The Benefits of Matched Illumination for Radar Detection of Ground Based Targets

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***Abstract*—This paper compares the radar detection performance of a narrow band rectangular pulse, linear chirp and nonlinear stepped frequency waveform approximating to a matched target illumination against two target types (a farm tractor and a main battle tank) in the presence of clutter (soil/sand, rocks and woodland).**

I. Introduction

The improvements in the detection performance of a radar transmitting a waveform which is matched to the target transfer function (TTF) and employing a receiver which is matched to the ensuing echo have been discussed in the literature in recent years [1],[2]. The matched waveform strategy suggests that the signal to noise ratio (SNR) on the receiver output may be increased by several decibels (dB) over the case of a linear frequency modulated (LFM) chirp waveform of an equivalent energy. However, there is a relative paucity of measured data published in the open literature to support these claims. Additionally, it is presumed that the frequency response of clutter differs from that of ground based vehicle targets of interest and so there exists the tantalising possibility that a waveform may be designed which both enhances the detection of the targets of interest whilst suppressing clutter. In this study we use a combination of measured target responses of two die-cast metal scale model vehicles at a suitably scaled wavelength, with and without clutter and modelled matched filter detection to quantify and compare the detection performance of three transmitted waveforms; (i) a narrow band unmodulated rectangular pulse, (ii) a LFM pulse and (iii) a matched waveform approximated by the dwell time weighting of several stepped frequencies. In each case the total energy in the transmitted waveform is held constant. The detection performance of each waveform is quantified using three terms: (i) the transmitted to received energy ratio, (ii) the SNR and (iii) the signal to clutter ratio (SCR).

Section II of this paper presents the theory of matched waveform detection and identifies the waveform design strategy to maximize the SCR. In section III, we describe the practical measurement work and the simulation work to model the matched receiver. The results are presented in section IV and finally, section V draws some conclusions.

II. Theory

The detection of radar targets was modelled along the lines of the signal flow diagram presented in Fig. 1 below [3]. In this model the transmitted illumination $W(\omega)$ is incident on the target, characterized by its transfer function $TTF(\omega)$, and the clutter, characterized by its transfer function $H_{clutter}(\omega)$. This results in the returns $S(\omega)$ and $C(\omega)$ from the target and clutter, respectively. We note that:

$$S(\omega) = W(\omega) \cdot TTF(\omega) \tag{1}$$

and

$$C(\omega) = W(\omega) \cdot H_{clutter}(\omega) \tag{2}$$

$S(\omega)$ and $C(\omega)$ combine and are corrupted by white Gaussian noise N_0 which results in the signal $R(\omega)$. This signal is then fed into the receiver, represented by its transfer function $H_{Rx}(\omega)$, and results in the output $G(\omega)$.

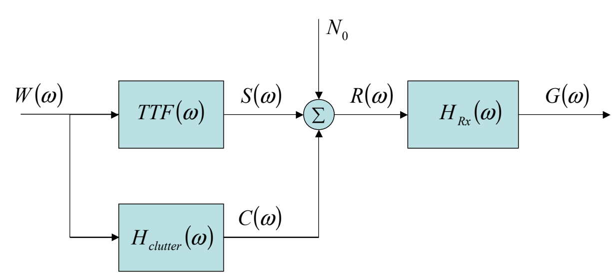

Figure 1. Signal Flow Diagram

The signal at the receiver input is therefore given by:

$$R(\omega) = S(\omega) + C(\omega) + N_0 \tag{3}$$

and the signal at the receiver output is given by:

$$G(\omega) = R(\omega) \cdot H_{Rx}(\omega) \qquad (4)$$

Matched illumination is obtained for the case when $W(\omega) = TTF^*(\omega)$ and the maximum SNR is obtained when $H_{Rx}(\omega) = S^*(\omega)$, where * denotes the complex conjugate.

The objective of matched illumination is to optimise the transmitted waveform, $W(\omega)$, for two objectives. Firstly, to maximize the target echo signal, $S(\omega)$ and secondly to minimise the clutter return, $C(\omega)$. Multi-objective optimisation problems are often characterized by having multiple solutions known as a Pareto set. However, it can be shown that the maximum SCR does not depend on the illumination waveform since it is applied both to the target transfer function and to the clutter transfer function. It turns out that:

$$SCR = \int_{-\infty}^{\infty} \left| \frac{S(\omega)}{C(\omega)} \right|^2 d\omega = \int_{-\infty}^{\infty} \left| \frac{TTF(\omega)}{H_{clutter}(\omega)} \right|^2 d\omega \qquad (5)$$

i.e. the optimum illumination (at least against the clutter) is not a question of the waveform, but has to be investigated in the choice of appropriate limited bandwidth(s) where the ratio between the target and the clutter transfer functions is maximum. From this point of view, the best signal to noise plus clutter ratio (SNCR) is obtained by transmitting matched illumination and employing the matched receiver filter in order to maximise the SNR, and focussing both transmission and reception in the bandwidth(s) where the ratio between the target and the clutter transfer functions is a maximum.

III. Practical and Simulation Work

A. Practical Measurements

The $TTF(\omega)$ of two targets with and without clutter were measured in the laboratory. The measurement system was based on the use of a vector network analyser (VNA) operating in a reflection measurement mode over the band 75 to 105GHz. The VNA outputs a stepped frequency CW signal comprising 1601 discrete frequencies which approximates a linear FM chirp. The VNA output signal was transmitted from a waveguide horn antenna towards the target and echoes received back via the same antenna. The horn was orientated to transmit and receive on a vertical plane of polarisation. The received signal was transformed to the time domain via an inverse Fast Fourier Transform (inverse-FFT), time gated in order to isolate the target reflection and then the time gated data was transformed back into the frequency domain using an FFT. Two targets were considered; an M1A1 Abrams main battle tank (MBT) and a farm tractor, both as 1:32 scale die-cast metal models. These are notable since one is overtly military and the other civilian. Scaling the wavelength by the same factor as the model targets means that the laboratory measurements equate (approximately) to looking at the life sized vehicles using a band of 2.34 to 3.28 GHz. It is worth noting that no attempt is being made to determine the true target responses of these vehicles but that two arbitrary targets were selected having considerable differences in their geometry and therefore in their transfer functions. Therefore, the full polarimetric signatures over all angular ranges were not measured since it was necessary only to capture a few examples of target transfer functions. The targets were mounted on a board whose reflection was at least 15dB lower than those of the vehicles and was therefore considered to be negligible. Target detection in clutter was carried out by placing the vehicles on the board upon which sand (to represent soil clutter), gravel (to represent clutter from rocks) or twigs and foliage (to represent woodland clutter) was also distributed. The transfer function of the target was measured in a head on and side on aspect. Similarly, the transfer functions of the clutter scenes was measured and also the composite target and clutter for various combinations of targets/aspects and clutter. The tractor and its transfer function in the head-on case and the tank and its transfer function in the head-on case are illustrated in Figs. 2 and 3, respectively.

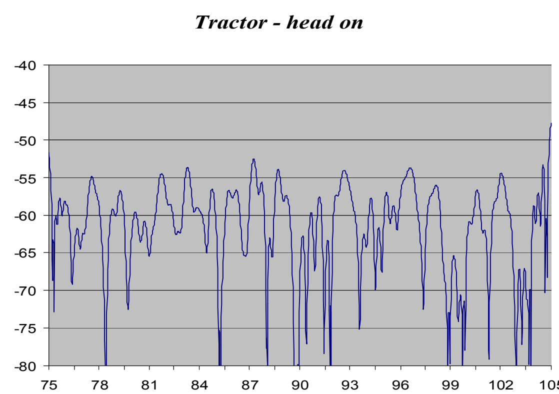

Figure 2. Tractor (top) and Transfer Function, head-on (bottom)

The two transfer functions of the targets differ quite markedly from each other. The vertical scale of the transfer functions in Figs. 2 and 3 is an arbitrary scale of reflectivity in dB. Both are characterized by peak to peak variations of 30dB or more.

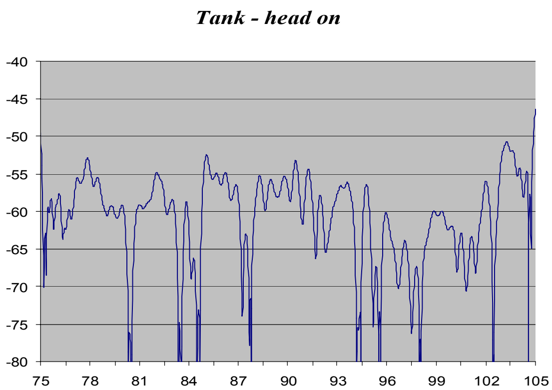

Figure 3. Tank (top) and Transfer Function, head-on (bottom)

B. Modelled Detection Performance

Three transmitted waveforms $W(\omega)$ were considered: (i) a rectangular pulse centred at 90GHz having a bandwidth of 2.2%, a LFM chirp over the full measurement band of 75 to 105GHz and the matched illumination over the band 75 to 105GHz all having the same total energy content. The receiver is modelled as having a noise figure of 10dB and a noise bandwidth, B_N given by:

$$B_N = \frac{\int_{-\infty}^{\infty} |H_{Rx}(\omega)|^2 \, d\omega}{|H_{Rx}(\omega_0)|^2} \qquad (6)$$

where $H_{Rx}(\omega_0)$ represents the peak value of the receiver transfer function and noting also that $H_{Rx}(\omega) = S^*(\omega)$.

The derivation of the matched transmitted waveforms, $W(\omega)$, was computed on the basis of the measured $TTF(\omega)$. The computer simulation then derived the signals $S(\omega)$, N_0 and $C(\omega)$ and hence the composite signal $R(\omega)$. The simulation also derived the receiver transfer function, $H_{Rx}(\omega)$ as that function which is matched to $S(\omega)$ for the case of the matched illumination. The function $H_{Rx}(\omega)$ was maintained for all three test waveforms (rectangular pulse, LFM chirp and matched illumination). Finally, the output signal $G(\omega)$ was computed. Three metrics were used to quantify the detection performance of each waveform and target plus clutter scene, namely: (i) the transmitted to received energy ratio, (ii) the SNR and (iii) the signal to clutter ratio (SCR).

In addition to this, the frequency bands yielding the optimum SNCR were identified for the cases of the targets in the various clutter scenes (soil, rocks and woodland) and for a uniform clutter transfer function (= -50dB) for reference purposes. These bands were selected on the basis that the SCR was within 35dB of its peak value (or 15dB for the uniform clutter transfer function) and were of width ≥ 5 frequency points (i.e. ≥ 75MHz). The -35dB level and 75MHz bandwidth were arbitrarily selected thresholds which captured the principal SCR peaks and avoided overly complex waveforms associated with the noisy SCR profiles. The three detection metrics for the reduced matched illumination bands of optimum SNCR were not simulated in this study.

IV. Results

The different combinations of target type, aspect and clutter type generate a mass of statistics. A summary of the results with a representative sample is given below.

A. Detection Metrics - Summary

The transmitted to received energy ratio and the SNR of the rectangular pulse varies somewhat from one target/clutter combination to the next. This is because all its power is concentrated into a narrow band which may coincide with a peak (or trough) in the target transfer function. This suggests that the best detection performance results from a CW waveform (i.e. an infinitely narrow one) at a frequency coincident with the maximum value of $TTF(\omega)$, however, this is not a practical waveform for most applications. In general, the spectrum of a narrow band rectangular pulse does not coincide with a $TTF(\omega)$ peak and so, in general, it is outperformed by the matched illumination. The matched illumination always outperforms the linear FM chirped waveform.

For the MBT target (head-on and side-on aspects) the transmit to receive energy ratio is between 20 to 38 dB superior for the matched illumination over the other two waveforms. This means that between 20 to 38 dB more transmitted power is required for the rectangular pulse and LFM waveforms in order to recover the same received energy, and hence the same detection performance, than for the matched illumination. The SNR of the matched illumination is between 19 and 43 dB better than that of other two waveforms. The SCR of the matched illumination is between 1.3 and 11 dB worse than that of the other two waveforms. For the tractor (both aspects) the transmit to receive energy ratio is between 10 to 40 dB superior for the matched illumination over the other two waveforms. The SNR of the matched illumination is between 10 and 46 dB better than that of the other two waveforms. The SCR of the matched illumination is between 0.1 and 17 dB worse than that of the other two waveforms.

B. *Detection Metrics – Representative Sample*

The case of the MBT in a head on aspect in the presence of rock clutter is fairly representative of the trends observed throughout all the tests. For this situation we find that 30dB more transmitted power is required for the rectangular pulse and 28dB more power for the LFM chirp than is required for the matched waveform in order to recover the same received energy and hence the same detection performance. The SNR of the matched illumination is some 30 and 37dB better than those of the rectangular pulse and LFM waveforms, respectively. The SCR resulting from the matched illumination is around 6dB worse than the other two waveforms. This anomalous result arises because the waveform has not been optimised for the best SNCR since the transmitted energy is spread across the whole frequency range (75 to 105GHz) instead of being focussed into a few narrow, optimal bands.

C. *Matched Illumination Bands of Optimum SNCR*

For the matched illumination case of optimum SNCR, *W(ω)* was derived as an approximate match to *TTF(ω)* by identifying those bands for which the SCR exceeded an arbitrary threshold and then deriving nonlinear chirp waveforms within each band which are matched to *TTF(ω)*. Bands narrower than 5 FFT points were dismissed as these were regarded as noisy phenomena. The nonlinear chirps were synthesized using stepped frequency waveforms in which the step size was taken as 18.75MHz, this being the limitation of the VNA used. An example of a matched waveform is illustrated in Figs. 4, 5, 6 and 7. This case considers the tank target in a head on aspect with a constant clutter spectral power density at -50dB. Fig. 4 illustrates that there are three bands of maximum SCR which are within 15dB of its peak value. Within these bands, the *TTF(ω)* is sampled in order to produce three corresponding matched waveforms, as illustrated in Fig. 5. Fig. 6 illustrates the stepped frequency samples necessary to provide the matched illumination within the three bands previously identified. The matched waveforms may be produced by varying the power or dwell time at each frequency sample. In this study, a variation of dwell time is assumed and results in nonlinear chirp waveforms. Fig. 7 illustrates the nonlinear chirp waveforms necessary to provide the matched illumination within each band. The total matched waveform can be formed by stitching the three nonlinear chirps together.

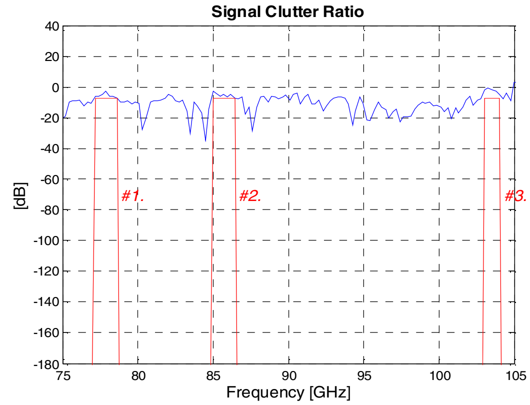

Figure 4. Bands of Maximum SCR (Tank, head-on)

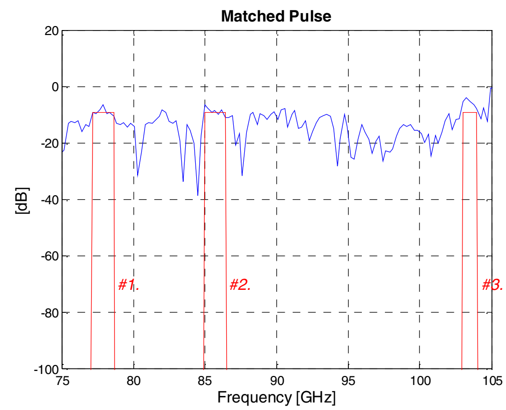

Figure 5. Bands of Matched Illumination (Tank, head-on)

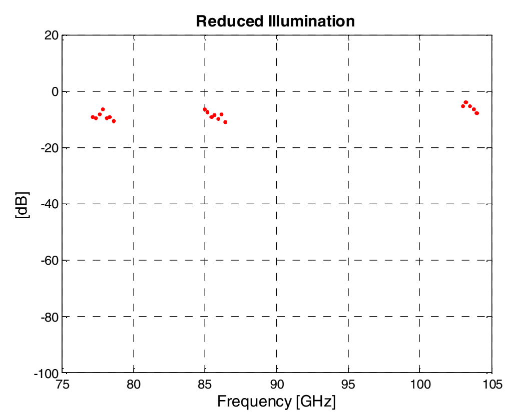

Figure 6. Bands of Optimum SNCR (Tank, head-on)

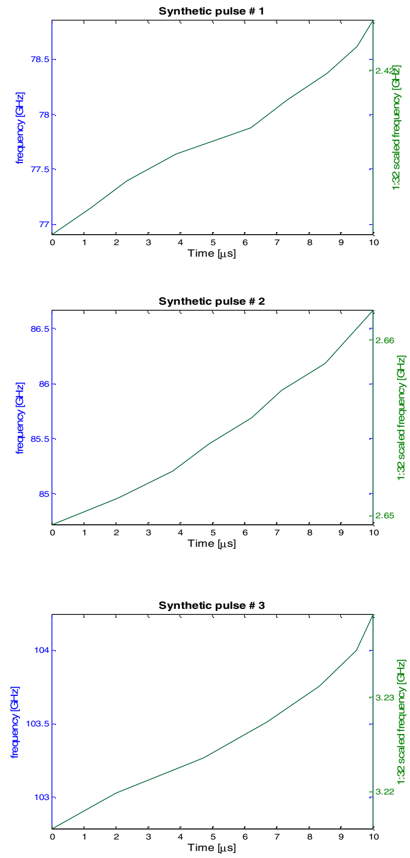

Figure 7. Nonlinear Chirp Waveforms of Matched Bands (Tank, head-on)

V. CONCLUSIONS

This study has shown how the transfer functions of targets may be used as the basis of matched illumination waveform design and has quantified the potential benefits of these waveforms. Very significant improvements in the ratio of the transmit to receive energy and in the SNR result from the use of matched target illumination and matched receiver response. However, some degradation in the SCR is noted for the matched illumination/matched receiver response case. Improvements in the SCR could be obtained by using reduced matched illumination bands which are optimized for optimum SNCR. This study has also revealed that target transfer functions can vary considerably, having peak to peak variations by as much as 30dB. Since targets are characterized by such large variations there are significant advantages to be gained from the design of appropriate waveforms, if only in the selection of the centre frequency of a crude narrowband signal. Furthermore, it is believed that the target transfer function nulls are equally important as the peaks for the purposes of automatic target recognition and matched waveform design.

Future work will seek to quantify the performance of the reduced matched illumination bands. The detection of one target using the waveform optimized for the detection of a different target will also be explored in a future study.

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