Dynamic Range Enhancements in Radar Systems

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Abstract

The extension of existing Radar and Electronic Surveillance Measures (ESM) systems dynamic range is integral to the Electro-Magnetic Remote Sensing (EMRS) Defence Technology Centre (DTC) requirement for current sensors to see deeper into clutter (i.e. see small targets in the presence of large clutter levels e.g. urban clutter). The rationale behind this requirement being this additional capability greatly enhances the utility of military and commercial systems, thereby greatly improving technology exploitation and business opportunities within the currently identified market segments.

Keywords: *radar, radio, position, communications, linearisation, dynamic, range, systems, transmitters, receivers, phase, noise, enhancements, improvements, distortion, mitigation, intermodulation, IP3, IM, IM3, clutter, sensitivity, jamming, ESM.*

Rationale

Military and commercial electronic sensors and communications systems are, limited by the dynamic range of the hardware used to implement them. In communication receiver systems it is still practically impossible to operate a receiver at its full sensitivity near to base stations and other transmitters (both in and out of band). In Radar a similar problem exists when trying to detect small targets in a highly cluttered environment. In particular urban clutter and jamming can quickly drive the receiver system into limit and suppress sensitivity to small targets. The classic solution is to use Automatic Gain Control (AGC) or Sensitivity Time Control (STC). Unfortunately this produces changes in receiver sensitivity which, in many situations, the operator may not be aware of.

This research work for the DTC endeavoured to take a holistic view of this problem in order to provide new methods and techniques to assist across a number of domains [1]. Therefore the research work is generic in nature. Typical problems addressed include:

- The ability to operate sensitive ESM and Radio-communications receivers close to transmitters operating in the same frequency bands.
- The ability to operate Radars in urban and littoral clutter environments without loss of receiver sensitivity.

Markets & Applications

Markets

Defence and Security: The extension of existing system dynamic range would greatly enhance the utility of military systems. The DTC members are ideally placed to make use of the work results.

Communications, Transport and Automation: Dynamic range is a key parameter in mobile phone base stations.

Applications

Electronic Sensors: Radar (including Phase Array Radar (PAR), Bistatic Radar, FMCW monostatic Radar, Miniature Radar, Missile Guidance Radar, Millimetre Wave Radar, Radiometry, Stealth detection, Industrial Radar); Location and Positioning Systems; Passive Bistatic Radar.

Communications: ESM, Cellular Systems, including 3G (UMTS) and 4G (OFDM-MIMO) technologies, Broadcast, Satellite, and Ultra Wide Band (UWB) systems.

Transmitter Linearisation

This section reports the research results related to Transmitter Linearisation using novel Envelope Elimination and Recovery (EE&R) amplifiers [1], to eliminate the power output and phase changes that occur during long Radar transmit pulses.

Pulse Droop Effects with High-Cost Amplifiers

Reduction in Pulse Energy: The theoretical reduction in target SNR is shown in Figure 1 below. As expected, a droop of X dB causes an SNR loss of approximately $X/2$ dB. Hence, for a typical 1 dB droop, the SNR loss is ~0.5 dB.

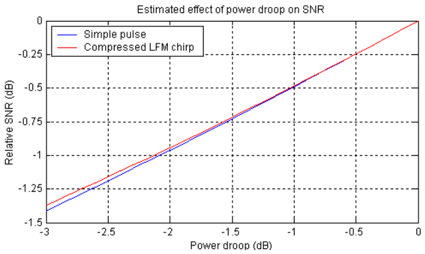


Figure 1: Theoretical effect of power droop on SNR

Simulated Effects on Pulse Compression Waveforms: The reduction in power of the target peak in range cell 300 for various levels is summarised in Figure 2. This shows that a pure power droop of X dB results in a loss of SNR of approximately ⅔ X dB, slightly greater than the theoretical $X/2$ dB. Phase decay has relatively little effect, either separately or in combination.

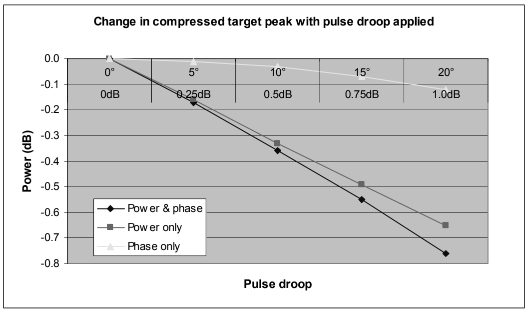


Figure 2: SNR loss in target range cell due to pulse droop

Figure 3 shows that by compensating for pulse droop, there is a slight improvement in the detectability of small targets on the near side of a large scatterer, but there could be a reduction in the detectability of targets on the far side of a large scatterer.

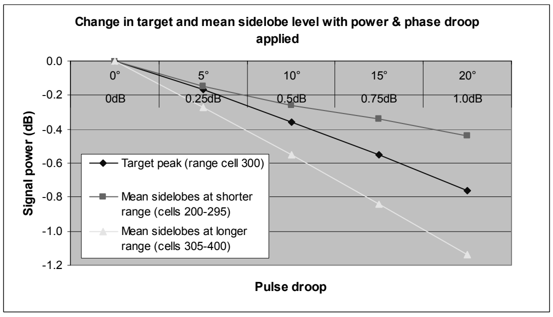


Figure 3: Relative effects on target peak and range sidelobes at shorter / longer ranges when combined power & phase droop applied

Pulse Droop Effects with Low-Cost Amplifiers

Reduction in Pulse Energy: Assuming a decaying exponential pulse envelope with a maximum power droop of 3 dB at the end of the pulse, gives the reduction in total pulse energy as ~1.5 dB. This is equivalent to an increase of ~9% in maximum detection range, for all radar sensors.

Effect on Pulse Compression Waveform: A total simulated improvement of ~2 dB in the compressed target SNR (approximately 12% improvement in maximum detection range or 12 km for a typical ground based surveillance radar system), and 0.8 dB in the mean peak-to-sidelobe ratio on the shorter range side of a target (approximately 5% increase in maximum detection range) for a FM pulse compression radar.

Transmitter Linearisation Findings

The requirement for EE&R amplifiers (i.e. long transmit pulses with minimal power droop), is clearly evident when the BMD Radar system performance requirement is considered. In this case, we ideally require transmit energy on target for duration of between 3-6 ms to enhance SNR.

Furthermore, Radar systems employing low cost amplifiers, which use the EE&R methods, offer comparable performance to high cost amplifiers, which don't use EE&R methods; further work will quantify the EE&R method cost benefit in terms of a typical PAR systems.

Phase Noise Mitigation

Oscillator Model

From the view point of the phase noise performance of Radar microwave LOs the "interesting" part of the standard phase noise model curve is the middle section with the inverse square law frequency characteristic.

The output phase noise in this region is given by:

$$S_\phi(\omega) = \left(\frac{\omega_0}{2Q}\right)^2 \frac{2kFT}{P_s \omega_m^2} \qquad (1)$$

Phase Noise Mitigation Effects in Radar Systems

Phase Noise Characteristics: In Radar systems the phase noise from the LO normally dominates over other sources. The phase noise for a typical LO has two components:

- Device noise or white noise – uncorrelated sample-to-sample;
- Flicker noise which caused a random walk – strongly correlated between adjacent samples.

The random walk produces the characteristic 20dB / decade roll-off versus carrier offset frequency. The phase noise model is valid over the short time intervals typical of target echo times.

Moving target indication (MTI): A practical radar system typically uses a number of refinements to improve some aspects of the performance of the MTI process. In particular it is normal to adjust the frequency of the MTI filter notch to match the mean velocity of the clutter. And in fast moving airborne systems this is essential to make the MTI process work at all. It is common to use some kind of adaptive process to track the clutter's Doppler as so adjust the response of the MTI filter for optimum rejection. This works well to remove the relatively constant Doppler offset frequencies, but offers no improvement against random effects of radar phase noise.

Phase noise cancellation: For phase noise sources common to transmit and receive some of the lower frequency components of phase noise are essentially cancelled out. The cancellation effect caused by the finite echo time has been modelled in the frequency domain where it has the effect of causing a 20 dB/decade roll-off in the phase noise below a carrier offset frequency equal to the reciprocal of the target echo time. N.B: The errors caused by phase noise are extremely small in well designed radar systems. Values in the range of 0.01 degrees or 0.0002 radians are typical.

Phase Noise Cancellation for a real Radar System

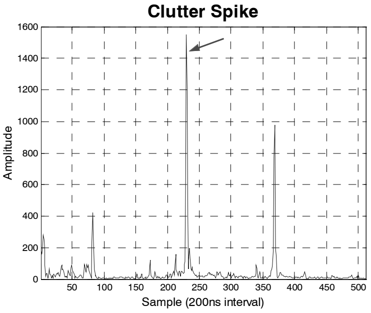


Figure 4: High magnitude clutter spike

Figure 4 shows a high level isolated clutter spike (radio-communications antenna mast). Figure 5 shows the clutter phase for this high level isolated clutter spike.

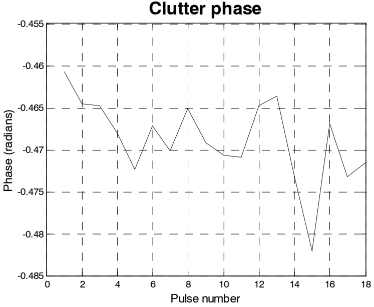


Figure 5: High magnitude clutter spike phase

The standard deviation of phase noise from the high level clutter discrete is 0.004 radians. This is close to the expected value from the LO datasheet (0.003 radians). This result confirmed the validity of the measurement data.

Phase Noise Mitigation Findings

The results show that, using limited data so far, phase noise cancellation may be possible in areas with very high level clutter discretes close to the wanted targets, e.g., littoral and harbour environments.

Receiver Linearisation

Novel Receiver Digital Post Distortion

Post distortion procedure: Before post-distortion can be applied there are a number of other operations to be performed on the captured data; to compensate for time, phase and magnitude offsets. These signal processing operations are illustrated in Figure 6.

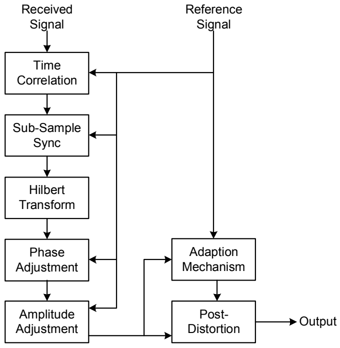


Figure 6: Digital signal processing flow

The post-processing procedure detailed in Figure 6 was simplified and improved for radar applications.

Experimental set-up: This experimental set-up used for investigating post-distortion in receivers is shown in Figure 7. The experimental set-up contains test signal generation, distortion in the simple receiver, signal capture and post-processing. The set-up is based on practical generic receiver architecture.

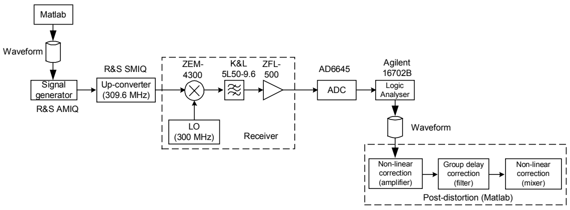
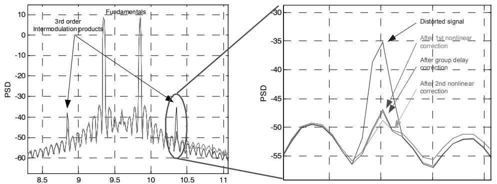


Figure 7: Experimental Set-Up for Post-Distortion Investigations

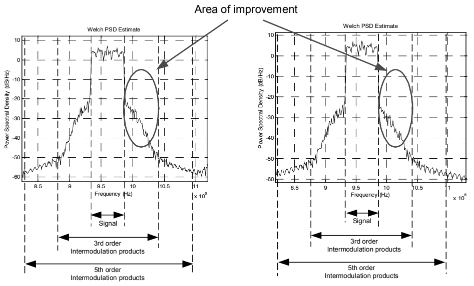
Narrow-band results: Results of the compensation of the distortions introduced in the narrowband signal are shown in Figure 8. The detail in Figure 8(b) shows the successive suppression of third-order intermodulation products at the output of successive post-distortion stages. The total improvement in IM3 is approximately 15 dB for the wideband case.



(a) (b)

Figure 8: PSD of the signal (a) before and (b) after double post-distortion with group delay correction

Wide-band results: Results of the compensation of the distortions introduced in the wideband signal are shown in Figure 9. The total IM3 improvement is ~ 3-5 dB for the wideband case.



(a) (b)

Figure 9: PSD of (a) distorted and (b) post-distorted signal (without band-pass filter)

Novel Mixer Circuits

Feed-forward method: Figure 12 illustrates a basic form of feed-forward error correction for a mixer [4].

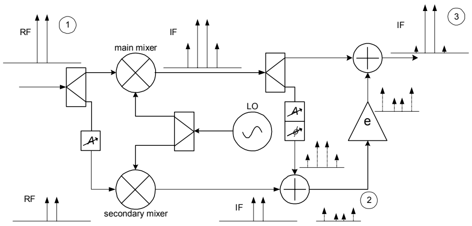


Figure 10: Architecture diagram for feed-forward mixer

Figure 11 shows simulation results for the feed-forward method in the narrow-band signal case. For high power 2-tone input signal, IM products were strongly attenuated at the expense of increased noise floor. Phase matching was found to be absolutely critical: < 1° for good IM suppression.

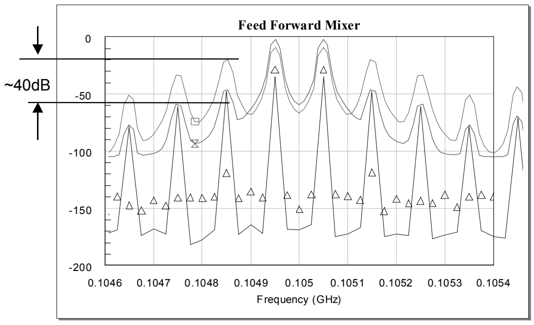


Figure 11: IM3 improvement with feed-forward mixer method, narrow-band case

Frequency retranslation method: Figure 12 illustrates a basic form of frequency retranslation error correction for a mixer.

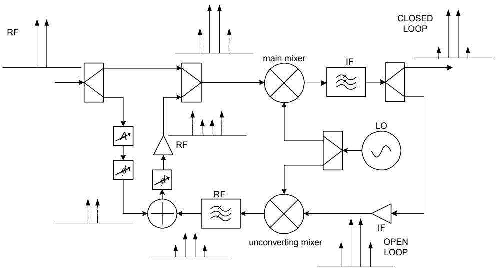


Figure 12: Architecture diagram for frequency retranslation mixer

Figure 13 shows simulation results for the frequency retranslation method in the narrow-band signal case. Whilst excellent reduction in IM3 products is achieved, higher order products are actually increased. For high power 2-tone input signal, IM products less well attenuated than feed-forward method however, the noise floor remained at a low level.

The study showed the circuit is sensitive to phase and amplitude variations (but not as sensitive as frequency retranslation method), and as such would require DSP control in a practical system.

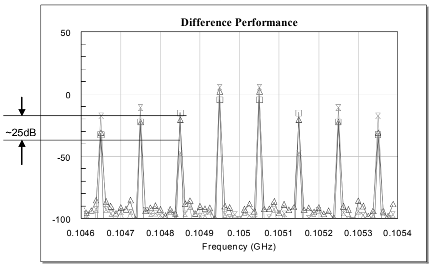


Figure 13: IM3 improvement with frequency retranslation mixer method, narrow-band case

Following analysis of simulation results it was decided the frequency retranslation method held the greatest potential for dynamic range enhancement. The hardware build and experiments therefore concentrated on this method. It was found that with careful adjustment of phase and amplitude shifters, IM products could be well attenuated. Figure 14 shows experimental test results for the frequency retranslation methods for the wideband signal case, ~25 dB IM improvement.

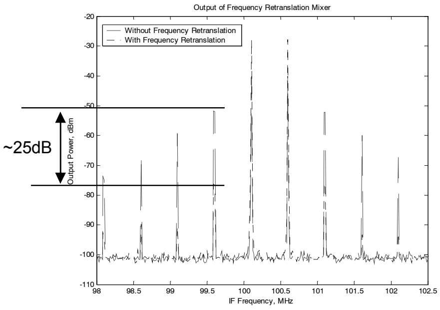


Figure 14: Experimental results showing IM3 improvement for frequency retranslation mixer , wideband case

Future Work

In the next year, it is planned to expand existing models and realise receiver post-distortion algorithms based on RMRL's transmitter linearisation algorithms. A generic flexible receiver post distortion method to enable rapid simulation & design of dynamic range enhancement solutions for radar systems is also planned. Study advanced embedded signal processing method for phase and amplitude balance in practical frequency retranslation mixer methods to enable dynamic range improvement. Experimental investigation will be used to verify the researched methods work in practice. Technology pull-through to support major MOD research programmes is envisaged.

A Patent Application has been filed to protect the subject matter of this work.

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