-bandwidth signal. If this phase term is omitted, there will be discontinuities in the phase of the wide-bandwidth signal. The necessary phase term is given by

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

where $T_p = nT_{pn}$. This phase term may be added to the narrow-bandwidth signals before they are upsampled, thus requiring fewer multiplications and leading to a faster implementation of the procedure.

Time-Shift

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

$$\Delta t(k) = \left(k-\frac{n}{2}+\frac{1}{2}\right)T_{pn} \quad (8)$$

Since the signals are sampled at the A/D rate f_{ad} (after they have been upsampled), the time-shift in terms of number of samples is

$$m(k) = \Delta t(k)\, f_{ad} \quad (9)$$

It is important that $m(k)$ is an integer, since fractional values would have to be rounded, leading to errors in the

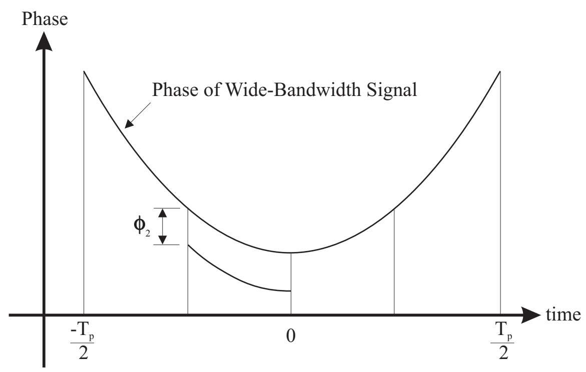

Figure 2: Addition of Phase-Correcting Term ϕ_2 to Narrow-Bandwidth Signals

Table I: Radar Parameters of Simulated Data

centre frequency	f_c	5.3 GHz
radar bandwidth	B	100 MHz
slant-range resolution	$\rho_r = \frac{c}{2B}$	1.5 m
pulse length	T_p	4000 ns
A/D (complex) sample rate	f_{ad}	120 MHz
PRF	f_{prf}	400 Hz
aircraft speed	v	90 m/s
azimuth beamwidth	α_{az}	6 °

constructed wide-bandwidth signal and therefore degradation in image quality. This requirement can be achieved however by adjusting either 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.

III. SIMULATION RESULTS

In order to quantify the effects on image resolution from using stepped-frequency waveforms, simulated SAR data was created using a single point target. The narrow-bandwidth signals in the raw image were combined using the method described in the previous section, and then the wide-bandwidth image was processed with the Chirp Scaling algorithm. Table I shows some of the radar parameters that were used to create the wide-bandwidth synthetic SAR image, whose resolution characteristics are then compared to the stepped-frequency resolution characteristics. These parameters were chosen to be close to the German E-SAR C-Band instrument. The radar parameters of the stepped-frequency simulations were the same, except that B, T_p and f_{ad} decreased by a factor of n, and f_{prf} increased by a factor of n. The lower boundary of the PRF is determined by the Doppler bandwidth, given by

$$B_d = \frac{4v \sin\left(\frac{\alpha_{\text{az}}}{2}\right)}{\lambda} \tag{10}$$

Substituting the values shown in Table I gives $B_d = 333$ Hz, and therefore a PRF of 400 Hz was selected. The upper PRF boundary depends on the unambiguous range, which is 375 km for a PRF of 400 Hz. This is well beyond the intended swath range. However even if only 10 frequency steps are used to achieve higher range resolution, the unambiguous range drops to only 37.5 km. In the simulations, the furthest slant range distance is 6.023 km, which is well below 37.5 km. If the increase in PRF becomes intolerable, one might have to resort to methods such as multiple PRF ranging [2 pg. 116].

In order to measure the range mainlobe width (at half-power points) and the peak sidelobe level (in dB below mainlobe) accurately, the complex range data were up-sampled by a factor of 20. Fig. 3 and Fig. 4 show the effect on mainlobe width and peak sidelobe level as a function of the number of frequency steps used in the simulation. The mainlobe width for most frequency steps is either 1.5 m, the theoretical mainlobe width associated with a bandwidth of 100 MHz, or slightly below 1.5 m, and the peak sidelobe level for most frequency steps is about −10 dB. Exceptions occur at 7 and 9 frequency steps. These can be explained by analysing the required time-shift according to (9), which reveals that these are the only two instances where $m(k)$ is not an integer. When using 7 frequency steps, the mainlobe split into two separate peaks, and the mainlobe width recorded in Fig. 3 is in fact only the width of one of the peaks.

The above analysis was also carried out using transmit pulses with a finite rise and fall time of 40 ns, yielding very similar results. The azimuth resolution in all instances was not affected by using stepped-frequency waveforms.

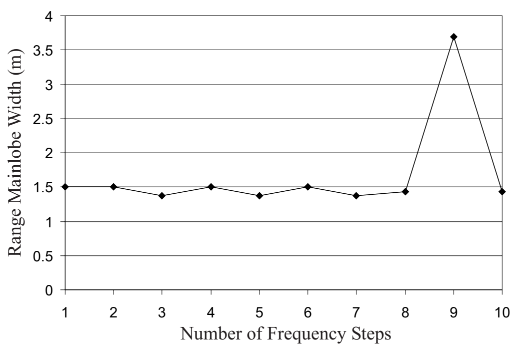

Figure 3: Effect on Range Mainlobe Width as more Frequency Steps are used

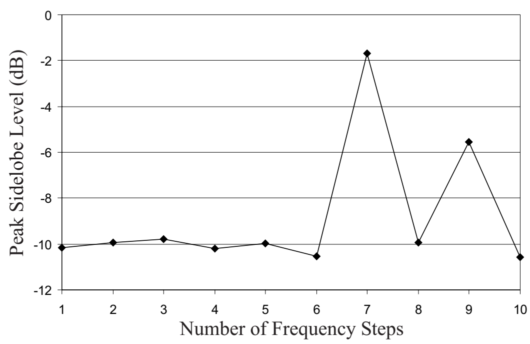

Figure 4: Effect on Peak Sidelobe Level as more Frequency Steps are used

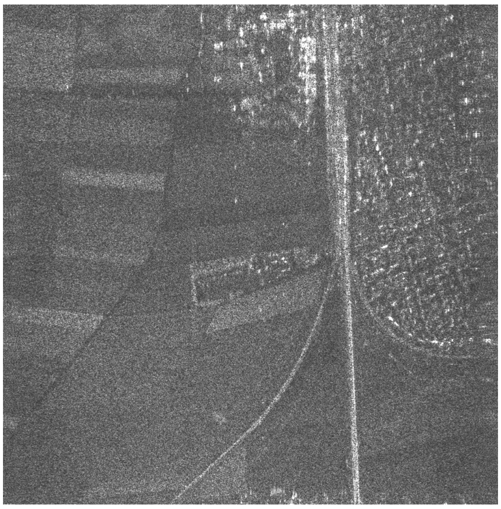

Figure 5: Single Look E-SAR Image, processed with Chirp Scaling Algorithm after being constructed from five Frequency Steps

IV. RESULTS USING E-SAR DATA

In order to verify the stepped-frequency approach on real data, the frequency spectrum in range of a raw E-SAR image was divided into five parts, each part approximating the frequency spectrum of a fictitious narrow-bandwidth pulse. It is only an approximation, since the rectangular window, which was used to split the wide-bandwidth frequency spectrum, introduces ringing in the time domain. Nevertheless, an inverse FFT was then applied to the narrow-bandwidth spectra, effectively yielding the time-domain return of five narrow-bandwidth pulses. These signals were then shifted in the time domain in a similar manner as described in Section II, in order to approximate the return of a real stepped-frequency radar as closely as possible.

The method which was used to split the E-SAR image into five parts suggests that there is an analogous frequency-domain method to combine narrow-bandwidth pulses. This method might only be an approximation to the method described in this paper, but it might be more efficient to implement, and therefore further research in this regard is currently being carried out by the authors.

Fig. 5 shows the result which was obtained after combining the five frequency steps using the method described in Section II, and then processing the raw image using the Chirp Scaling algorithm. No visible difference could be detected between this image and the original single-step image, except for targets at the near and far swath which became fainter. This is due to information being shifted out of the range extent when performing the time-shift.

V. CONCLUSIONS

The simulation results and the results obtained using E-SAR data have verified that it is possible to combine a number of narrow-bandwidth chirp pulses stepped in frequency. Furthermore, the method described to combine the stepped-frequencies does not introduce any "ghost images" or spill-over of energy into successive range bins in the resulting wide-bandwidth image. The results have also shown that the upsampling procedure does not significantly degrade the final image quality. When designing a stepped-frequency radar, care must be taken to ensure that the amount by which the narrow-bandwidth pulses are shifted is a discrete number of samples, and that the increase in PRF can be tolerated.

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VII. REFERENCES

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