Suppression of Range Sidelobes of Random Modulations

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Abstract— **A technique is described to cancel the range sidelobes due to the use of a random waveform for radars. The technique is based on the deterministic relationship (a complex conjugation) between the range sidelobes either side of a target.**

The technique is demonstrated by simulation and is also shown to work with recorded data from a practical noise radar demonstrator.

The most important field of application for this technique is likely to be to improve the dynamic range of noise radars which must work in the presence of direct leakage between the transmitter and receiver, simplifying the system design.

Keywords— cancellation; dynamic range; noise radar

I. Introduction

As is discussed for example in [1, 2], noise radars have two great advantages: minimal cross-correlation and low probability of interception and exploitation. It is also well known [2] that the two principal challenges to developing noise radars are implementing the processing required to perform the matched filtering (i.e. to compute the cross-ambiguity function) in real time and controlling the sidelobes caused by the random modulation.

Technological developments make it possible to implement the processing required to perform the matched filtering in real time. This paper proposes a technique to reduce the range sidelobes due to reflections from very short range targets. It does this by noting that the instantaneous sidelobe levels at positive range, which tend to mask the targets, are the complex conjugates of those below zero range (i.e. just before the ambiguous range), a region which is generally free of targets.

II. Dynamic Range of Radars

It will be seen in section III C, below, that the dynamic range issues mean that the radar applications most suited to noise waveforms are those with the lowest powers, and as discussed further in section III A, the main drivers towards the use of such modulations are its Low Probability of Interception (LPI) and Low Probability of Exploitation (LPE) capabilities, so a suitable 'low power' application to consider is a low-power marine radar such as is used for navigation of small military ships for which a radar compliant with the standards promulgated by the International Maritime Organization are not required. A smaller radar may then be used, of a performance comparable, for example, to the Simrad BR-24 Mk III/IV [3].

The BR-24 uses Frequency-Modulated Continuous Wave modulation. It has a mean power output of 13dBm. The 5.2° azimuth beam width and 24rpm scan rate equate to a dwell time of 36ms. If a radar can in practice perform coherent integration over a third of this dwell time then the noise bandwidth will be about 80Hz. A coherent integration time of this length will avoid excessive problems due to scanning modulation. Then, if the receiver noise figure is 6dB, the noise floor will be -149dBm, so the total dynamic range between the transmitted power and the noise floor will be 162dB.

With 60dB isolation between the transmission and reception, the dynamic range between the noise floor and the direct leakage of the transmitted into the receiver must therefore be approximately100dB

It is noted [2] that small Battlefield Surveillance Radars will use a similar mean transmitter powers and thus have similar dynamic range requirements.

III. Characteristics of Noise Radars

This section of the paper expands on the essential features of noise radars, outlined above, and serves as an introduction to the explanation of the importance of the technique described in this paper and how it operates.

A. Low probability of Interception and Exploitation

The wide variety of noise-like signals available with high time-bandwidth products makes it virtually impossible to provide efficient interception schemes to use against noise radars, and if detected, their lack of features makes them very hard to identify [4].

B. Minimal Cross-Correlation

One of the advantages of noise radar is the ability to operate many systems with high duty cycle in the same frequency spectrum, by making use of the very large number of very different waveforms which can operate in the same spectrum, relying on the very low cross-correlation between these waveforms, which are a consequence of their high time-bandwidth products.

C. Dynamic Range

Since the dynamic range of the signals which the radar receiver must be able to handle is driven by the transmitter power, which determines the power received from the strongest targets, and by the noise floor, which determines the weakest signals which can be detected, noise radar is easier to implement with applications which use relatively low transmitter power levels.

If, like the BR-24 [3], our noise-modulated radar uses an RF bandwidth of 65MHz, the pulse compression gain will be 65MHz/80Hz or almost 60dB. We can see therefore that further techniques will be required to further suppress the correlation sidelobes by an additional 40dB in order to achieve the goal of 100dB dynamic range which was set in section II. One known way to do this is to make use of the CLEAN algorithm [5]. Another way is to use the technique described below.

IV. CANCELLATION TECHNIQUE

As mentioned in the introduction, the technique relies on measuring the correlation (range) sidelobes just before zero range and subtracting these from the down-range returns to suppress the sidelobes.

The notation used to explain how the technique works is as follows:

The transmitted signal is $r(t)$ and its spectrum is $R(\omega)$

The received signal is $s(t)$ and its spectrum is $S(\omega)$

If $\sigma(\tau)$ represents the profile of radar reflectivity with range, where the latter is represented as a time of flight from the radar to the target and back, then the relationship between the transmitted and received signals is

$$s(t) = r(t) \otimes \sigma(\tau) \quad (1$$

where '⊗'represents a correlation.

If the output of the matched filter is $y(t)$ and its spectrum is $Y(\omega)$, then the matched filtering operation can be represented by

$$Y(\omega) = S(\omega)\times R^*(\omega) \quad (2$$

where '*'represents a complex conjugation.

If we now consider the particular case of a return from a single path, such as the direct leakage between transmitter and receiver, and assume that this is at zero range, i.e.

$$\sigma(\tau) = 0;\ \forall\tau \neq 0 \quad (3$$

then, apart from a scaling constant represented by $\sigma(0)$, $s(t)$ is equal to $r(t)$.

$$Y'(\omega) = R(\omega)\times R^*(\omega), \quad (4$$

The multiplication by the complex conjugate removes the phase information

$$Y'(\omega) = |R(\omega)|^2. \quad (5$$

As is very well known, the Fourier transform, or the inverse Fourier transform, of a purely real function has real components which are symmetrical about zero and imaginary components which are anti-symmetrical about zero, i.e. the signal components at equal distance either side of zero, in this case the range sidelobes of signal at range zero, will be complex conjugates of each other.

A. Effect of Leakage at Non-Zero Range

If the leakage, i.e. the target sidelobes which should be cancelled, is not at zero range, then the sidelobes will not be symmetrical about zero range, but about the range of the return. This range can be estimated by using the data and a correction made for it. The estimation can be made either in the time domain, using a 'centre of gravity' technique, or if there is truly one target, by the rate of change of phase with frequency. Although both techniques work well with simulated signals, the 'centre of gravity' technique has been observed to work better with real signals.

In general, the return will not be in the centre of a range bin. In this case the technique is to shift the received signal by the fraction of the range cell to move the dominant reflection into the centre of a range bin and then to subtract the complex conjugates of the sidelobes on either side of the bin containing the dominant reflection.

In the examples shown the resulting offset, of a fraction of a bin, in the range profile was not actually corrected, although the information exists to correct it if desired.

The position of the strongest return was estimated by taking the power in the range cell containing the highest signal and the powers in the two cells either side of this and estimating the centre of gravity of the power profile.

The shift of a fraction of a bin was actually a circular shift obtained by performing a discrete Fourier transform on the data, the multiplying each bin by $\exp(2\pi j\tau n/N)$ where n is the index of the bin, N is the total number of bins τ is the required shift in range bins. The range profile is then recovered by performing an inverse Fourier transform.

As can be seen from the discussions in the previous sections, it can be seen that the 'goal' is to obtain 40dB cancellation, careful alignment of the range to the leakage is required. The following table shows the limit of cancellation as a function of mis-estimation of the range of the leakage signal and is derived from the simulation experiments discussed in the next section:

Misalignment (Range Cells)	Limit of Cancellation (dB)
0.3	+3
0.1	-3
0.03	-13
0.01	-23

Table 1:Limitation of Cancellation Due to Misalignment in Range

The method of estimating the position of the peak has an error of less than 0.01 at high signal to noise ratios. Of course, if the return does not have a high signal to noise ratio its sidelobes will be below the noise floor and the cancellation process will not be needed.

B. *Multiple Strong Targets*

The technique described above for correcting for the actual range of the strong signal will not work if there is not a single dominant return. The technique is thus best suited to the case where there is one such return, for example where the performance is dominated by direct leakage from the transmitter to the receiver.

C. *Effect of Noise*

It should be noted that subtracting the complex conjugates of the signals either side of the dominant signals actually adds the noise powers in the 'up range' and 'down range' cells and thus degrades the overall noise figure of the radar by 3dB, but this is considered acceptable if it can make the difference between a 'workable' radar and one which is not workable.

It should also be noted that the criterion that has been implicitly used above, that the compression sidelobes should equal the noise floor, will actually produce a 'floor' comprising the power in the compression sidelobes plus the noise power which will degrade system noise figure by 3dB.

For effectively perfect performance, i.e. less than 0.5dB degradation of the system noise figure, the compression sidelobes should be about 10dB below the noise floor, but this is, again, actually a second-order issue in the design of the system architecture.

V. SIMULATIONS

It should perhaps be noted that all the simulated and real results make use of discrete Fourier transforms to implement the matched filtering, but the principle described above does not make use of the 'circular' nature of the discrete Fourier transform, as can be understood from considering the case where the data is over-sampled and zero-padded so that it does not fold back in either time or frequency. In that case it can be seen that the argument still applies, i. e. that the technique compares the sidelobe pattern either side of the large signal and that these sidelobes are complex conjugates of one another.

Figure 1 shows the simulation of an 'A scope' (signal level versus range) display for a noise radar. Each component of the signal was pure Gaussian noise and the signal has a time bandwidth product of 4096. There is no noise added to the signal. The mean sidelobe level is 36dB below the peak, as expected.

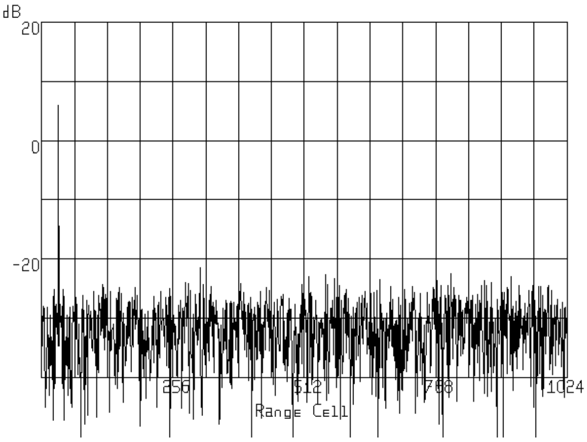

Figure1: Range Sidelobes of Simulated Noise Radar

The signal is at range of 31.5 cells. Of course the ambiguous range is 4096 cells, but only the first 1024 cells are shown. It can be seen that the sidelobe pattern is symmetrical around the peak return.

Figure 2 show the output of the cancelling process.

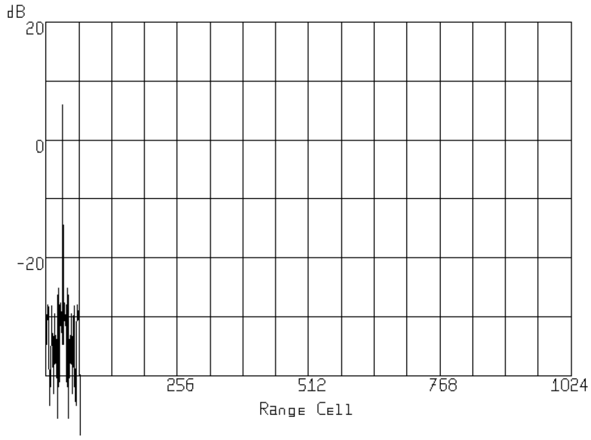

Figure2: Cancellation of Range Sidelobes of Simulated Noise Radar

The cancellation assumes that for real radar data, the ranges between zero range and the cell containing the peak might also contain targets, so the cancellation only starts when the range of the 'image' sidelobes is less than zero. The cancellation therefore starts at cell 63, beyond which the suppression of the range sidelobes is essentially perfect.

In all the pairs of 'A-scope' pictures in this paper the absolute power is arbitrary, but it is consistent within the pair.

VI. EXPERIMENTAL RESULTS

The experimental results shown below were obtained by processing data obtained with the radar described in [2]. In brief this was an X-band radar using a 'floodlight' horn antenna for transmission and a rotating marine radar antenna for reception.

Figure 3 shows the PPI of the data used in the experiment.

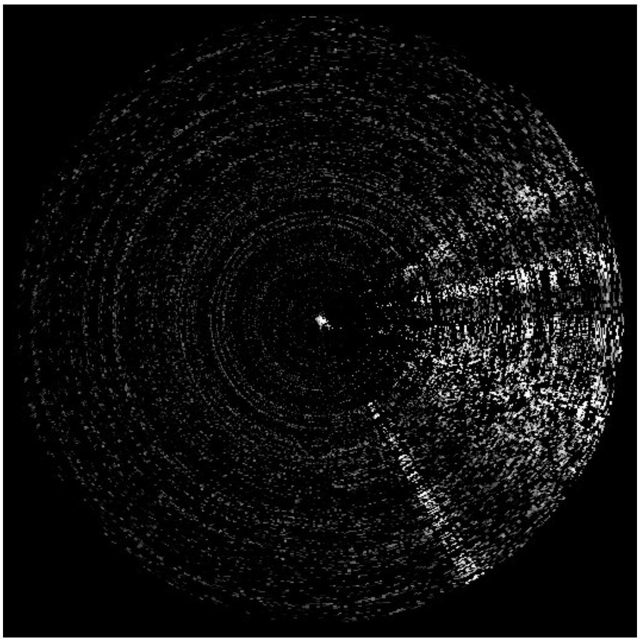

Figure3: Noise Radar PPI

It will be observed that the PPI is not particularly impressive, showing few distinctive features, but the data is nonetheless useful. The maximum indicated range is about 5km, the picture orientation is North-up and the radar was installed about 1km South of the Fraunhofer-FHR site in Watchberg, Germany.

The brighter areas of the PPI correspond approximately to the areas illuminated by the fixed transmit antenna and the other areas are in its 'back lobe.'

The 'rings' at constant range occur because the same instantiation of the noise waveform was used on each spoke so the range sidelobes follow the same pattern on each spoke, with peaks at the same ranges.

The ground clutter is rolling agricultural land, so the radar image contains no recognisable features, although it does show large-scale spatial correlation which may indicate stronger returns or dead ground.

The features within the clutter, and to some extent the rings, have been enhanced by application of a 'fast time constant,' i.e. differentiation of the video signal, which is also called 'anti rain clutter' processing to suppress the general background clutter and noise levels and enhance variations in the levels.

The intrinsic transmit/receive isolation is of the order of 100dB, and the range sidelobes of the leakage are below the noise floor, but the 'rings' which can be seen in the back-lobe region show that they nonetheless present.

Figure 4 shows the first 1024 cells (about 3.1km) of the signal from a bearing of about 72 degrees East of North.

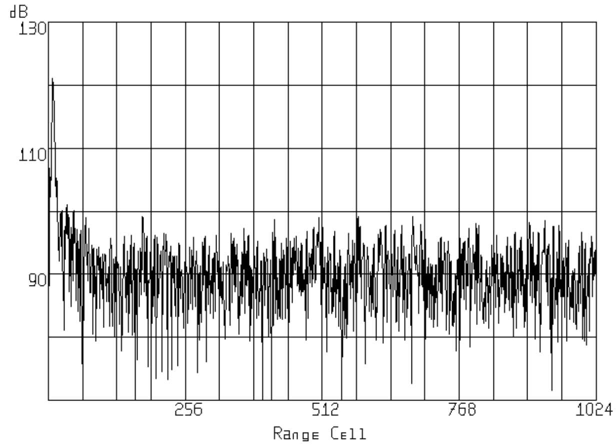

Figure 4: A-Scope of Real Noise Radar

The mean 'floor' is about 30dB below the peak. The time-bandwidth product of this data is about 33dB, so we might expect the floor to be dominated by the range sidelobes of the strong target. Figure 5 shows the outcome of the cancellation process.

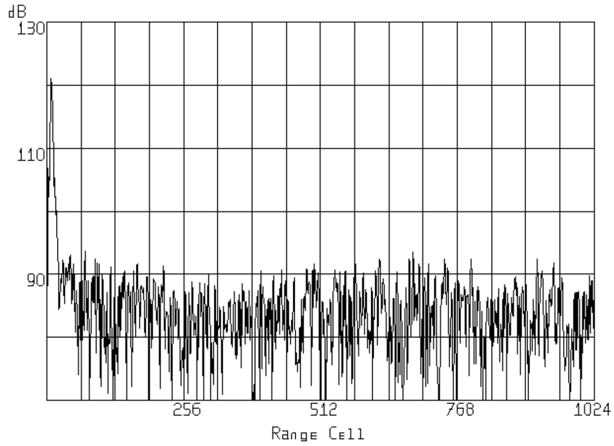

Figure 5: A-Scope of Cancelled Noise Radar Data

It can be seen that the range sidelobes in this practical case have been reduced by something of the order of 10dB. This example shows the principle can work with real data, although it is something of a 'best case' since with this data the direct leakage signal is very weak so in many cases there is not one 'dominant' return.

As an auxiliary test, the average cancellation achieved over the whole illuminated sector was measured for different values of the assumed range to the return. Figure 6 shows the cancellation achieved:

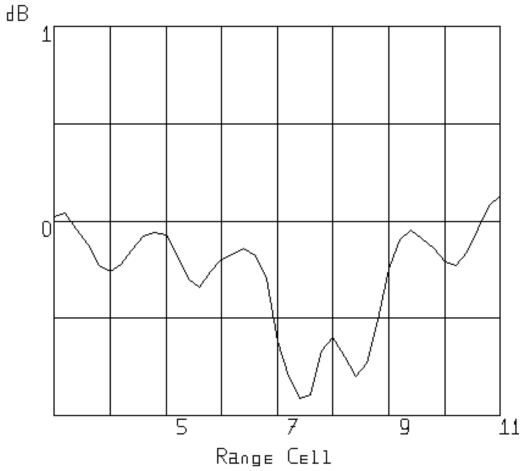

Figure 6: Average Cancellation over Main Beam Region Versus Assumed Range to Dominant Return

The 'reference level' of 0dB cancellation actually corresponds to the 3dB increase in the background which would be seen if the sidebands were uncorrelated, or, as discussed in section IV C, if cells contained only noise. Cancellations which are positive imply that the sidelobes are correlated but that the error in the range estimate is causing them to be added rather than subtracted.

It can be seem that the results follow smooth curves, showing that the random waveforms and the noise is not significantly affecting the measurements which shows that there is an underlying physical process to this, in accordance with the argument in section IV above. Although the improvement are relatively minor improvements (less than 1dB) the results may therefore be considered to be reliable. The results show that the best cancellation is obtained by assuming that the dominant return is from a range of either cell number 7.5 or 8.5 (18m or 20.4m).

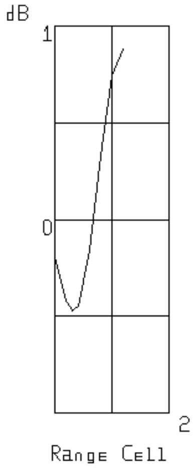

Figure 7: Average Cancellation over Sidelobe Region Versus Assumed Range to Dominant Return

Figure 7 shows the similar plot of average cancellation versus assumed range to the dominant return measured in the 'back lobe' of the transmit antenna. This figure is drawn to the same scale of figure 6 for comparison. It can be seen that, although the achievable cancellation is lower, the best is achieved by assuming that the return comes from a range of about 0.35 cells (0.84m) which is more consistent with the leakage paths within the transceiver, whilst those which dominate within the main beam of the transmitter comes from short range targets outside the radar itseld.

The behaviour is compatible with the situation where the direct transmit-leakage path is at very low level and where, in the main beam region, the largest signal is due to a large close-range target. Together with the simulation results, this suggests that the cancellation technique will indeed work well when it is most needed, i.e. where practical design considerations limit the transmit-receive isolation to a practical level of more like 60dB than the 100dB, or so, which was achieved with the experimental system.

VII. Conclusions

A new technique has been described which can enhance the dynamic range of noise radars by suppressing the range sidelobes due to the use of random modulations.

The technique has been demonstrated with simulated data and has also been shown to work with real noise radar data.

The technique shows great promise for improving the dynamic range of noise radars when this is limited by the range sidelobes of single return, most typically by the direct leakage between transmitter and receiver.

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