Adaptive Radar for Improved Small Target Detection in a Maritime Environment

Simon Haykin
McMaster University

Brian Currie
McMaster University

Thia Kirubarajan
McMaster University

McMaster University
1280 Main Street West, Hamilton, Ontario, L8S 4L8

Contractor Report Number: Technical Report #03-01

Contract Number W7714-020643/001/SV

Contract Scientific Authority. Alan D. Thomson (613) 991-1877

Defence R&D Canada – Ottawa

Contract Report

DRDC Ottawa CR 2003-095

April 2003

Adaptive Systems Laboratory

Institute for Life-related Systems
McMaster University

Technical Report #03-01
April 15, 2003

Adaptive Radar for Improved Small Target Detection in a Maritime Environment

Simon Haykin
Brian Currie
Thia Kirubarajan

Summary

In 2002, we co-authored a report presenting an enhaustive literature search on adaptive transmit radar waveforms.† That report listed the list of references, preceded by short accounts of the individual papers.

The present report presents a distilled version of that earlier report and updates it by including a few more references that were found subsequent to the previous report. Most important, the report presents a much more detailed account of the distilled list of papers, focusing on two important issues:

- Target detection in clutter, and
- Target tracking in clutter

with emphasis on how to select the transmit radar waveform viewed in the context of the ambiguity surface.

The report concludes with a proposed strategy based on the Costas array as the framework for radar waveform selection.

---

†S. Haykin, B. Currie, and T. Kirubarajan, "Literature Search on Adaptive Radar Transmit Waveforms", Technical report #02-01, December 2002

Adaptive Radar for Improved Small Target Detection in a Maritime Environment

List of Contents

1. Background

The major impediment to radar detection of small targets floating on the ocean surface is the radar return from the sea surface itself, termed *sea clutter*. The nature and dynamics of the sea surface are determined by environmental factors - primarily wind - which continually change. The net result is that sea clutter is a nonstationary signal. In order to accommodate this changing signal environment, we employ various adaptive techniques in the detection process.

The return radar signal is the result of the radar transmitter's microwave illumination of the sea surface interacting with the physical sea and target surfaces, and scattered back toward the radar. The dynamics of sea clutter and those of the target are coupled, with the nature of coupling being determined by whether the target is self-propelled (as in the case of a fishing boat) or just floating (as in the case of a small piece of ice). We cannot control the dynamics of the sea surface or the target. However, within practical limits, we can control the nature of the microwave illumination. Based on our understanding of the interaction of the illumination with the sea and target surfaces, we seek to craft an illumination signal that will maximize the detectability of the target of interest in a robust manner.

Historically, practical or economic considerations have limited the form of the transmitter illumination to be fixed at the design stage of the radar. For example, inexpensive marine radars use a magnetron to produce uncoded, monochromatic pulse trains. Therefore, most of the adaptivity developments have been in the receiver function. Typically, various statistical parameters of the clutter and target are estimated, and used to adapt decision thresholds to provide maximal probability of detection at a desired constant probability of false alarm. We refer to techniques that adapt using only received signal processing as *adaptive-receive systems*.

More recently, advances in technology - such as higher power linear power amplifiers and very-high-speed digital-to-analog converters - have made practical the idea of generating arbitrary waveforms in real-time, in response to changes in the radar's operating environment. The radar can now adapt both its transmitter illumination and the processing of the received signal in order to improve performance. We refer to this second type of radar systems as *adaptive-transmit*.

Within the class of adaptive-transmit systems, we distinguish two primary subclasses: *adaptive-transmit-select and adaptive-transmit-create*. In the adaptive-transmit-select systems, the transmit waveform is adaptively selected from a repertoire of signal waveforms built into the radar library when it was designed. For example, the system might choose from among N pre-designed compression waveforms. In the adaptive-transmit-create systems, the form of the transmit is created in real-time in response to the specifics of the received signal. For example, each transmit pulse can be given an arbitrary amplitude and frequency/phase profile. It is the pulse-creation capability that is built in at design time, but not the final waveform.

Figure 1 shows a block diagram of the basic concept of an adaptive-transmit radar to be used for target detection and tracking.

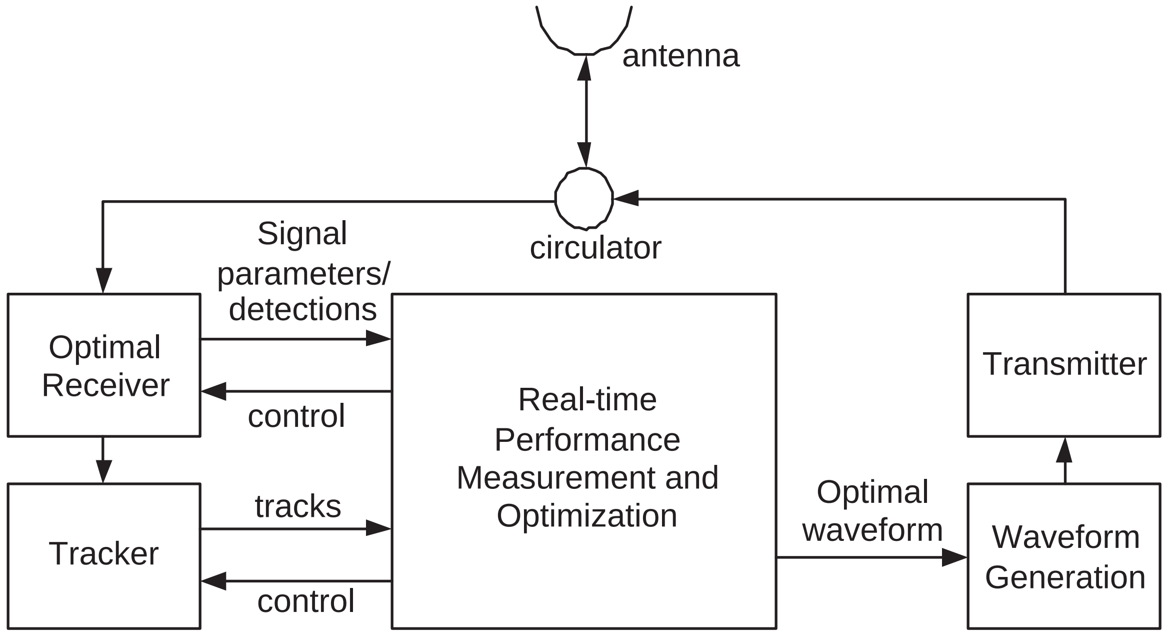

Figure 1 Block diagram of the basic concept of adaptive-transmit radar.
(See the text for discussion of the block functions).

The heart of the system is the real-time performance measurement and optimization block. Having chosen some initial transmit waveform, the detection and tracking performance are evaluated using a *performance metric*. An optimization procedure is run to select or create the next transmit waveform, which is produced by the waveform generator. At the same time, the processing in the receiver and tracker is adapted to optimally process the new transmit signal. The process continues in an iterative manner. The waveform may be changed on a pulse-by-pulse basis, or between blocks of pulses. One of the key design issues is the choice of the performance metric to be used in the optimization process. Various suggestions are presented in the papers reviewed below. Some metrics require access to various properties of the received signal in addition to the declared detections.

2. Ambiguity Function as a Tool for Radar Transmitter Design[1]

2.1 Ambiguity Surface

Signal detection in noise is maximized when the receive filter is matched to the transmit waveform. The output of the matched filter is equal to the cross-correlation between the received signal and the transmitted signal, and may be written as

1. The material for this section is largely taken from Skolnik (1980).

$$\text{Output} = \int_{-\infty}^{\infty} s_r(t)s^*(t-\tau)dt \tag{1}$$

where $s_r(t)$ is the received signal, $s(t)$ is the transmitted signal, the asterisk denotes complex conjugation, and τ is the time delay. The transmit signal can be expressed as

$$s(t) = u(t)e^{j2\pi f_o t} \tag{2}$$

where $u(t)$ is the complex (baseband) modulation, and f_o is the carrier frequency. The received signal is assumed to be the same as the transmitted signal except for the time delay τ_o and a Doppler frequency shift ν:

$$s_r(t) = u(t-\tau_o)e^{j2\pi(f_o+\nu)(t-\tau_o)} \tag{3}$$

The change in amplitude of the received signal compared to the transmitted signal is ignored, since amplitudes are later normalized.

The output can be determined by substituting equations (2) and (3) into (1). It is customary to set $\tau_o = 0$ (that is, to "centre" the filter response at the target delay) and to set $f_o = 0$ (that is, to remove the effect of the carrier and consider the situation at baseband). Assigning the symbol χ to represent the matched filter output, we get

$$\chi(\tau, \nu) = \int u(t)u^*(t-\tau)e^{j2\pi\nu t}dt \tag{4}$$

We see from Eq. (4) that the matched filter response, $\chi(\tau,\nu)$, is obtained by correlating a signal with its Doppler-shifted and time-shifted version; that is, $\chi(\tau,\nu)$ is the two-dimensional correlation function in delay and Doppler (Rihaczek, 1969).

The squared magnitude $|\chi(\tau,\nu)|^2$ is called the *ambiguity function*, and its plot is termed the *ambiguity diagram*. When plotted in 3D, the ambiguity diagram will image the *ambiguity surface*.

There are several properties of the ambiguity function that are of relevance:

1. Maximum value of $|\chi(\tau, \nu)|^2 = |\chi(0, 0)|^2 = (2E)^2$ (5)

2. $|\chi(\tau, 0)|^2 = \left|\int u(t)u^*(t-\tau)dt\right|^2$ (6)

3. $|\chi(0, \nu)|^2 = \left|\int u^2(t)e^{j2\pi\nu t}dt\right|^2$ (7)

4. $\int_{-\infty}^{\infty}\int |\chi(\tau, \nu)|^2 (d\tau) d\nu = (2E)^2$ (8)

Equation (5) states that the maximum value of the ambiguity function occurs at the origin, and its value is $(2E)^2$, where E is the energy contained in the received signal.

Equations (6) and (7) describe the behaviour of the ambiguity function on the time-delay (range) axis and the Doppler-frequency (velocity) axis, respectively. Along the τ axis the function $\chi(\tau,\nu)$ is the autocorrelation function of the modulation $u(t)$, and along the ν axis it is proportional to the spectrum of $u^2(t)$.

Equation (8) states that the total volume under the ambiguity function is a constant, equal to $(2E)^2$.

If there were no theoretical restrictions, the ideal ambiguity diagram would consist of a single peak of infinitesimal thickness at the origin and zero everywhere else. However, equations (5) and (8) dictate that the $|\chi|^2$ function peak at the origin is of fixed height and the function encloses a fixed volume. A reasonable approximation to the ideal ambiguity diagram might appear as in Fig. 2. (Note that in the figures, there is a change in notation. Compared to the equations above, τ is replaced by T_r, ν by f_d, and τ is then used for the radar pulse length.) This waveform does not result in ambiguities since there is only one peak, but the single peak might be too broad to satisfy the requirements of accuracy and resolution. The peak might be narrowed in order to improve accuracy, but in order to conserve the requirement for a constant volume, peaks in other parts of the diagram may start to form, creating ambiguities. Thus there must be a trade-off between the requirements for accuracy (resolution) and ambiguity.

2.2 Examples of Ambiguity Diagrams

Two-dimensional plots of the ambiguity diagram use shading to indicate regions in which $|\chi(\tau,\nu)|^2$ is large (completely shaded), regions where $|\chi(\tau,\nu)|^2$ is small but non-zero (lightly shaded), and regions where $|\chi(\tau,\nu)|^2$ is zero (clear).

Single pulse of sine wave. Figure 3 shows the ambiguity diagram for a single pulse of sine wave. The measurement accuracy (resolution) in range is determined by the pulse length, while the accuracy in Doppler is determined by the pulse bandwidth (inverse of the pulse length).

Periodic pulse train. Figure 4 shows the ambiguity diagram for a sinusoid modulated by a train of five pulses. Each pulse is of width τ, the pulse repetition period is T_p, and the duration of the pulse train is T_d. Here the range accuracy is still determined by pulse length τ, but the Doppler accuracy is determined by the inverse of the pulse train duration. The penalty paid for the increased Doppler accuracy is the appearance of additional peaks in the ambiguity diagram.

Single frequency-modulated pulse. Consider a pulse of duration T, during which the frequency is swept linearly across a bandwidth B. Figure 5 shows the associated ambiguity surface. The accuracy along either the range or Doppler axis can be made as good as desired by increasing T

and B (within practical considerations). However, neither range nor velocity can be determined without knowing the other since both depend upon frequency shift. This difficulty can be overcome by transmitting a second pulse with reversed frequency chirp.

2.3 Use of the Ambiguity Diagram

The particular waveform transmitted by a radar is chosen to satisfy the requirements for (1) detection, (2) measurement accuracy, (3) resolution, (4) ambiguity, and (5) clutter rejection. The ambiguity function, and its plot, the ambiguity diagram, may be used to assess how well a waveform can achieve these requirements.

For a point target, *detection* does not depend upon the shape of the transmitted waveform, only on the energy E in the received signal. Since the ambiguity function is normalized by $(2E)^2$, the ambiguity diagram is seldom used to assess the detection capabilities of a waveform.

The *accuracy* with which the range and velocity can be measured by a particular waveform depends on the width of the spike, centred at $|\chi(0,0|^2$, along the time and frequency axis. The *resolution* is also related to the width of the central spike, but in order to resolve two closely spaced targets, the central spike must be isolated. It cannot have any peaks nearby that can mask another target close to the desired target.

The presence of peaks not at the origin can lead to *ambiguity* in the measurement of target parameters. An ambiguous measurement is one in which there is more than one choice available for the correct value of a parameter, but only one choice is appropriate.

Finally, the ambiguity diagram may be used to determine the ability of a waveform to *reject clutter* by superimposing on the range-Doppler plane the regions where clutter is found. If the transmitted waveform is to have good clutter-rejection properties, the ambiguity function should have little or no response in the regions of clutter. For the case of maritime surveillance, the sea clutter will occupy different parts of the range-Doppler plane depending upon various environmental factors such as sea state, wind conditions, and radar look-angle with respect to the wind and waves. Since the sea clutter is a dynamic process, we can envision on-line estimation of the range-Doppler parameters of the sea as a function of radar azimuth. Having specified a given clutter range-Doppler distribution, we need an algorithm to synthesize the optimum transmit waveform to provide maximal clutter rejection, thereby optimizing target detection. Thus, the transmit waveform would be determined adaptively, in response to the currently prevailing sea clutter conditions. This concept of adaptively manipulating the ambiguity function of the transmit waveform has been addressed by several authors, and is explored more fully in what follows.

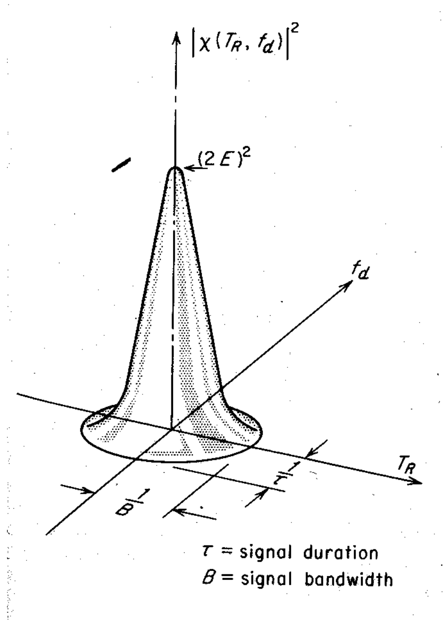

Figure 2: An approximation to the ideal ambiguity diagram, taking into account the restrictions imposed by the requirement for a fixed value of $(2E)^2$ at the origin (Eq. 5) and a constant volume enclosed by the $|\chi|^2$ surface (Eq. 8). (from Skolnik, 1980)

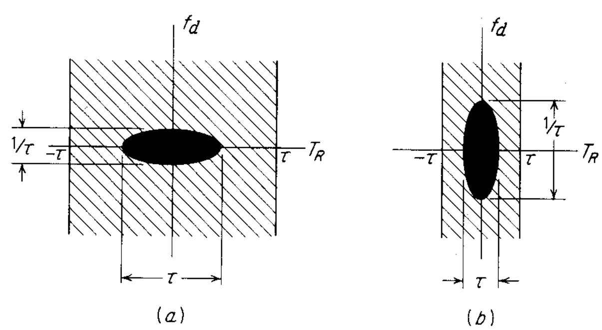

Figure 3: Two-dimensional ambiguity diagram for a single pulse of a sine wave: (a) long pulse, (b) short pulse. (from Skolnik, 1980)

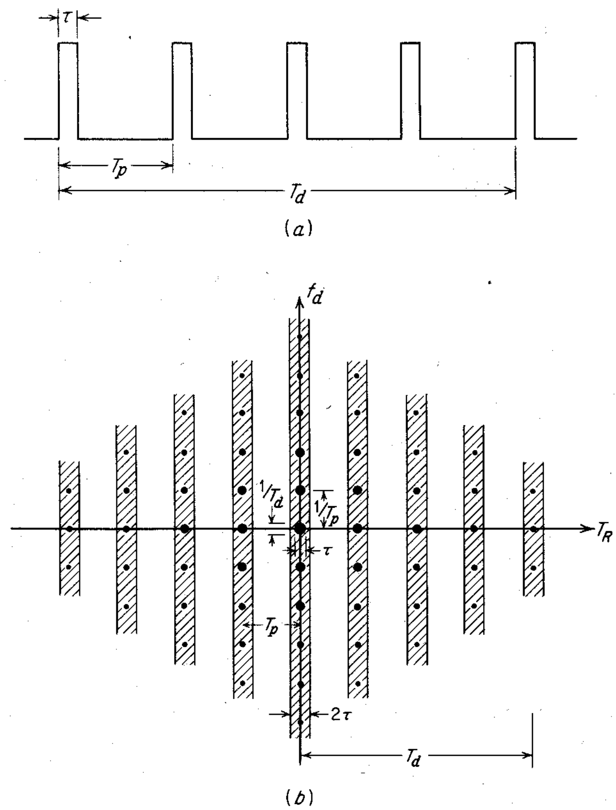

Figure 4: (a) Pulse train consisting of five pulses; (b) ambiguity diagram for (a). (from Skolnik, 1980)

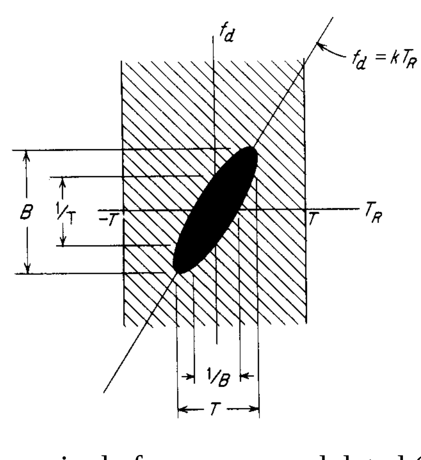

Figure 5: Ambiguity diagram for a single frequency-modulated (chirp) waveform. (from Skolnik, 1980)

3. Manipulation of the Ambiguity Function of the Transmitted Waveform

There are a number of papers that deal with various aspects of manipulating the ambiguity function of the transmitted waveform in order to improve the detection of a target of interest in a background of neighbouring interference. The ideal ambiguity function is a “thumbtack” shape (narrow central peak surrounded by a low-level pedestal), centred on zero range delay and zero Doppler, in the range-delay Doppler-frequency plane. Real finite waveforms cannot achieve this ideal, in that they will have undesired sidelobes occupying various parts of the plane. By changing the pulse characteristics on a pulse-by-pulse basis within a pulse burst, it is possible to have the sidelobes of one pulse cancelled by another pulse, such that the composite ambiguity function has much lower sidelobes in the desired parts of the delay-Doppler plane.

For their transmit signal, DeLong and Hofstetter (1969, 1967) consider burst waveforms, i.e., finite trains of uniformly spaced, identically shaped, nonoverlapping subpulses with arbitrary amplitudes and phases. The amplitude variation is constrained, which, in turn, constrains the energy. DeLong and Hofstetter assume that the clutter cross-section in range-delay and Doppler frequency is known. Although never exactly true, they argue that the parts of the range-Doppler plane that might be affected by clutter can be estimated at design time. There are two items to be specified: the amplitude and phase for each subpulse of the transmit waveform, and the appropriate weighting function to be applied to the received signal. The metric used by DeLong and Hofstetter is the final signal-to-interference-plus-noise (clutter+noise) ratio (SINR). They develop an optimization algorithm for designing the transmit and weighting functions, given the locations of the target and clutter in the delay-Doppler plane; and thereby demonstrate the results of their method using a 32-pulse example, with a theoretically possible noise-limited SINR of 20 dB if all the clutter were removed. Compared to a constant-amplitude zero phase pulse train, the DeLong-Hofstetter method improves the SINR from 2.5 dB to 11.6 dB, a gain of 9.1 dB. Compared to a constant-amplitude quadratic phase burst, the method increased the SINR from 12.3 dB to 16.6 dB, a gain of 4.3 dB. When replacing the amplitude variation constraint with only an energy constraint, they achieved a SINR of 19.8 dB.

In their 1969 paper, DeLong and Hofstetter comment that “For certain radar applications (e.g., target tracking), it is conceivable (given some advances in transmitter technology) that a future radar might continuously adapt its transmission and its receiver to achieve maximum signal-to-interference ratio on the desired target”. However, they further comment that “Other applications, e.g., surveillance, require that the radar examine all range cells in a given angular resolution cell with the same transmission. Such a radar might or might not use a different weighting function for each range cell; certainly it would not do so except as a last resort, all other means of suppressing interference proving inadequate”.

DeLong and Hofstetter suggest the idea of using a composite clutter distribution in the delay-Doppler plane as a “penalty” function, penalizing the cross-ambiguity (between the signal and weighting) function of the design for having sidelobes in a specified region of the delay-Doppler plane.

In the case of maritime surveillance with a coherent radar, we should be able to use target-free resolution cells to estimate, in real-time, the portion of the Doppler spectrum occupied by the sea clutter as a function of bearing. This continuously updated clutter Doppler map could be used to specify the delay-Doppler penalty function.

Bell (1993) presents an information-theoretic approach for designing waveforms for detecting extended targets so that the mutual information between the target ensemble (pattern) and the received noisy signal is maximized. The end result is optimal target detection or maximum SNR for extended targets with assumed scatter models. The basic idea in Bell's approach is to excite the mode of the target with the largest eigenvalue by appropriately selecting the transmitted waveform. This will, in turn, maximize the output SNR. The same approach can be used for target identification and classification (among a known class of targets or scatter modes) through adaptive waveform selection. It is also shown that the shape of the waveform (in addition to the SNR) has a significant impact on target identification and classification performance. The disadvantage of Bell's approach is that the expected target impulse response, which models the target scattering behavior, must be known.

In a closely related context, Guey and Bell (1998) build on the composite ambiguity function (CAF) technique in the context of improving the imaging capabilities of the radar, that is, the radar ability to resolve targets closely spaced in the delay-Doppler plane. For their work, Guey and Bell focus on (that is, their metric is) sidelobe elimination in the imaging point-spread function (analogous to an optical imaging system), which, in turn, is determined by the range ambiguity function. Although the uncertainty principle imposes restrictions on simultaneously discriminating in both delay and Doppler (for a single pulse), by correctly selecting a set of waveforms and then properly combining their individual matched-filter outputs, it is possible to bypass these constraints. Guey and Bell show that the CAF of K waveform-diverse pulses will have no more ambiguity than any single waveform, but by choosing orthogonal signals, the ambiguity of the CAF may be reduced to a factor of as little as $1/K$. The study is restricted to constant amplitude signals, but the properties of the CAF are studied when using phase-coded, frequency-coded, and jointly phase- and frequency-coded signals. Several examples are given in which the CAF shows reduced sidelobes through cancellation and distribution of the energy more evenly throughout the delay-Doppler plane.

Most waveform design algorithms consider the problem of detecting only a single target. With multiple targets, the shape of the ambiguity function and the Doppler resolution are crucial for simultaneous detection of multiple targets. For example, linear FM yields a tapered ridge across the ambiguity function, which makes it difficult to detect different targets with different Doppler and range values. Typically, the Doppler resolution is limited by the pulse length. Biddiscombe (1995) discusses the possibility of improving the nominal Doppler resolution (reduce the width of the main lobe on the Doppler axis) by using the product of the ambiguity functions of different FM sweeps, especially at high SNR values. However, the algorithm is limited by the significant additional computation needed for ambiguity function multiplication.

Wong (1998) considers radar/sonar systems in a battlefield environment, commenting that Guey and Bell's approach to minimizing the total ambiguity does not take into account the problem of distributing the ambiguity into undesirable areas of the delay-Doppler plane, such as areas of strong clutter or jammers. Wong proposes the inclusion of an appropriate cost metric measuring the performance or penalty associated with the distribution and the size of the ambiguity of any particular pulse-diverse signal waveform choice. Wong considers the use of a code division multiple-access (CDMA) type of digital pulse compression scheme to create a transmit signal $s(t)$ consisting of a K-pulse pulse-diverse pulse train, with L chips per pulse. He presents an optimization algorithm for designing $s(t)$, using the cost function metric. He develops separate algorithms for phase-only and frequency-only modulations. Wong (2000) considers optimization of pulse-diverse FSK-PSK pulse trains, and gives examples in which the radar ambiguity volume is reduced by over 80% in desired areas of the delay-Doppler plane. Of course, the basic requirement for application of the algorithms is the specification of the value of the cost as a function of delay and Doppler. Here again, an on-going clutter Doppler map could be kept in order to specify this cost function.

Wong (1998) also presents a new optimization based approach for adaptive pulse diverse compression waveform design. The adaptation is based on the criticality of different Doppler-delay regions with respect to waveform ambiguity functions. Most radar systems use pulse trains whose constituent pulses are identically modulated by a preset compression waveform. The use of a preset compression waveform yields suboptimal performance with time-varying clutter. In addition, for pulse trains with identical preset waveform from pulse to pulse, the total volume under the ambiguity function is not reduced irrespective of the pulse compression scheme. Returns from earlier pulses carry information about target-clutter pattern and this information is used to assign criticality (or weights) for different Doppler-delay regions with respect to the waveform ambiguity function. Based on the adaptive weighting, the paper uses an iterative optimization search approach (with optimum ambiguity reduction and distribution) to design compressed waveforms for subsequent pulses in the pulse train. This algorithm can be used for phase-only modulation or frequency-only modulation pulse compression. Wong and Chung (2000) present examples in which they specify certain areas in the delay-Doppler plane within which the ambiguity volume is to be minimized, then apply a genetic algorithm to derive a near-optimal FSK-PSK modulated pulse compression sequence.

Fielding (2001) discusss the adaptation of various parameters in an ESA radar for improved target search, detection and tracking is discussed. Similar to Blair (1998) and Kirubarajan (1998), the adaptation parameters include search revisit time, waveform and dwell time. However, the primary criterion for selecting these parameters is maximum detection and track formation range, which is useful when "early-detection" is desirable (for example, as in a surveillance scenario). The target detection or track formation range is expressed as a function of waveform characteristics and the waveform parameters maximizing the range are selected for transmission. The paper considers only the use of pulse-Doppler waveforms, which provide effective clutter suppression in air-to-air or air-to-ground (look-down) scenarios. However, the same approach can be used for maritime surveillance or search-and-rescue scenarios with appropriately modified waveform as well.

4. Design of Frequency-coded Transmit Radar Waveforms for Controlling the Sidelobe Distribution

From a design perspective, a major objective in the selection of a transmit radar waveform is how to control the sidelobe distribution in the delay-Doppler plane and do so in a practical fashion. To that end, we may mention the use of frequency-coded waveforms derived from the *Costas arrays*.

In 1984, Costas described a special class of permutation matrices that may be beneficially used to determine the frequency-time pattern of a uniform pulse train. Let T_r denote the chip duration period, and

$$p(t) = \begin{cases} 1, & 0 < t \le T_r \\ 0, & \text{otherwise} \end{cases} \tag{9}$$

denote the envelope of the transmitted radar signal. Then, according to Costas, the complex baseband representation of the frequency-coded waveform is defined by

$$s(t) = \sum_{k=0}^{N-1} p(t-kT_r)\exp\left(-j\frac{2\pi d_k}{T_r}t\right) \tag{10}$$

where N is the number of frequency-coded chips and $\{d_k\}$ is a permutation of integers 0,1,...,N-1. The important properties of the frequency-coded radar signal $s(t)$ are summarized here (Costas, 1984):

Property 1. Proper choice of the burst waveform can result in a transmitted radar signal whose range and Doppler resolutions are consistent with the prescribed signal duration and bandwidth.

Property 2. The sidelobe distribution in the delay-Doppler plane is well controlled, so that the ideal "thumbtack" ambiguity function behaviour is closely approximated.

For example, Figure 6(a) depicts a zero-offset three-dimensional plot of the Costas-30 ambiguity surface. Figure 6(b) depicts the Doppler-axis cut of this signal; the well-known (sinz)/z frequency behaviour is evident in this figure. Figure 6(c) depicts the delay-axis, with very well-behaved sidelobes and relatively few sharp excursions above the 1/N value.

On the basis of the results presented in Figure 6, we may say that the central peak in the ambiguity-function space provides good resolution in both delay and Doppler.

Chang and Bell (2002) explore a modified version of the Costas signal $s(t)$ defined in Eq. (10) by allowing the frequency

$$f_r = \frac{\alpha}{T_r}, \qquad \alpha > 0 \tag{11}$$

to take on values other than $1/T_r$. In particular, the sidelobe peaks appear in the region of the delay-Doppler plane where $f_r \le |\nu| < (N-1)f_r$, where ν denotes the Doppler-shift. Thus, we may choose f_r such that the delay-Doppler plane of interest will contain a minimum number of sidelobe peaks.

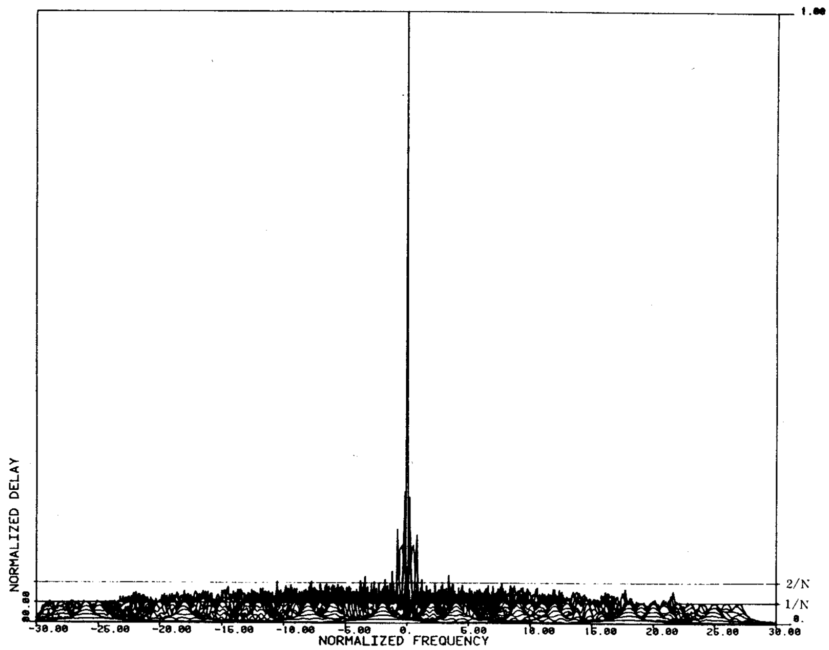

Figure 6(a): Welch-30 ambiguity surface zero-offset presentation
(from Costas, 1984)

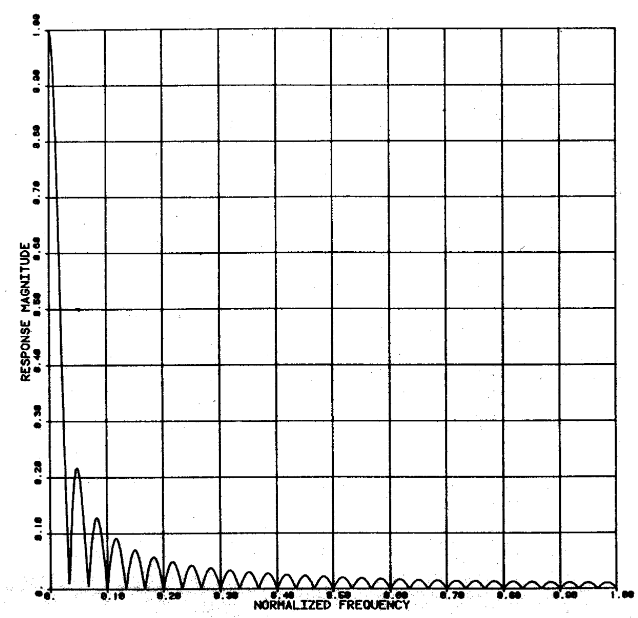

Figure 6(b): Frequency axis response for *x* = 0 for the Welch-30 pulse train
(from Costas, 1984)

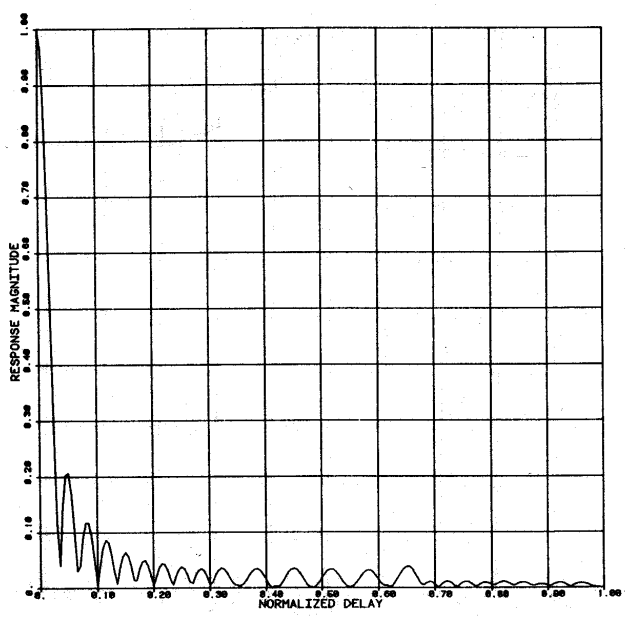

Figure 6(b): Delay axis response for $y = 0$ for the Welch-30 pulse train
(from Costas, 1984)

In the cited report, Chang and Bell consider the application of the modified Costas signal to the detection of a slowly moving object (e.g., fishing boat or small piece of ice) embedded in sea clutter. The Doppler interval of interest in such an environment is typically within 2000 Hertz. Then, as illustrated in Fig. 7, it is possible to choose a frequency-coded waveform having f_r greater than 2000 Hertz with no sidelobes appearing in the shaded frequency domain of interest, denoted by Θ. Similarly, with the proper choice of the chip duration T and the number of frequency-coded chips, we may exercise control over the sidelobe peaks appearing in the prescribed delay-Doppler domain of interest. Chang and Bell (2002) describe a procedure for determining the design parameters: f_r, T_r, and N.

A practical limitation of the Costas signal is the increase in the instantaneous bandwidth, which, in turn, requires even wider bandwidth components and therefore higher analog-to-digital (A/D) sampling rates. The net result is that higher bandwidth requirements will increase significantly for very high-resolution radars.

In the context of a *linear step-frequency radar signal*, Gill (1995) describes a procedure for the detection of a moving target in clutter. The procedure described therein overcomes the increased bandwidth requirement through the processing of a sequence of linearly increasing transmit frequency on a pulse-by-pulse basis, and exploiting the computational efficiency of the fast Fourier transform (FFT) algorithm. There may well be elements in the Gill procedure that could be extended to the computationally efficient implementation of the frequency-coded waveform embodying the Costas array.

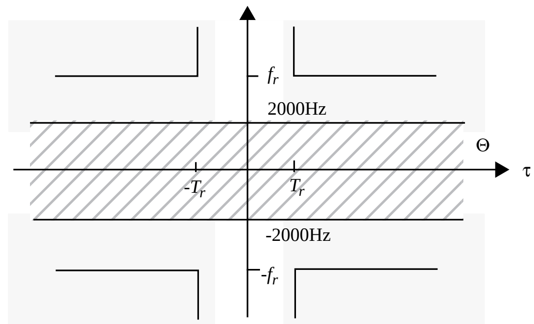

Figure 7: The domain of interest Θ for the sea clutter. We can choose f_r > 2000 Hz so that no sidelobe peaks appear in Θ. (from Chang, 2002)

5. Target Classification

The DeLong-Hofstetter and Wong papers are based on the concept of specifying the delay-Doppler properties of the interference (primarily clutter), and designing a waveform-diverse pulse train which minimizes the ambiguity function in the clutter areas of the delay-Doppler plane. In contrast, there are some papers that require specification of the target properties in order to design the optimum waveforms.

Guerci and Pillai (2000) seek to jointly optimize the transmit waveform modulation and receiver processing strategy in order to maximize target detection probability. They relax the "point target" assumption common to most surveillance radars, and, assuming some a priori knowledge concerning the range extended (non-point) targets scattering characteristics, suggest that an optimal pulse shape can be designed so as to maximize the energy reflected off a target. Specifically, the a priori knowledge they require is the impulse response of the target. Figure 8 shows the basis of the problem formulation as seen by Guerci and Pillai, with the objective being to jointly optimize the choice of transmit waveform $s(t)$ and receiver response $h_R(t)$ and therefore maximize the output SINR art some prespecified sampling instant $t = T_f$, subject to finite pulse duration and observation constraints. In the Guerci-Pillai approach, detection is considered in a background of additive coloured noise (e.g., interference multipath). Knowing the interference power spectrum, the Guerci-Pillai optimization procedure provided a gain of 9.6 dB compared to a conventional chirp waveform. Guerci and Pillai also applied their method to identifying one of N possible targets, reporting a 4 dB increase in signature separation compared to a conventional pulse.

In Pillai et al (2000a), the Guerci-Pillai approach is extended to consider the presence of clutter and noise, each Gaussian distributed. Figure 3 shows the simplified model. The authors present an iterative procedure for determining the optimal pair $\{f(t), h(t)\}$. Their simulations show that the conventional chirp can perform poorly. Again, they require specification of the target impulse response $w(t)$ and the spectral densities of the clutter and noise. Pillai et al (2000b) further extend the approach to accommodate multiple receiver channels (such as in a dual-polarized radar) by specifying the cross clutter spectral densities and having multiple matched filters, as shown in Fig. 10.

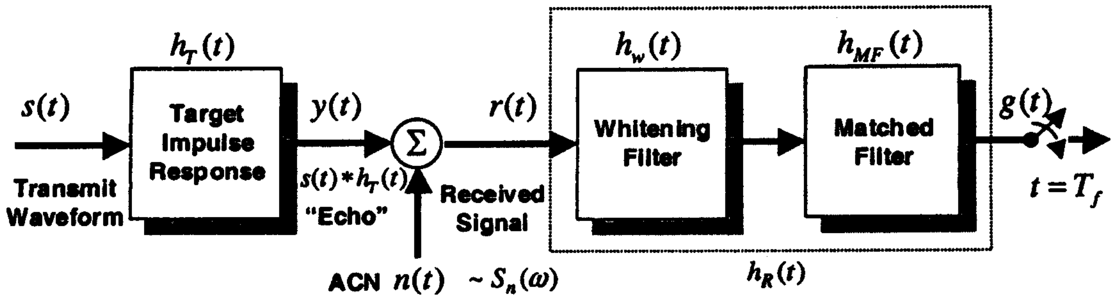

Figure 8: Transmitter-receiver signal chain block diagram (from Guerci and Pillai, 2000)

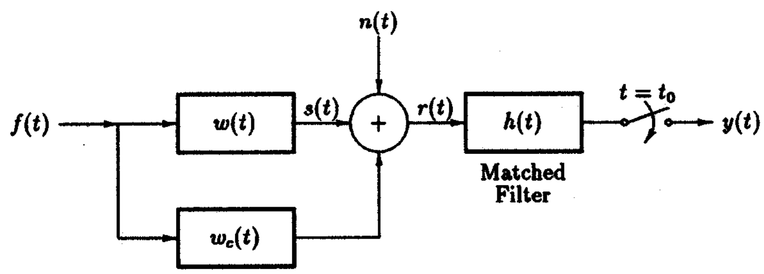

Figure 9: Addition to include the effects of signal-dependent interference (clutter) (from Pillai et al, 2000a)

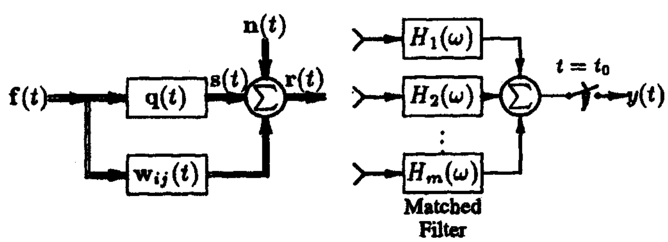

Figure 10: Modification to include the use of multiple channels, e.g., orthogonal polarizations (from Pillai et al, 2000b)

Garren et al (2001a) report on the application of these techniques to the detection and identification of two battle tanks. They examine the form of the optimum transmit waveform generated by their algorithm, and find that it is a narrow-frequency CW waveform of long duration. This waveform has poor range resolution compared to the standard chirp, and the authors comment that the selection of the optimized transmit waveforms will involve a compromise between range resolution and SINR. Furthermore, for high clutter-to-noise ratios (CNR of tens of dB), their algorithm offers negligible SINR gain. The CNR needs to be below 10 dB. Garren et al (2001b) studied SINR gain when there was uncertainty in the aspect angle of the target (tank). At X-band, most of the SINR gain for the optimized waveform was lost when the aspect uncertainty had a standard deviation of more than only 0.5°. It thus appears that the algorithm performances extremely sensitive to the correct specification of the target impulse response. Finally, Garren et al (2002) consider the use of full-polarization system for tank detection and identification. Results are reported only for a VHF radar. The technique is shown to focus the majority of the transmission energy into one or few narrow frequency band(s) for a given relative target aspect angle.

6. Adaptive Waveform Design and Selection with Tracking Considerations

In order to maximize the benefits of adaptive radar, the adaptation should take into account some performance metrics in the form of detection, tracking and classification performance. That is, there should be a feedback loop between postprocessing (detector, tracker or classifier) algorithm and the radar adaptation algorithm (see Figure 11). This can be achieved by adapting the radar to optimize the expected performance at the output of the postprocessing algorithm. While SNR has been the most dominant performance metric in the adaptive radar literature, improvement in SNR does not always result in better tracking or classification performance. For example, as shown by Blair et al. (1998), in phased array radar systems, high energy waveforms with high SNR detections have low range resolution, resulting in poor tracking performance. In this part of the report, we review some papers that deal with adaptive radar in conjunction with feedback from postprocessing.

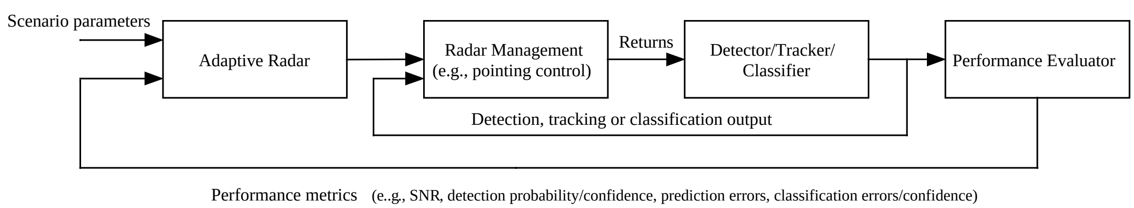

Figure 11: Adaptive radar with feedback from detection, tracking or classification algorithm

In most radar tracking systems, the operations of detection and tracking are treated as two separate and independent subsystems and the radar adaptation is based primarily on detection (e.g., maximizing the SNR or SINR). Niu et al. (1999, 2000, 2002) have presented a systematic framework for waveform selection with combined consideration of detection and tracking (see Figure 12). This procedure is based on the previous work by Rago et al. (1998). Realistic issues like imperfect detection ($P_d < 1$), false alarms ($P_{fa} > 0$), expected target dynamics and signal processing (e.g., matched filter sampling grid) are accounted for in selecting waveforms. These papers address a number of important issues and provide answers based on the Hybrid Conditional Averaging (HyCA) by Li et al. (1991), which uses the algebraic Riccati equation modified by a Markov chain technique and handles false alarms and missed detections. The HyCA technique is used to evaluate the relationship between the pulse shape and detection performance. Some of the issues addressed in these papers are:

1. Choosing LFM (linearly frequency modulated) upsweep vs. LFM downsweep vs. CF (constant frequency) pulses
2. Performance enhancement through multipulse waveforms

3. Windowing to control ambiguity function sidelobes

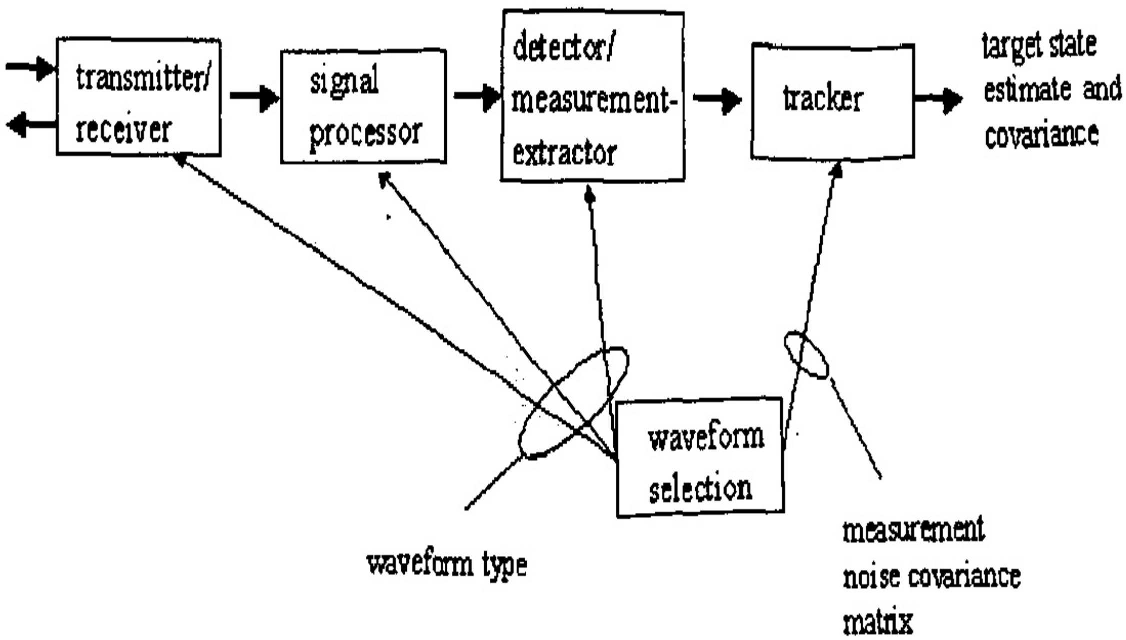

Figure 12: Adaptive waveform design and selection combined with tracking
(from Niu et al. (2002))

It is shown analytically through HyCA and through simulations that LFM upsweep provides the best performance since its position and velocity errors are negatively correlated (in contrast to the positive correlation between the position and velocity tracking errors). In addition, the expected target motion characteristics defined in terms of the maneuvering index (as defined by Bar-Shalom et al. (2001)), which is the ratio of target motion uncertainty and the sensor measurement uncertainty, plays a central role in selecting the optimal LFM upsweep frequency rate. The frequency sweep rate is shown to increase with lower maneuvering index (nearly constant velocity targets). It is also shown that amplitude window functions like Hamming weighting can be used to control the ambiguity function sidelobes. Hamming weighting appears to provide a significant improvement over the traditional rectangular envelope.

In addition, the above papers consider other radar processing issues as part of waveform design. For example, the use of mismatched filters to yield robust detections when the target is not in the center of a resolution cell, in which case the detection probability is degraded, is considered. The choice of measurement extraction techniques in the presence of threshold exceedances in contiguous cells is also discussed. Direct averaging, strongest neighbor and amplitude averaging are some of the measurement extraction possibilities. It is also shown that the threshold exceedances can be input directly into a tracker (i.e., without measurement extraction) like, Probabilistic Data Association Filter or Multiple Hypothesis Tracker, without any significant loss of performance.

Kershaw et al. (1994, 1997) describe a one-step ahead optimization approach (see Figure 13) for optimal waveform selection with detection and tracking consideration. A Kalman filter (without clutter) or a Probabilistic Data Association filter (in the presence of clutter) can be used for optimal waveform generation, including multiple waveform classes. A number of waveform parameters like waveform peak power, maximum pulse length, carrier frequency and waveform type (e.g., triangular, Gaussian, LFM) are used for optimization. Waveforms are designed by minimizing the mean-square tracking error of a Kalman filter or a Probabilistic Data Association filter. Assuming an optimal detector, the measurement noise covariance depends on waveform properties, and with use of the expressions of the tracking filter, the next waveform is selected. In this approach, the tracking equations depend explicitly on the actual parameters of the designed waveform. In addition to mean-square tracking error, other performance metrics like target detection speed, which is valuable in surveillance situations, can be used for optimization. While the algorithm presented in these papers assumes a constant pulse repetition frequency and constant pulse energy, extensions relaxing these constraints are possible. Also, the algorithm in these papers is not limited to amplitude only modulated waveforms modeled using a multiplicative waveform control variable.

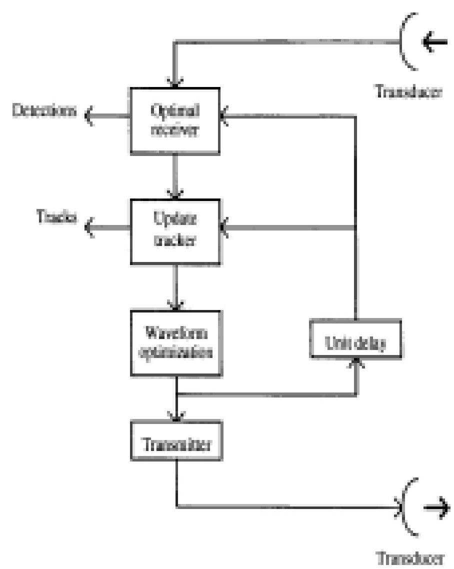

Figure 13: One-step ahead optimization approach for waveform design with tracking
(from Kershaw, 1994)

In the papers cited in this section, waveform design and adaptive radar processing are based on detection and tracking performance metrics. This can be contrasted with adaptive waveform design techniques based on the ambiguity pattern and measurement level performance evaluation with attention to coded and frequency hopped models. Such techniques are discussed by Bellegarda (1991), Costas (1984), DeLong (1967, 1969), and Fielding (2001). These papers are *reviewed elsewhere* in this report. Such techniques optimize the operating SNR without explicitly considering tracking or detection performance.

7. Adaptive Radar Management with Tracking Considerations

The US Navy's Naval Surface Warfare Center in Dalghren, VA, developed the tracking and adaptive radar resource management benchmark problem to compare different tracking and phased array management algorithms developed by Blair et al. (1998). While the current work does not consider phased array radar, the lessons learnt from the US Navy benchmark may be useful for other radar systems. In addition, the simulation/experiment setup used in the US Navy benchmark (see Figure 14) can be used as a basis for adaptive radar simulation, experimentation and comparison with other radar systems and algorithms. The tracker/radar manager was required to select a waveform from a suite of predesigned waveforms so as to minimize radar energy and dwell time while maintaining a certain tracking performance (e.g., RMS estimation errors, track loss%). In addition, the resource manager is required to select the revisit interval, detection threshold, and pointing direction with feedback from the tracker.

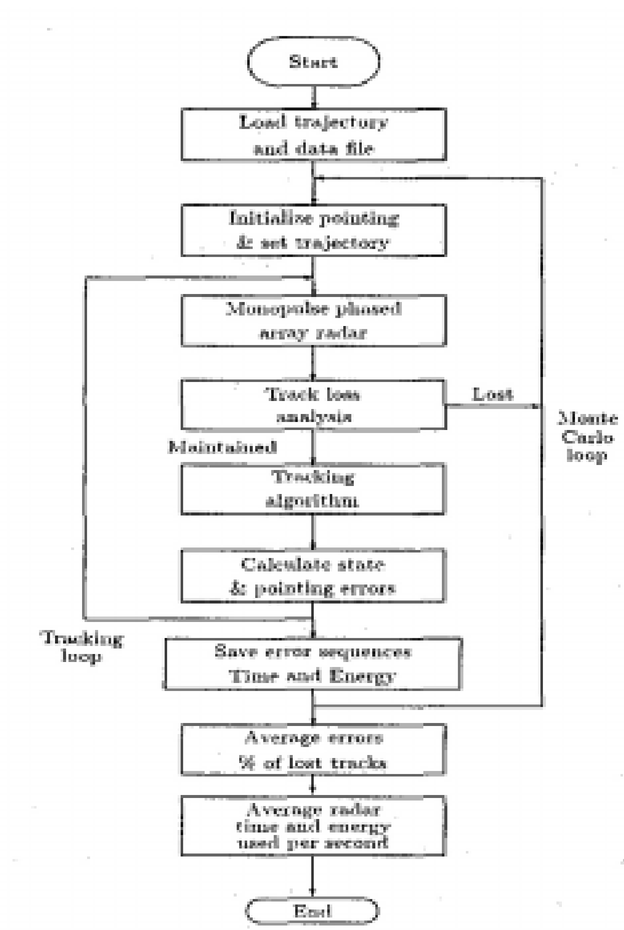

Figure 14: US Navy tracking and adaptive radar management benchmark setup
(from Blair, 1998)

Different tracking algorithms like the Multiple Hypothesis Tracking algorithm by Blackman (1999) and the Probabilistic Data Association Filter by Kirubarajan (1998) and Kalman Filter were used in conjunction with a radar manager for adaptation. In these algorithms, the expected measurement prediction errors (quantified by innovation covariance values) were used to select the revisit interval. The waveform and the threshold were selected such that a certain Constant False Alarm Rate (CFAR) was maintained. Adaptation of radar operating parameters was necessary due to target maneuvers and changing clutter patterns and electronic counter measures. It was shown that significant savings in radar energy, dwell time, and revisit interval (compared with the tracker without adaptation) are possible by adaptive radar control with feedback from the tracker while maintaining real-time feasibility in terms of computation (see the tradeoff plot in Figure 15). Similar plots were obtained for radar waveforms.

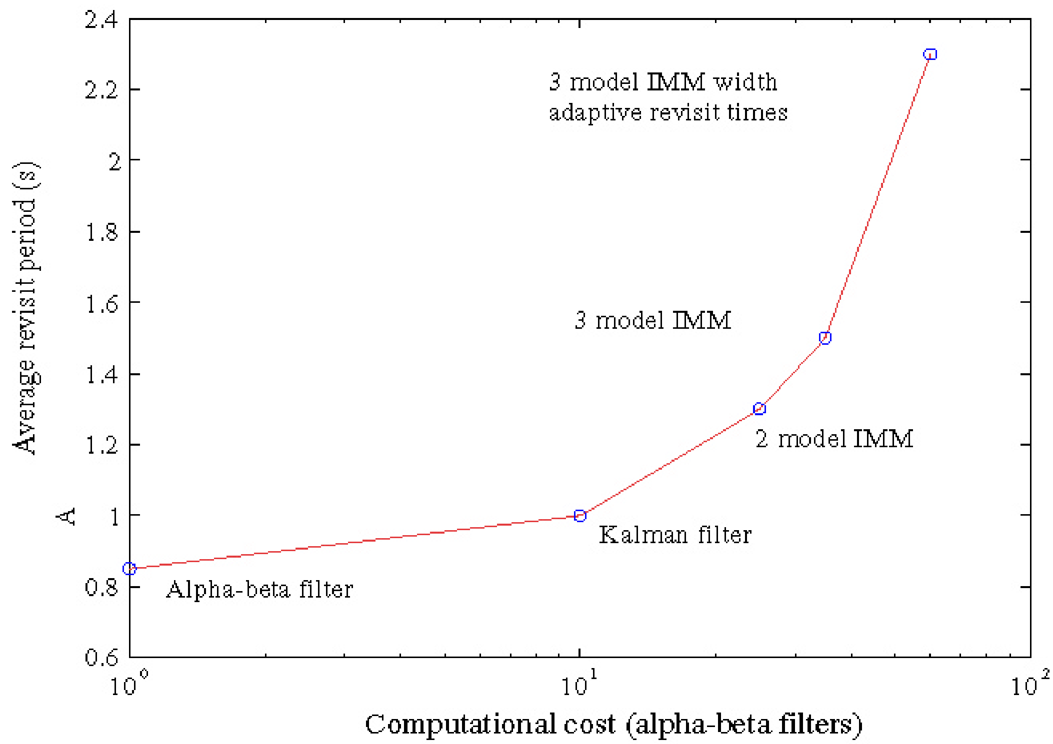

Figure 15: Benefits of adaptive radar control with feedback from tracker (from Blair (1996))

The US Navy benchmark experiment, which included realistic simulations of SPY-1B radar as well as live experiments with military aircraft, showed the benefits of adaptive radar management with tracking considerations. Similar experiments with different trackers and waveform adaptation techniques are also possible within the current project.

Turning next to the issue of adaptive waveform selection with tracking considerations, we have reviewed some papers that handle the problem of adaptive radar in conjunction with the underlying usage objective, namely, target detection, tracking, or classification. Using different optimization criteria (e.g., maximum target detection/track formation range, minimum innovation errors, maximum discrimination), the waveforms are designed or selected. Instead of a priori waveform adaptation, real-time adaptation with feedback from the tracker or classification algorithm is used. In addition to waveform adaptation techniques based on detection, tracking or classification performance, simulation and experimentation setup for adaptive radar performance evaluation was also discussed in this part of the report. These represent some promising leads for further exploration and experimentation.

8. Proposed Strategy for Adaptive Selection of Transmit Radar Waveform

The Costas array described in Section 4 provides the basis for a strategy for the adaptive selection of the transmit radar waveform.

When target detection and tracking considerations are both factored into waveform design of the transmit radar waveform, it is necessary to account for the accuracy of the resulting measurements as well as the true target detection and false alarm probabilities. The waveform design procedure with tracking consideration is as follows (but, the optimization based waveform design and selection can use the SNR or tracking accurary as the criterion --- the framework will be the same with or without tracking considerations).

- Start with a delay-Doppler domain of interest for the environment under study
- Evaluate the accuracies of the resulting measurements (e.g., range-Doppler standard deviations) for the waveforms in the library and the corresponding P_d and P_{fa}
- Evaluate expected tracking results at the next revist for different waveforms, taking into account target motion, and measurement/environmental characterististics
- Evaluate the corresponding signal-to-clutter ratio (SCR) values
- Assign criticality weights for different regions of the environment based on previous returns, SCR, tracking results, and target/region priorities
- Select measurement scheduling time and the frequency-coded waveform based on the combined cost criterion (which includes the weights on SCR, tracking results and target priorities) through optimization or enumerative search
- Transmit the selected frequency coded waveform
- Modify the frequency-coded waveform in accordance with changes in the performance metric

Figure 16 depicts the selection procedure for the two cases: detection without tracking, and detection with tracking.

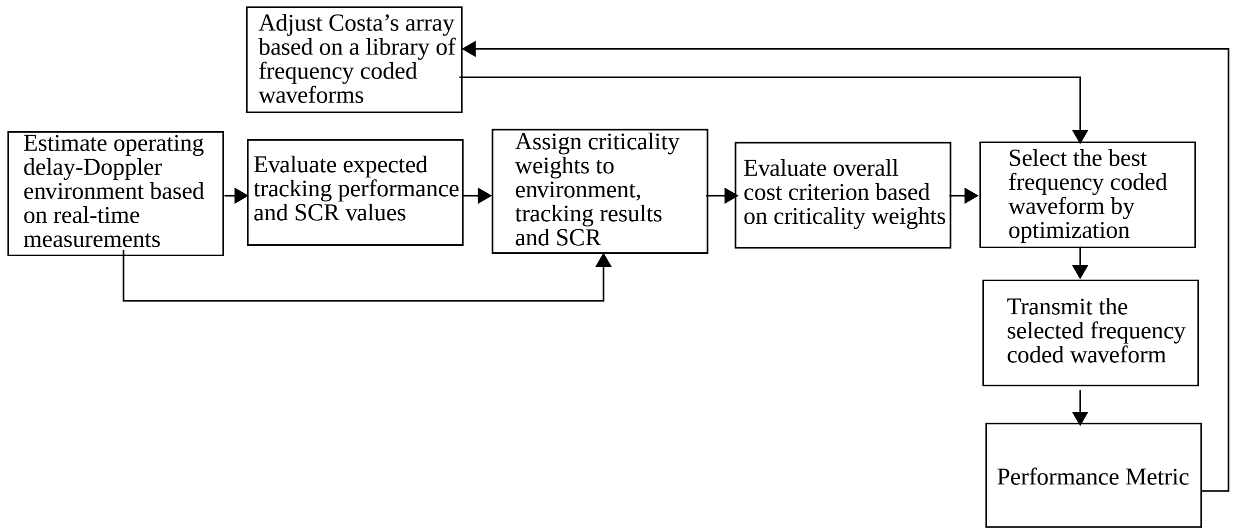

Figure 16: Proposed concept for an adaptive transmit radar system

References

Bell, M.R., 1993, “Information theory and radar waveform design”, IEEE Trans. Information Theory, Volume: 39, Issue: 5, pp.1578-1597, September.

Bellegarda, J.R. and E. L. Titlebaum, 1991, E.L., “The hit array: an analysis formalism for multiple access frequency hop coding”, IEEE Trans. Aerospace and Electronic Systems, Volume: 27 Issue: 1, pp. 30 -39, January.

Biddiscombe, J.A. and Kingsley, S.P., 1995, "An investigation into the principles of signal detection using multiple simultaneous waveforms", Proc. IEE Colloquium on Advanced Transmission Waveforms, London, UK, June.

Blackman, S.S., R.J. Dempster, M.T. Busch and R.F. Popoli, 1999, R.F., “IMM/MHT solution to radar benchmark tracking problem”, IEEE Trans. Aerospace and Electronic Systems, Volume: 35 Issue: 2, pp. 730 -738, April.

Blair, W.D. and G. A. Watson, 1996, “Benchmark Problem for Radar Resource Allocation and Tracking Maneuvering Targets in the Presence of ECM”, Technical Report NSWCDD/TR-96/10, Naval SurfaceWarfare Center, Dahlgren Division, Dahlgren, Virgina, September.

Blair, W.D., G. A. Watson, T. Kirubarajan and Y. Bar-Shalom, 1998, “Benchmark for radar allocation and tracking in ECM”, IEEE Transactions on Aerospace and Electronic Systems, Volume: 34 Issue: 4, pp. 1097 -1114. October.

Chang, C-F, and M.R. Bell, 2002, “A Technique for Arranging the Sidelobe Distribution of Frequency Coded Waveforms”,

Costas, R., 1984, “A study of a class of waveforms having nearly ideal range-Doppler ambiguity properties”, Proceedings of the IEEE, pp. 996-1009, August.

Daum, F., 1992, “A system approach to multitarget tracking”, in Multitarget-Multisensor Tracking: Applications and Advances, Y. Bar-Shalom (ed.), Boston: Artech House, Vol. 2, pp. 149-181.

DeLong, D.F. and E.M. Hofstetter, 1967, “On the design of optimum radar waveforms for clutter rejection”, IEEE Trans. on Information Theory, IT-13, no. 3, July.

DeLong, D.F. and E.M. Hofstetter, 1969 “The design of clutter-resistant radar waveforms with limited dynamic range”, IEEE Trans. on Information Theory, IT-15, no. 5, May.

Fielding, P.J. and A. M. Kinghom, 2001, “Waveform optimisation for efficient resource allocation in airborne AESA radar systems”, Multifunction Radar and Sonar Sensor Management Techniques, IEE Ref. No. 2001/173, pp. 3/1 -3/6.

Garren, D.A., M.K. Osborn, A.C. Odom, J.S. Goldstein, S.U. Pillai, J.R. Guerci, 2001a, “Enhanced target detection and identification via optimized radar transmission pulse shape”, IEE Proceedings on Radar, Sonar, Navigation, vol. 148, no. 3, June.

Garren, D.A., M.K. Osborn, A.C. Odom, J.S. Goldstein, S.U. Pillai, J.R. Guerci, 2001b, “Optimal transmission pulse shape for detection and identification with uncertain target aspect”, Proceedings of the 2001 IEEE Radar Conference.

Garren, D.A., A.C. Odom, M.K. Osborn, J.S. Goldstein, S.U. Pillai, J.R. Guerci, 2002, “Full-polarization matched-illumination for target detection and identification”, IEEE Trans. on Aerospace and Electronic Systems, vol. 38, no. 3, July.

Gill G.S., 1995, “Step Frequency Waveform Design and Processing for Detection of Moving Targets in Clutter”, IEEE International Radar Conference.

Golomb, S. and H. Taylor, 1982, “Two-dimensional synchronization patterns for minimum ambiguity”, IEEE Trans. Information Theory, Volume: 28 Issue: 4, pp. 600-604, July.

Grettenberg, T., 1963, “Signal selection in communication and radar systems”, IEEE Trans. Information Theory, Volume: 9, Issue: 4, pp. 265- 275, October.

Guerci, J.R. and S.U. Pillai, 2000, “Theory and application of optimum transmit-receive radar”, IEEE International Radar Conference, Radar 2000.

Guey, J-C., and M.R. Bell, 1998, “Diversity waveform sets for delay-Doppler imaging”, IEEE Trans. on Information Theory, vol. 44, no. 4, July.

Huizing, A.G., and J.A. Spruyt, 1992, “Adaptive waveform selection with a neural network”, International Conference Radar 92.

Kershaw, D.J. and R.J. Evans, 1997, “Waveform selective probabilistic data association”, IEEE Trans. on Aerospace and Electronic Systems, vol. 33, no. 4, October.

Kershaw, D.J. and R.J. Evans, 1994, “Adaptive waveform selection for tracking in clutter”, American Control Conference.

Kershaw, D.J. and R.J. Evans, 1994, “Optimal waveform selection for tracking systems”,

Kirubarajan, T., Y. Bar-Shalom, W.D. Blair and G.A. Watson, 1998, “IMMPDAF for radar management and tracking benchmark with ECM”, IEEE Trans. Aerospace and Electronic Systems, Volume: 34 Issue: 4, pp. 1115 -1134, October.

IEEE Trans. Information Theory, Volume: 40 Issue: 5, pp. 1536 -1550, September.

IEEE Trans. Aerospace and Electronic Systems, Volume: 33 Issue: 4, pp. 1180 -1188, October.

Li. X.R and Y. Bar-Shalom, 1991, “Stability evaluation and track life of the PDAF for tracking in clutter”, IEEE. Trans. Automatic Control, Volume: 36 Issue: 5, pp. 588-602, May.

Maric, S.V. and E. L. Titlebaum, 1990, “Frequency hop multiple access codes based upon the theory of cubic Congruences”, IEEE Trans. Aerospace and Electronic Systems, Volume: 26 Issue: 6, pp. 1035 -1039, November.

Niu, R., P.K. Willett and Y. Bar-Shalom, 1999, “From the waveform through the resolution cell to the tracker”, Proc. IEEE Aerospace Conference, Volume: 4, pp. 371 -385, March.

Niu, R., P. Willett and Y. Bar-Shalon, 2000, “Further analysis of waveform effects on tracking performance”, Proc. IEEE Aerospace Conference, Volume: 3, pp. 417 -431, March.

Niu, R., P. K. Willett and Y. Bar-Shalom, 2002, “Tracking considerations in selection of radar waveform for range and range-rate measurements”, IEEE Transactions on Aerospace and Electronic Systems, Volume: 38 Issue: 2, pp. 467 -487, April.

Pillai, S.U., H.S Oh, D.C. Youla, J.R Guerci, 2000a, “Optimum transmit-receive design in the presence of signal-dependent interference and channel noise”, IEEE Trans. on Information Theory, vol. 46, no. 2, March.

Pillai, S.U., H.S Oh, J.R Guerci, 2000b, “Multichannel matched transmit-receive design in presence of signal-dependent interference and noise”, Proceedings of the IEEE Sensor Array and Multichannel Signal Processing Workshop.

Rago, C., P. Willett and Y. Bar-Shalom, 1998, “Detection-tracking performance with combined waveforms”, IEEE Trans. Aerospace and Electronic Systems, Volume: 34 Issue: 2, pp. 612 -624 April.

Rihaczek,A., 1969, Principles of High-resolution Radar, McGraw-Hill, New York.

Schweppe, F. and D. Gray, 1996, Radar signal design subject to simultaneous peak and average power constraints, IEEE Trans. Information Theory, Volume: 12, Issue: 1, pp. 13- 26, January.

Skolnik, M., 1980, Introduction to Radar Systems, McGraw-Hill, New York.

Sowelam, S. and A. H. Tewfik, 1994, “Optimal waveform selection in range-Doppler imaging”, Proc. IEEE International Conf. Image Processing, 1994. Volume: 1, pp. 441 -445.

Sowelam, S.M. and A.H. Tewfik, 2000, “Waveform selection in radar target classification”, IEEE Trans. Information Theory, Volume: 46 Issue: 3, pp. 1014 -1029, May.

Wong, K.T., 1998, “Adaptive pulse-diverse radar/sonar waveform design”, Proceedings of the 1998 IEEE Radar Conference, RADARCON 98.

Wong, K.T. and W-K. Chung, 2000, “Pulse-diverse radar/sonar FSK-PSK waveform design to emphasize/de-emphasize designated Doppler-delay sectors”, IEEE International Radar Conference, Radar 2000.

DOCUMENT CONTROL DATA

(Security classification of title, body of abstract and indexing annotation must be entered when the overall document is classified)

1 ORIGINATOR (the name and address of the organization preparing the document Organizations for whom the document was prepared, e g Establishment sponsoring a contractor's report, or tasking agency, are entered in section 8)

Adaptive Systems Laboratory
Institute for Life-related Systems, McMaster University
1280 Main Street West, Hamilton, Ontario, L8S 4L8

2 SECURITY CLASSIFICATION (overall security classification of the document, including special warning terms if applicable)

UNCLASSIFIED

3. TITLE (the complete document title as indicated on the title page Its classification should be indicated by the appropriate abbreviation (S,C or U) in parentheses after the title.)

Adaptive Radar for Improved Small Target Detection in a Maritime Environment (U)

4 AUTHORS (Last name, first name, middle initial)

Haykin, Simon; Currie, Brian; Kirubarajan, Thia

5 DATE OF PUBLICATION (month and year of publication of document)

April, 2003

6a NO OF PAGES (total containing information Include Annexes, Appendices, etc)

29

6b NO OF REFS (total cited in document)

42

7 DESCRIPTIVE NOTES (the category of the document, e g technical report, technical note or memorandum If appropriate, enter the type of report, e g interim, progress, summary, annual or final Give the inclusive dates when a specific reporting period is covered)

Contractor report

8 SPONSORING ACTIVITY (the name of the department project office or laboratory sponsoring the research and development Include the address)

Defence R&D Canada – Ottawa
3701 Carling Avenue, Ottawa, Ontario
K1A 0Z4

9a PROJECT OR GRANT NO (if appropriate, the applicable research and development project or grant number under which the document was written Please specify whether project or grant)

11ar11

9b CONTRACT NO (if appropriate, the applicable number under which the document was written)

W7714-020643/001/SV

10a ORIGINATOR'S DOCUMENT NUMBER (the official document number by which the document is identified by the originating activity. This number must be unique to this document)

Technical Report #03-01

10b OTHER DOCUMENT NOS (Any other numbers which may be assigned this document either by the originator or by the sponsor)

DRDC Ottawa CR 2003-095

11 DOCUMENT AVAILABILITY (any limitations on further dissemination of the document, other than those imposed by security classification)

(X) Unlimited distribution
( ) Distribution limited to defence departments and defence contractors, further distribution only as approved
( ) Distribution limited to defence departments and Canadian defence contractors, further distribution only as approved
( ) Distribution limited to government departments and agencies, further distribution only as approved
( ) Distribution limited to defence departments, further distribution only as approved
( ) Other (please specify)

12 DOCUMENT ANNOUNCEMENT (any limitation to the bibliographic announcement of this document This will normally correspond to the Document Availability (11) However, where further distribution (beyond the audience specified in 11) is possible, a wider announcement audience may be selected)

UNCLASSIFIED

SECURITY CLASSIFICATION OF FORM

13 ABSTRACT (a brief and factual summary of the document It may also appear elsewhere in the body of the document itself It is highly desirable that the abstract of classified documents be unclassified Each paragraph of the abstract shall begin with an indication of the security classification of the information in the paragraph (unless the document itself is unclassified) represented as (S), (C), or (U) It is not necessary to include here abstracts in both official languages unless the text is bilingual)

In 2002, we co-authored a report presenting an enhaustive literature search on adaptive transmit radar waveforms.= That report listed the list of references, preceded by short accounts of the individual papers

The present report presents a distilled version of that earlier report and updates it by including a few more references that were found subsequent to the previous report. Most important, the report presents a much more detailed account of the distilled list of papers, focusing on two important issues.

• Target detection in clutter, and
• Target tracking in clutter

with emphasis on how to select the transmit radar waveform viewed in the context of the ambiguity surface.

The report concludes with a proposed strategy based on the Costas array as the framework for radar waveform selection

14 KEYWORDS, DESCRIPTORS or IDENTIFIERS (technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document They should be selected so that no security classification is required. Identifiers such as equipment model designation, trade name, military project code name, geographic location may also be included If possible keywords should be selected from a published thesaurus e g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus-identified If it is not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title)

adaptive transmit radar

UNCLASSIFIED

SECURITY CLASSIFICATION OF FORM