High Resolution VHF SAR Processing Using Synthetic Range Profiling

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Abstract—This paper demonstrates the use of stepped-frequency waveforms to obtain high resolution SAR images without imposing severe instantaneous bandwidth requirements on the radar system. Although azimuth compression and motion compensation are essential to obtain high resolution SAR images, this paper only discusses how to obtain high range resolutions. Especially at VHF frequencies it is very difficult to obtain high range resolutions, because the effective pulse bandwidth required would amount to a large percentage of the centre frequency. After briefly introducing the theory of synthetic range profiling as applied to SAR, this paper goes on to discuss the synthetic range profile of an A320 airbus, which serves to demonstrate the feasibility of synthetic range profiling. More attention is then given to simulation results, which introduce the problems encountered when sampling the returning echo waveforms.

INTRODUCTION

Synthetic range profiling (SRP) is a processing technique to obtain high range resolution using stepped-frequency waveforms without imposing severe instantaneous bandwidth requirements on the radar system. A total radar bandwidth of $64 \times 1.5 = 96\,\text{MHz}$ can be synthesized by sequentially transmitting 64 pulses, each pulse stepped in frequency by 1.5 MHz. The final slant-range resolution that can therefore be achieved is about 1.56 m.

This is illustrated in Fig. 1, which shows a surface plot of three point targets that were resolved using SRP. These simulated point targets, which were 6 m apart in ground range, were "illuminated" with 64 monochrome pulses stepped in frequency, each pulse having a bandwidth of 1.5 MHz, which corresponds to a slant-range resolution of only 100 m. However the use of stepped-frequency processing yielded a final slant-range resolution of 1.56 m.

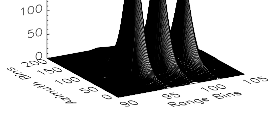

Figure 1: Surface plot of three point targets that were resolved using synthetic range profiling

The CARABAS system is a practical example of an airborne SAR system which operates in the lower part of the VHF-band to produce surface images using stepped-frequency waveforms [2].

SYNTHETIC RANGE PROFILING APPLIED TO SAR

To produce SAR images with stepped-frequency waveforms basically requires the production of one SRP per *coarse* range bin. Obtaining a SRP involves the following steps [5]:

1. Transmit a burst of n pulses, each pulse shifted in frequency by a fixed frequency step size Δf.
2. Collect one I and Q sample of the target's baseband echo response in each coarse range bin for every transmitted pulse. These samples are the frequency-domain measurements of the target's spectral profile.
3. Apply an inverse discrete Fourier transform (DFT^{-1}) on the n complex samples in each coarse range bin to obtain an n-element SRP of the target in the respective coarse range bin.

In contrast with data obtained from pulse-compression radars, the data is already compressed in the range direction at this stage, since the slant-range resolution has been obtained synthetically using the inverse discrete Fourier transform. The azimuth resolution, however, can be obtained as in pulse-compression radars by coherently integrating the range-resolved echo signals that were obtained during the real beam dwell time. This aspect is not addressed in this paper. Furthermore, to obtain high resolution images, motion compensation and range curvature would have to be addressed as well. Another problem not discussed in this paper is the variation of the radar response with frequency and observation angle [1], which varies significantly over the synthetic aperture path.

The synthetic slant-range resolution is given by

$$r_{\text{res}} = \frac{c}{2n\Delta f} \quad , \tag{1}$$

and the slant-range ambiguity length is given by

$$w_s = \frac{c}{2\Delta f} \quad . \tag{2}$$

Ideally the matched filter integration length, given by $\frac{c\tau_p}{2}$, where τ_p is the pulse length, should equal the slant-range ambiguity length w_s. This leads to a pulse length of

$$\tau_p = \frac{1}{\Delta f} \quad . \tag{3}$$

When the integration length is greater than w_s, foldover will occur due to integration of scatterers outside the unambiguous range length. However if the integration length is smaller than w_s, the echo signal will only contain energy integrated from a range depth smaller than the slant-range ambiguity length.

SYNTHETIC RANGE PROFILES OF AEROPLANES

The feasibility of using stepped-frequency waveforms to produce high resolution down-range profiles has already been demonstrated by the production of SRPs of aeroplanes [4]. Fig. 2 shows the SRP of an A320 airbus that has been produced by transmitting linear chirp pulses at 55 different frequencies at L-Band. Two pulses were transmitted at each frequency in order to carry out *moving target indication* (MTI) processing. Each pulse had a bandwidth of 3.6364 MHz, which resulted in a compressed pulse width of $\tau_c = 275$ ns. The pulse resolution was therefore $\frac{c\tau_c}{2} = 41.225$ m, which is about the length of a large aircraft. The frequency spacing was 1.875 MHz, which corresponds to a range-delay extent of 80 m, which is about twice the length of the pulse resolution. The total processed radar bandwidth was 103.125 MHz, which results in a slant-range resolution of 1.45 m.

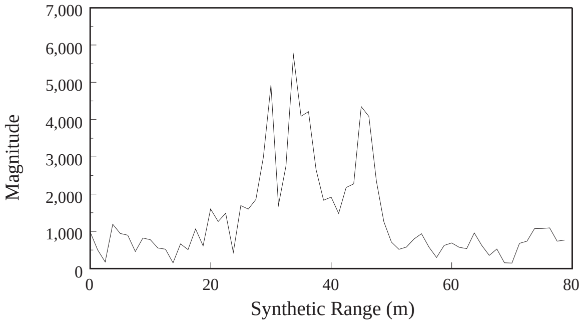

Figure 2: Synthetic Range Profile of an A320 airbus

Table 1: Parameters of radar using SRP

Frequency Step Size	Δf	1.5 MHz
Number of Steps	n	64
Start Frequency	f_0	90.75 MHz
Stop Frequency	f_{63}	185.25 MHz
Total Radar Bandwidth	B	96 MHz
Slant-Range Resolution	r_{res}	1.56 m
A/D sampling frequency	f_{ad}	1.5 MHz
Coarse Range Bin Size	R_{bin}	100 m
Pulse Length	τ_p	666.67 ns
Pulse Repitition Frequency	PRF	11.52 kHz

SIMULATION RESULTS

Table 1 gives the parameters that were used to obtain the simulated SAR data. Fig. 3 shows the magnitude along a range line of a single resolved point target. The dashed line indicates the coarse range bin in which the point target is situated. Samples were collected in four successive coarse range bins, each bin having a slant-range extent of 100 m (corresponding to a 667 ns pulse). Note that the instantaneous bandwidth and the A/D sampling frequency required are only 1.5 MHz, compared with the final processed bandwidth of 96 MHz. The original PRF of 180 Hz was increased by a factor of 64, giving a final PRF of 11.52 kHz. A radar mounted on an aircraft which flies at a height of 10 km, mapping out a 4 km wide swath in slant range, requires a PRF of less than 37.5 kHz to avoid ambiguity problems. However if it is required that one pulse has to be received before the next pulse is transmitted, this increase in PRF will be unacceptable. The technique of *multiple PRF ranging* [3 pg. 116] may be used to solve this problem.

In Fig. 4 a range line displaying three resolved targets is shown. The important thing to note in Fig. 4 is the spill-over of energy into the successive range bin. The next section discusses this problem in more detail.

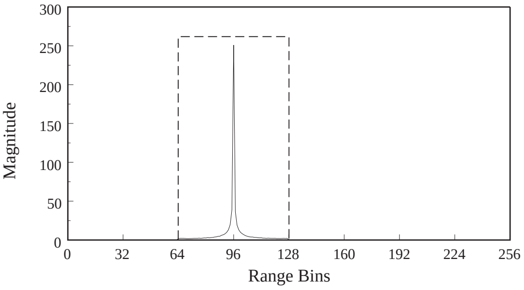

Figure 3: Synthetic range profile of a single point target in one coarse range bin

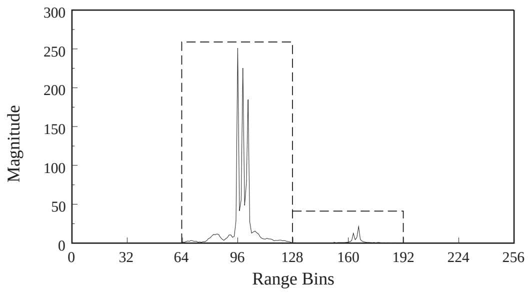

Figure 4: Synthetic range profile of three point targets in one coarse range bin, showing spill-over of energy into successive range bin

SAMPLING CRITERIA

Fig. 5 shows that for a single point target it is possible to avoid spill-over of energy into the successive range bin by sampling the matched filter output exactly at the peak of the triangular waveform. This scenario was followed when the data of Fig. 3 was produced. However as soon as there is more than one point target (which is the case in practice), there will be an inevitable spill-over of energy into the next range bin, as illustrated in Fig. 5. Sampling still takes place at the theoretical peak of the first pulse, but some of the energy of the second pulse and even more energy of the third pulse is also sampled in the next coarse range bin. This explains the decrease in amplitude of the second and third pulse as seen in Fig. 4.

A solution to the problem of spill-over of energy would be to sample every second coarse range bin during one transmitted pulse, and then every other second coarse range bin during the next transmitted pulse. This, however, will increase the PRF by a factor of two. Further investigations are being carried out using windowing functions and overlapping coarse range bins, in order to arrive at a satisfactory solution regarding the sampling of returning waveforms.

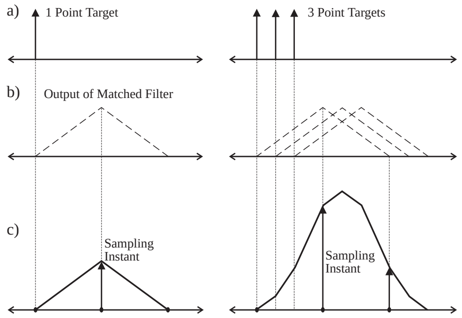

Figure 5: Sampling the output of the matched filter

SKIPPING FREQUENCIES

An important advantage of using stepped-frequency waveforms is the capability of skipping certain frequencies that would otherwise be corrupted by external sources such as broadcast FM and mobile radio. Before transmitting a pulse, the receiver could predict how much interference there will be at a particular frequency, and then decide to skip that frequency. Since the order in which frequencies are transmitted is not important, the radar could try to transmit a skipped frequency at a later stage in the burst. Another way out would be to interpolate the I and Q values of skipped pulses from those I and Q values of surrounding pulses.

CONCLUSIONS

The results that have been obtained from simulated SAR data show that it is feasible to use stepped-frequency waveforms to produce high resolution VHF SAR images. Not only do stepped-frequency waveforms alleviate the instantaneous bandwidth requirements of the radar system, but they also offer the capability of skipping frequency regions that might be polluted by external sources. This is expected to be a major feature of such a system, since the amount of interference at the VHF band is expected to be quite severe.

Further work will have to be carried out to investigate the effects of interpolating missing pulses, to solve the problems of the matched filter effect satisfactorily, to investigate the use of multiple PRF ranging and to implement high resolution SAR azimuth processing.

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