Analog Clutter Cancellation Algorithms for Dynamic Range Reduction

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ABSTRACT

Advanced radar receivers having an instantaneous dynamic range exceeding 90 dB are currently under development. These receivers must operate linearly to achieve satisfactory performance in a severe clutter environment. Presently available, state-of-the-art analog-to-digital converters (ADCs) having sufficiently high sampling rates do not have adequate dynamic ranges to digitize the outputs of these receivers.

A technique has been developed that effectively reduces the dynamic range of the input signal prior to digitization. The dynamic range reduction is accomplished through a process that predicts the next radar return signal from the previous return signals, generates a replica waveform, and subtracts this replica waveform from the radar return signal prior to digitization. This process allows the radar return signal to be digitized without distortion by an ADC having a limited dynamic range. The full dynamic range of the radar return signal is then restored by adding the replica waveform to the ADC Output. Tests and evaluations using both synthetic and recorded radar data have demonstrated in excess of a 30 dB reduction in the dynamic range of the signal at the ADC input when strong clutter is present.

INTRODUCTION

Modern air-surveillance radars must often contend with clutter-to-noise ratios (CNRs) in excess of 80 dB. Such conditions are typical for air-traffic-control (ATC) radars

Note: Voltage response of single range cell for 1536 consecutive radar pulses for scanning radars

Fig. 1. Dynamic Range Reduction Example

Fig. 1A. Input Analog Signal

Fig. 1B. Cancelled Analog Signal

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located in metropolitan areas, and for airborne early warning (AEW) radars using medium or high PRF waveforms in severe ground clutter environments. Thus, both civilian and military radars require receivers having a very large instantaneous dynamic range to permit operation without degrading target detectability when clutter conditions are severe.

Radar receivers having an instantaneous dynamic range exceeding 90 dB that can linearly process such large clutter returns are currently being developed by Rome Laboratory. These receivers can obviate the requirements for sensitivity-time control (STC) and automatic gain control (AGC) circuits, which desensitize the receiver and produce undesired amplitude modulations on the radar return signal when pulse compression waveforms are used. A dynamic range limitation still exists, however, due to the capabilities of presently available, state-of-the-art analog-to-digital converters (ADCs).

Most modern radars utilize coherent baseband processing, i.e., they form an analog inphase (I) and a quadrature (Q) channel. These channels are formed prior to digitization so that the conversion rate is minimized. This baseband signal processing is subject to errors caused by amplitude and phase mismatch between the analog channels. A preferred design alternative, which is being implemented in a high dynamic range receiver channel configuration at Rome Laboratory, is to translate the receiver output to a low-IF center frequency (typically 1.5 times the radar waveform's bandwidth), and directly digitize the single channel data. The I and Q channels can then be formed in the digital processor without introducing effects due to analog channel mismatch.

The difficulty with such an implementation is that the ADC must now operate at a rate of nominally four-times the low-IF center frequency, which is typically between 5 and 10 MHz. At the required conversion rates of 20 to 40 Megasamples/second, currently available ADCs are limited to about 12 bits. As the processor noise level is typically set at a level that will toggle the two least-significant bits, the ADC will have about 30 dB less dynamic range than the receiver channel.

An approach to overcoming this ADC dynamic range limitation [1, 2] is to predict the radar return signal for pulse n by using the radar signal returns from pulses $n-1$ to $n-p$. The replica waveform that is generated by the prediction algorithm is subtracted from the radar return signal at low-IF, thus reducing the dynamic range of the resulting waveform in the analog receiver, i.e., before the ADC. The full dynamic range of the radar return signal is recovered in the digital processor by adding a similarly processed replica waveform to the ADC output.

Note that it is not necessary for the replica waveform to exactly match the radar return signal; it is only necessary that the voltage difference that is formed when the two waveforms are subtracted falls within the linear dynamic range of the ADC. This fact allows a degree of flexibility in the generation of the replica waveform.

The viability of the dynamic range reduction by predictive filtering concept has been demonstrated in computer experiments performed using both synthetic data and recorded

data collected using the Rome Laboratory L-band air-surveillance radar, an AN/TPS-63 radar, and an E-3A AWACS radar. Figure 1 illustrates the capability of the technique when operating on actual data. In this figure, the I and Q voltage levels are expressed in terms of quanta, and one millivolt is equivalent to one ADC quantum level. The data in this figure is from a single range cell in which a large clutter signal occurred as the radar scanned in azimuth. The data consists of 1536 consecutive pulse returns. The peak input voltage was reduced by 30.1 dB. This data was collected and digitized specifically for the experiments using the Rome Laboratory L-band air-surveillance radar [2]. In excess of 30 dB of dynamic range reduction, i.e., the equivalent of five ADC bits, was consistently demonstrated against large clutter signals in these experiments.

Fig. 2. Dynamic Range Reduction Processing Concept

DYNAMIC RANGE REDUCTION CONCEPT

The dynamic range reduction concept is illustrated in Figure 2. An estimate of the radar return signal at the ADC input is subtracted from the actual radar return signal to reduce the instantaneous dynamic range. This replica waveform is formed by applying a predictive filtering algorithm to the p previous radar signals that have been received and digitized. Prior to subtraction, the replica waveform is converted to analog form by a digital-to-analog converter (DAC), and smoothed with an analog bandpass filter. Subtraction of the resulting analog waveform from the radar return signal will reduce the dynamic range by a sufficient amount to ensure saturation-free operation by the ADC when large clutter returns occur. The reconstructed radar return signal is formed by adding a quantized and digitally bandpass filtered version of the replica waveform to the digitized, reduced dynamic range ADC output. The reconstructed radar return signal is then used in the prediction of the radar return signal for the next transmitted pulse. The predictive filtering process can be initialized by attenuating the first few radar signals and amplifying them after digitization. Such operation ensures that the ADC does not saturate during the start-up of the processing.

This dynamic range reduction concept relies on a strong pulse-to-pulse correlation of the radar return signal. This will be the case in most severe clutter environments, e.g., buildings

located near an airport surveillance radar. In cases where severe interference occurs that is not highly correlated from pulse-to-pulse, e.g., high-power mainlobe jamming, the receiver may have to use conventional techniques such as STC and AGC to avoid saturating the ADC.

Finally, it must be noted that the effects of the quantizer and the digital bandpass filter on the replica signal must very accurately match those of the DAC, the analog filter, and the ADC; otherwise artifacts will be introduced into the radar return signal that will degrade the sensor's performance. The accurate matching of these parallel signal paths is currently being investigated.

Fig. 3. Block Diagram of LPF

PREDICTION ALGORITHMS

Three significantly different algorithms for generating the replica waveform were investigated to determine the viability, achievable performance and computational requirements for the technique. Each algorithm used a different method to establish the coefficients of a linear prediction filter (LPF) for generating the replica waveform. The simplest method to implement was a delay-line canceller (DLC) configuration that used fixed, binomial weights. For the filter configuration shown in Figure 3, the predicted radar return signal, $\hat{X}(n)$, is:

$$\hat{X}(n) = \sum_{i=1}^p a_i X(n-i) \quad (1)$$

where:

- n is the pulse index
- p is the number of pulses used to form the replica waveform
- $X(n-i)$ are the actual radar return signal values
- a_i is the i^{th} LPF coefficient.

For binomial weighting:

$$a_i = (-1)^{i+1} p! / (p-i)! i! \quad (2)$$

The second approach was to use the Maximum Entropy Method (MEM) to establish the a_i values for the LPF. This approach was selected because Rayleigh clutter is well modeled by a third-order autoregressive process [3]. The Burg algorithm [4] was used to establish the filter coefficients. The Burg algorithm is preferred because it computes the filter coefficients directly from the available data, as opposed to techniques that first require the computation of the autocorrelation function.

A unique set of LPF coefficients was generated for each range gate. The coefficients were updated every 256 pulse repetition intervals (PRIs).

The final method computed the LPF coefficients recursively, using the Least-Mean-Square (LMS) algorithm [5]. The LMS algorithm differs from the others in that it adaptively updates the LPF coefficients for each range gate after each radar PRI. The LMS algorithm is a steepest-descent, gradient search technique that estimates the gradient of the mean-square error performance surface as the derivative of the squared error. For this algorithm, the updated LPF coefficients are calculated to be:

$$\vec{a}_{n+1} = \vec{a}_n + 2\mu e_n \vec{X}_n \quad (3)$$

where

$\vec{a}_n$ is the vector of the p LPF weights for pulse index n
 $\vec{X}_n$ is the vector of the p most-recent input data samples, i.e., $X(n-1), \dots, X(n-p)$

$$1/\lambda_{\text{MAX}} > \mu > 0 \quad (4)$$

$$e_n = X(n) - \hat{X}(n) \quad (5)$$

and λ_{MAX} is the largest eigenvalue of the correlation matrix of the input data. To simplify the procedure, the relationship:

$$\lambda_{\text{MAX}} \leq p E[X^2(n)] \quad (6)$$

is employed to determine the value of μ . This algorithm proved to be very efficient for generating the LPF coefficients.

EVALUATION DATA AND SIMULATION MODEL

The dynamic range reduction achieved by the three algorithms was evaluated using both synthetic data and recorded radar data. The synthetic data was produced using a random number generator to form radar return signals having large clutter components. This synthetic data was convolved with a model of a rotating radar antenna pattern to introduce both mainlobe and sidelobe effects. The recorded radar data was from three sources: the L-band air-surveillance radar at Rome Laboratory, an L-band TPS-63 radar, and the S-band AWACS radar. The results using the Rome Laboratory L-band data are presented in this paper. The parameters of this radar are provided in Table 1.

A simulation of the receiver/processor configuration that is shown in Figure 2 was developed. This simulation has been used to assess the effects that hardware limitations will have on the performance of the dynamic range reduction technique. Effects that have been evaluated include the DAC thermal noise and nonlinearity, the analog filter spectral shaping and delay, the ADC quantization noise and nonlinearity, and the analog and digital path mismatch that was discussed in Section 2.

Figure 4 illustrates a simulated processing example. In Figure 4A, a very large clutter return has been digitized after dynamic range reduction processing, and the total dynamic range of the radar return signal has been restored in the digital signal

Table 1. Rome Laboratory L-Band Radar System Parameters

Parameter	Value
Frequency GHz	1.265
Wavelength	23.7 cm
Peak Transmitted Power	100.0 kW
Antenna Gain	30.0 dB
Azimuth Beamwidth	2.5 deg
Elevation Boresight	3.0 deg
Elevation Beamwidth (with csc ² shaping from 9° to 30°)	8.0 deg
Pulse Width	1.0 μ s *
Pulse Repetition Frequency	1.0 kHz *
Antenna Scan Rate	6.0 rpm *
Azimuth Scan Sector	360.0 deg
Scan Period	10.0 sec *
Pulses per Beamwidth	69
Receiver Dynamic Range	70.0 dB
IF Bandwidth	35.0 MHz
Noise Bandwidth	2.0 MHz
Noise Figure	3.5 dB
Transmit/Receive Loss (Estimated)	3.5 dB

* Programmable Parameter

processor. No spectral artifacts are observed, and the processor noise level is at the expected level. In Figure 4B, a threshold-level target has been introduced into the scenario. The radar return signal for this target is at the expected level, validating that no signal suppression has occurred. Tests such as this using simulated data suggest that the dynamic range reduction technique will operate satisfactorily when implemented into hardware.

DYNAMIC RANGE REDUCTION PERFORMANCE

The average dynamic range reduction that was achieved against the largest clutter returns in the recorded Rome Laboratory L-band radar data is shown in Table 2. These results assume no processor latency, i.e., the radar return signal for PRI n is predicted using radar signals from PRI's $n - 1, n - 2, \dots, n - p$. From this data it is seen that the fixed-coefficient DLC implementation is unsuitable as a prediction technique when p exceeds two. The poor performance of the higher-order DLC configuration is caused by the excessive weight that the binomial coefficients apply to the older samples of the radar return signal. Coefficients other than the binomial values may provide better DLC algorithm performance when p is large.

Both the Burg algorithm and the LMS algorithm were found to provide over 30 dB of dynamic range reduction for the Rome Laboratory L-band radar data. Although the Burg algorithm, which was updated every 256 PRI's, achieved about 1 dB better dynamic range reduction than the LMS algorithm, it required significantly more computations to generate the filter coefficients. Therefore, the LMS algorithm would appear to be

the better choice for applications in which processor resources are limited.

Fig. 4. Spectra of Simulated Waveforms

Fig. 4A. Clutter Return Signal

Fig. 4B. Clutter-Plus-Target Return Signal

Performance was also evaluated for three consecutive scans of data collected in one azimuth sector using the Rome Laboratory L-band radar. The results of this evaluation indicate that the clutter is sufficiently correlated from scan to scan to yield satisfactory cancellation performance when the LPF filter coefficients that are calculated from the data on one scan are applied to the data on a subsequent scan. Thus, the LPF coefficients may not have to be calculated during each scan. If, in fact, several scans can elapse before the recalculation of these coefficients becomes necessary, the processing requirements for implementing the Burg algorithm would be significantly reduced.

Table 2. Average Dynamic Range Reduction (dB) Achieved for Large Clutter Returns

p	DLC with		
	Binomial Weights	Burg Algorithm	LMS Algorithm
1	29.4	29.4	29.4
2	29.2	30.4	29.7
3	24.4	31.1	30.0
4	19.1	31.3	30.1
5	13.5	31.5	30.3

Processor latency was found to severely degrade the performance of the dynamic range reduction technique. Typically, a latency of 1 PRI will reduce the achievable dynamic range reduction by about 3.9 dB, 2 PRIs by 6.5 dB, 3 PRIs by 8.3 dB, and 4 PRIs by 10.0 dB. Thus the speed at which the replica waveform is computed and applied can have a more significant effect on the achievable performance than the accuracy with which this waveform matches the radar return signal, provided of course that the replica waveform is sufficiently accurate to prevent ADC saturation.

The nominal 30 dB of dynamic range reduction performance that has been achieved should not be viewed as an absolute limit for this technique. This value is very much a consequence of the relatively benign clutter environment at Rome Laboratory. Also, the fact that only 1 to 2 dB of improvement occurs as the value of p increases for the MEM and LMS algorithms can also be attributed to the test environment. Tests involving synthetic data suggested that an additional 5 to 7 dB of performance can be achieved, with the additional improvement expressed in dB being nominally a linear function of p . Also, under more dynamic clutter conditions, a higher-order LPF is expected to show a much greater performance improvement. Even so, the additional 1 to 2 dB improvement that has been demonstrated by the MEM and LMS algorithms is equivalent to between 0.12 and 0.26 of an ADC bit, and will correspondingly reduce the probability of receiver saturation.

CONCLUSIONS

The technique discussed in this paper appears to be a viable concept for allowing a wide instantaneous dynamic range receiver to operate linearly with a limited dynamic range ADC in severe clutter environments. The concept has been examined in scenarios for which a threshold-level target and extremely strong clutter are simultaneously present. The target was

consistently detected, while artifacts generated by the technique were sufficiently small so as not to cause excessive false alarms.

Although the dynamic range reduction technique has performed well for both simulated and recorded data, actual hardware experiments will be required to validate its true performance. Such experiments will be conducted at Rome Laboratory in the near future, using the new high dynamic range receiver channel that is currently being installed. These experiments will quantify the ability of the technique to perform when actual analog hardware effects exist in the replica waveform's feedback path, and in environments in which both weather clutter and jamming are present.

Thus, the dynamic range reduction by predictive filtering technique can potentially be used to interface high dynamic range receiver channels and powerful digital signal processors through limited dynamic range ADCs. This design approach could cost-effectively enhance the performance of both military and civilian radars that operate in severe ground clutter environments.

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