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A SYSTEM PERFORMANCE FEASIBILITY STUDY FOR A SANDWICH WIRE FREQUENCY SQUINTING RADAR ARRAY ANTENNA

by

H.C. Chan

This work was sponsored by the Department of National Defence, Research and Development Branch under Project No. 041LC.

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CRC REPORT NO. 1411
OTTAWA, JUNE 1987

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(Radar and Communications Technology Branch)

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A SYSTEM PERFORMANCE FEASIBILITY STUDY FOR A SANDWICH WIRE FREQUENCY SQUINTING RADAR ARRAY ANTENNA

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ABSTRACT

Sandwich Wire Antenna Arrays are attractive for their light-weight and low-cost. However, this class of antennas has not been used in radar systems because of its moderate power handling capability and a lack of satisfactory design procedures for low-sidelobe applications. Recently, there has been interest in employing the Sandwich Wire Antenna in surveillance radar systems on small naval vessels. Design studies for sandwich wire antennas have been undertaken through industrial contracts. Being a travelling wave antenna, it produces a main beam with a frequency dependent squint. There is concern that this squint may have adverse effect on the signal processing system designed for radar systems employing conventional antennas. In this report, a feasibility study is carried out to evaluate the effects of the frequency squint on existing radar signal processing performance. In addition, new modes of operation designed to exploit the frequency squint are identified and evaluated.

1. INTRODUCTION

1.1 Background

Frequency scanned array antennas have been successfully designed and implemented in radar systems. The frequency scanning property is utilized, in most instances, in the elevation dimension to obtain target height information. Conventional antenna design in surveillance radar applications often avoids frequency scanning in the azimuthal dimension and relies on mechanical rotation of the antenna or radiating element phasing to obtain azimuthal coverage. Modern naval surveillance radar systems require light-weight and high performance antennas. There are two basic types of antennas commonly employed in maritime surveillance radar systems. The first uses a single feed-horn with a double-curvature reflector. The other uses a linear feed-array with a single-curvature reflector. Because of constraints on the physical dimensions of the reflector, single feed-horn double-curvature reflector antennas generally have modest azimuthal sidelobe characteristics. Linear feed-array single-curvature reflector antennas possess better azimuthal sidelobe characteristics since the aperture current amplitude and phase can be accurately controlled.

This performance is achieved with increased mast-head weight and cost owing to the required complex parallel-feed structure.

For extended range of radar coverage, it is desirable to mount the antenna at the maximum allowable height, usually at or near the mast-head. The stability of a vessel is affected to a great extent by the mast-head weight. In the past, complex surveillance radars have been fitted to relatively large naval vessels, and these vessels can tolerate moderately heavy mast-head weight without experiencing serious stability problems. However, the requirement for highly sophisticated radar systems now extends to vessels with a displacement as low as 300 tons. Consequently the weight of the antenna chosen for the radar becomes an important factor in the overall system design.

It was brought to the attention of the Radar Research Laboratory (RRL) of the Communications Research Centre(CRC)[1] that it might be feasible to produce a low cost, light-weight and high performance planar array antenna using the so-called sandwich wire antenna technology[2]-[4]. This technology was introduced in the late fifties by Rotman and Karas[2]. It utilizes printed circuit techniques which are used successfully in low frequency microstrip circuits. It provides the benefits of a high degree of design flexibility and manufacturing control. In addition, substantial reduction in the weight of the antenna is possible.

A sandwich wire planar array antenna is composed of a number of microwave line sources. These line sources consist basically of three continuous coplanar conductors. The two outer conductors, parallel to each other, are at ground potential. The centre conductor is etched onto a sheet of flat dielectric material which is held in place by the two outer conductors. The centre conductor is etched in a periodic undulation along the axis of the line source. The configuration of a typical sandwich wire line source is depicted in Figure 1. The period of the centre conductor undulation is made approximately equal to the wavelength of the nominal radar frequency. Since radiation by an antenna is a result of the time varying current distribution on the antenna aperture, the radiation of energy from a sandwich wire antenna is sustained by the current distribution resulting from the signal travelling from one end of the line source to the other. In order to maintain a travelling wave, the sandwich wire must be properly terminated with a matched load at the far end of the element to dissipate the unradiated energy so as to minimize reflection and maintain the desired radiation pattern.

Sandwich wire antenna technology has thus far not been exploited in radar applications primarily because of its modest power handling capability. When sandwich wire antennas were first introduced, pulse compression radar was still in its infancy. Pulse compression enables a pulse of a given energy to be transmitted at a lower peak power but for a longer duration, with resolution being retained by pulse coding. Before pulse compression techniques had matured, most radars relied on high peak transmit power to obtain good detection range. This posed tremendous problems

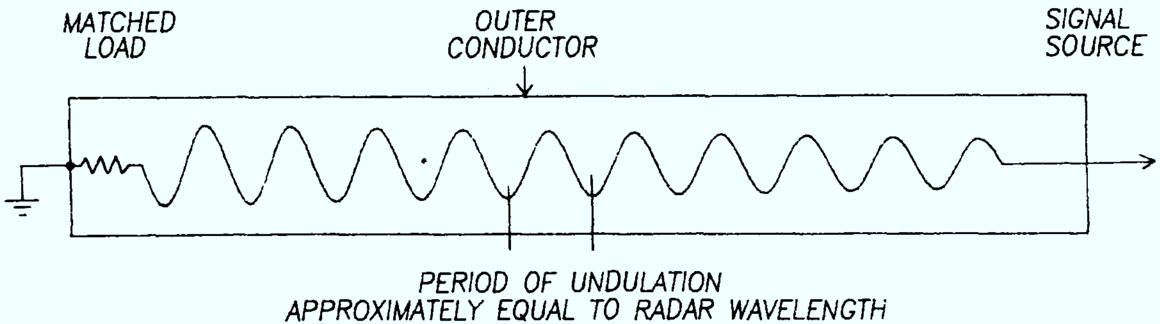

Figure 1 - **Typical Sandwich Wire Antenna Line Source**

in the design and reliablity of sandwich wire antennas. Another reason is that there is no satisfactory theory explaining the radiation mechanism of sandwich wire antennas when low sidelobes are required.

Interest in employing sandwich wire antennas in radar applications is rekindled as radar technology advances and as demand for light-weight, high-performance radar antennas increases. Many advances have been made in recent years in pulse compression radar technology, both in frequency synthesis techniques for waveform generation and surface acoustic wave(SAW) devices for matched filtering operation. Consequently, modern radars do not rely solely on the brute force approach of transmitting high peak power to obtain good detection range and range resolution. Canadian Marconi Company(CMC), has employed sandwich wire antennas in non-radar applications where low sidelobe levels are not essential. CMC intends to develop a sandwich wire array antenna as a low cost, but high performance replacement antenna in its line of naval surveillance radar systems. The RRL also has a keen interest in the development of light-weight high performance radar antennas.

Since the sandwich wire antenna is a series-fed, travelling wave array, there is a frequency dependent squint in the pointing direction of the main beam. For a benign radar environment, this type of antenna should be very cost effective. In a naval radar, where frequency agility is required as an electronic counter-counter measure (ECCM), the frequency squint may present complications in some of the signal processing functions of the radar. A feasibility study is required to determine whether the predicted performance of the antenna justifies further research and development.

The main thrust of this study is two fold. First, it is to establish whether this antenna can be used as a low-cost, high-performance, replacement antenna in existing naval surveillance radar systems. Second, it is to investigate whether the frequency squinting characteristic can be exploited to provide improved radar system performance.

1.2 Overview of the study

This study has been given the name "HISQUAMS" which stands for High Performance Squinting Antenna for Maritime Surveillance. As mentioned in the previous section, there are two objectives in this study. In this section, the scope of the study is outlined.

1.2.1 Feasibility of employing the sandwich wire antenna as a replacement antenna in existing naval surveillance radar systems

There are three facets to this problem:

- Basic antenna properties
- Signal processing aspects
- ECCM aspects

(a) Basic properties of the squinting antenna

The antenna is one of the most critical elements in a radar system. Some of the desirable characteristics for a naval surveillance radar antenna are light physical weight, high gain, narrow azimuthal beamwidth, wide bandwidth and low sidelobe levels. CMC believes that the sandwich wire antenna is capable of meeting or exceeding all of these requirements in contrast to a conventional reflector type antenna. As a basis for evaluating two antennas with a common set of performance requirements, a brief specification of a conventional naval surveillance radar system is given in Table I.

Table I: Specifications of a naval surveillance radar

Nominal radar frequency	3 GHz
Agile bandwidth	500 MHz
Peak power	20 KW
Average power	800 W
Pulse repetition frequency	740 Hz
Chirp-pulse length(BT=250)	50 micro-sec.
Aux. short pulse-length	0.5 micro-sec.
Polarization	Vertical
Antenna gain	28.5 dB
Azimuthal beamwidth	2.9 degrees
Elevation beamwidth	30 degrees
First sidelobe level	-28 dB

Owing to the presence of the frequency squint, most of the parameters for the sandwich wire antenna will be a function of radar frequency. Consequently, more definitive information on these antenna parameters must be obtained before any conclusion can be drawn with regard to the suitability of this antenna as a replacement antenna for existing naval surveillance radar systems. This information is also essential for the second objective of this study, namely, the determination of whether the frequency squint can be exploited to provide improved radar performance.

A contract was initially awarded to CMC to study the basic properties of the sandwich wire antenna. A report[5] of the findings has been submitted and includes the following items:

- Antenna pattern study
- Bandwidth and impulse response study
- Squinting characteristic
- Electronic elevation pattern control
- Alternative desquinter configurations
- Manufacturing tolerance effects

It became evident from the CMC study that the theory and design procedures for the sandwich wire antenna were still incomplete. Further research was needed to develop a thorough understanding of, and the design procedures for, the sandwich wire antenna. Cyrus Research Limited, which is associated with the Department of Electrical Engineering of the University of Manitoba, was awarded a contract to carry out this study. The performance evaluation of radar signal processing systems including the ECCM aspects was carried out within the RRL.

(b) Signal processing apsects

To enhance the detection capability of a radar system, various signal processing techniques are incorporated. These signal processing techniques are designed to manipulate the radar signal parameters such as amplitude, phase and Doppler frequency, so that certain features of a potential target can be extracted. It is, therefore, of interest to determine whether detrimental effects would be introduced in signal processing performance if a frequency squinting antenna were used instead of a non-squinting antenna.

(c) ECCM aspects

The ECCM performance of a radar system must also be evaluated if an antenna with frequency squint is employed. The evaluation was carried out in the general context of probability of intercept and jamming resistance. Specific ECCM techniques such as frequency agility and coherent sidelobe cancellation was included in the signal processing evaluation.

1.2.2 Exploration of new modes of operation for the frequency squinting antenna to improve radar system performance

The sandwich wire antenna is attractive from the considerations of cost saving and weight reduction alone. There is also the possibility that its frequency squinting characteristic may be exploited to provide improved radar system performance. The latter part of this study will be devoted to identifying modes of operation for the squinting antenna in which a possible enhancement of radar performance may be obtained. An initial evaluation of the feasibility of each mode of operation identified will be carried out.

2. EVALUATION OF THE EFFECT OF FREQUENCY SQUINT ON RADAR SIGNAL PROCESSING SYSTEM PERFORMANCE

It should be emphasized from the outset that the considerations given to the signal processing aspects of the radar systems are concerned primarily with the frequency squinting effect of the proposed antenna. Other antenna parameters such as beamwidth, sidelobe levels, gain, etc. are intrinsic properties of the antenna, and are studied by Cyrus Research Ltd. The frequency squint, on the other hand, may alter signal processing performance and could affect the overall effectiveness of the radar. In subsequent analyses, a comparison of the signal processing performance is sought between the two antennas of equivalent electrical characteristics such as beamwidth, gain, etc. One is a conventional reflector antenna, and the other is a frequency squinting antenna.

2.1 Signal processing aspects

To facilitate the analyses, a hypothetical naval surveillance radar system is specified which represents the minimum signal processing requirements. This system is depicted in Figure 2 and is comprised of the following basic features:

- Frequency agility
- Pulse compression
- Moving target Indicator(MTI) filter
- Constant false alarm rate(CFAR) processor
- Coherent sidelobe canceller

The study is focused on the possible effects of antenna beam squint on the above signal processing functions.

2.1.1 Frequency agility

Frequency agility is employed in radar systems to make it more difficult for an enemy to apply effective jamming. By randomly changing the radar frequency from pulse to pulse, or from burst to burst, the enemy is forced to spread its jammer noise energy over the entire agile bandwidth or use a more sophisticated frequency following jammer. With a conventional, mechanically-rotated, reflector antenna, the frequency selection algorithm can simply be a one-to-one mapping of some pseudo-random sequences onto the agile frequency band. With a frequency-squinting antenna, however, the situation becomes much more complicated. The antenna azimuthal look-direction is no longer independent of the radar frequency. Two possible effects are immediately apparent. The first is the possible loss of signal energy at certain azimuths. The second is the resulting random ordering of radar returns from contiguous azimuths.

(a) Loss of signal energy.

The combined effect of the mechanical rotation of the antenna and the requirement of a uniformly random frequency selection causes the frequency of visit of the antenna beam to various azimuths to vary significantly. If there is no rotational movement, then the azimuthal coverage of a squinting antenna will also be uniform provided that the random sequence employed is truly uniform. The complicating factor is that the squinting range of the sandwich wire antenna is limited[1]. It does not cover the entire 360 degrees. Consequently, once the antenna has moved a

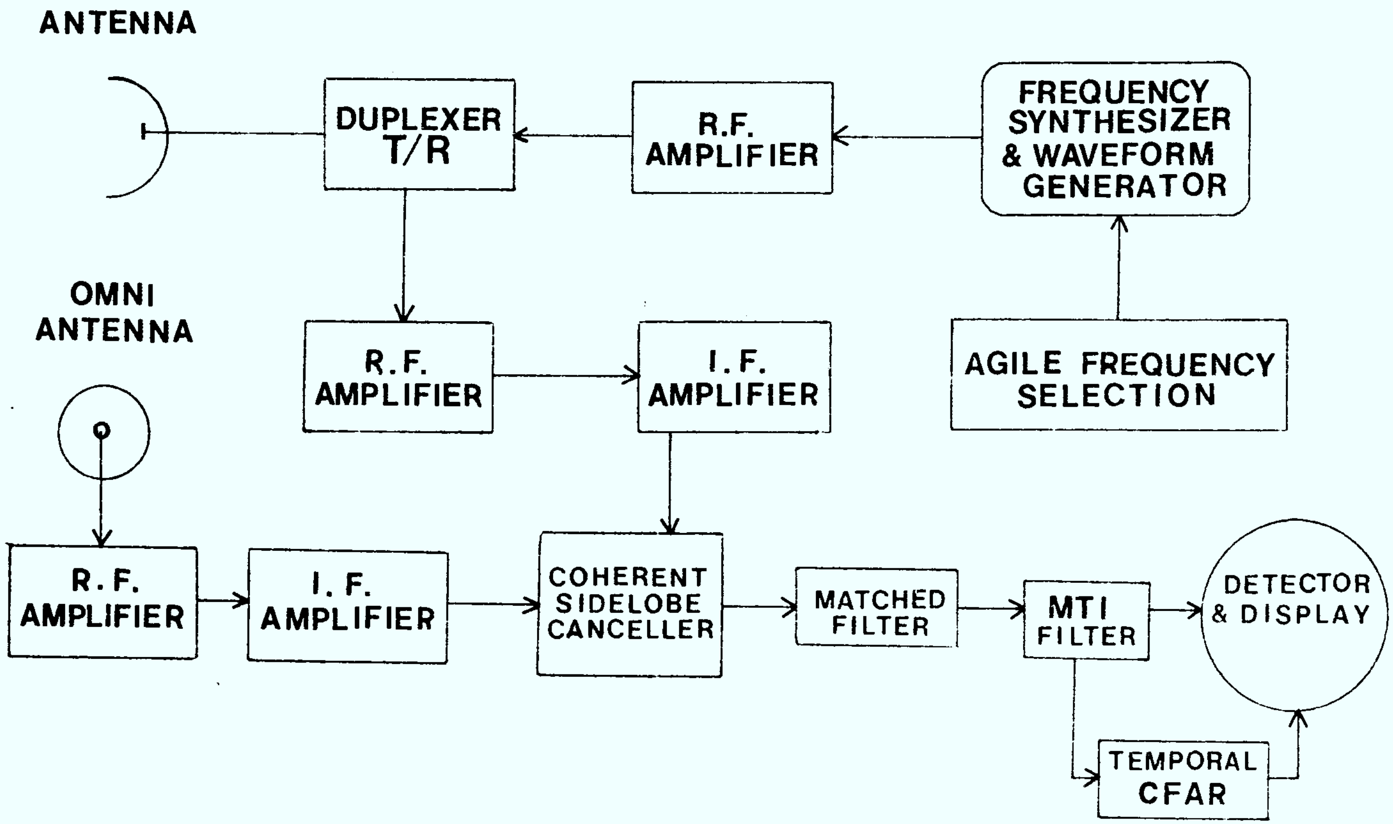

Figure 2 - Basic Naval Surveillance Radar System

certain angular distance from an azimuth, the antenna beam can no longer be directed to that azimuth with a frequency within the agile frequency band. It would be informative to obtain some indication of the possible degradation in azimuthal coverage when frequency agility is employed in conjunction with the frequency squinting antenna.

Let the two antennas, one being a conventional reflector type, the other a frequency squinting antenna, have parameter values such as those shown in Table I. Assume further that the antenna rotation rate and the radar system pulse repetition frequency(PRF) are 20 RPM and 740 Hz, respectively. For the reflector antenna, a simple calculation indicates that the number of pulses on target per scan is:

$$\text{Hits per 3dB beamwidth} = \frac{\theta_{3dB} \times \text{PRF}}{\omega} = 14.2 \qquad (1)$$

where θ_{3dB} = 3 dB beamwidth
ω = antenna rotation rate in degrees/sec.

For simplicity, it is assumed that the beamwidth of a reflector antenna does not change with frequency.

For comparison, a simple simulation may be performed for the case of the frequency squinting antenna with the following conditions:

(i) The agile frequency is drawn from a sequence of pseudo-random numbers[6] which can assume one of sixteen(0-15) discrete values, each of which corresponds to one of sixteen frequencies spaced equally across the agile frequency band.

(ii) The random numbers are uniformly distributed and uncorrelated among themselves.

The azimuthal coverage is represented by a histogram of 3600 cells, each of which represents a 0.1 degree azimuthal sector. The antenna beam position and the azimuthal region which the 3 dB beamwidth covers are computed by the simulation program according to the assumed rotational rate and PRF. The content of each cell in the histogram is incremented by one (pulse) every time that azimuthal sector is illuminated by no less than 3 dB peak power level. This histogram will be called the histogram of illumination.

The histogram of illumination of an azimuthal sector of 30 degrees over one antenna revolution is shown in Figure 3. The simulation is based on the agile frequency selected from a sixteen-valued pseudo-random sequence. This histogram of illumination is typical of all azimuthal sectors. It shows that the azimuthal coverage is no longer uniform as it is in the case of a reflector antenna. Certain azimuths receive as many as 20 pulses, while others receive as few as 8 pulses over one scan of the antenna.

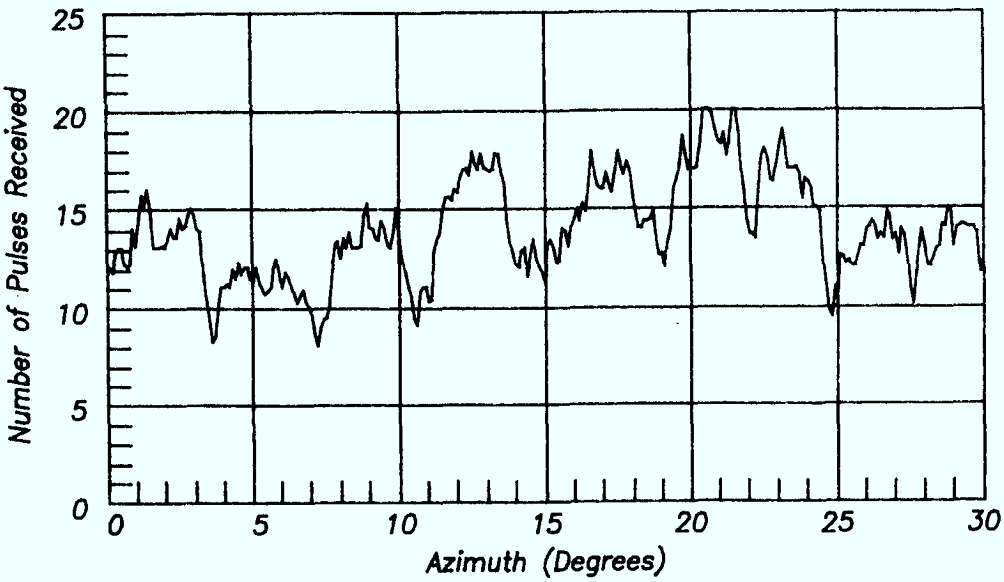

Figure 3 - **Histogram of Illumination of a Frequency Squinting Antenna with Non-Optimized Agile Frequency Selection**

In most radars, integration of returned pulses is employed to enhance detection probability. The integration gain is dependent on the number of pulses available for integration. Consequently, the probability of detection (P_D) in those azimuths which receive fewer pulses over one antenna scan will be degraded. In Figure 4, the required signal-to-noise ratio (SNR) as a function of number of pulses integrated, for a linear detector and non-fluctuating targets is shown. Curves are plotted for 90% probability of detection corresponding to five values of probability of false alarm (P_{fa}). There is a difference of close to 3 dB in the required SNR between the cases of 20 pulses and the case of 8 pulses integrated, for identical values of P_D and P_{fa}. Taking into account the two-way antenna pattern, there will be a substantial difference in the detection performance among different azimuths. It is apparent that some effort must be devoted to finding the proper algorithm for frequency selection which can satisfy the requirement of randomness in frequency and, at the same time, provide relatively uniform azimuthal coverage.

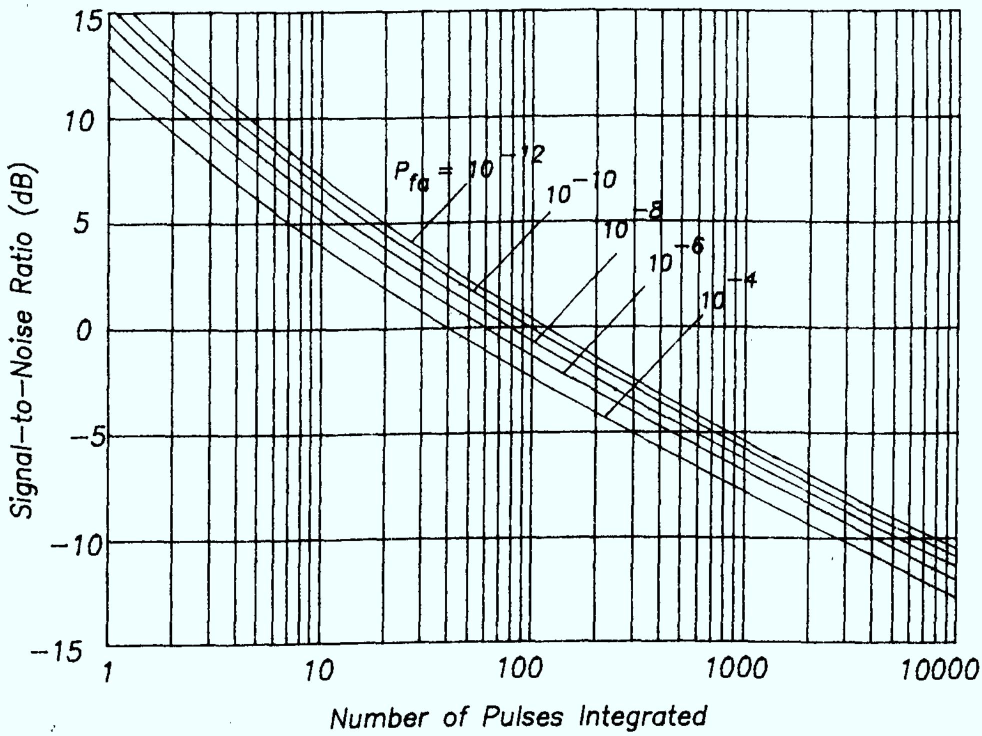

Figure 4 - **Required SNR as a Function of the Number of Non-Coherent Pulses integrated, for a Linear Detector, 0.9 Probability of Detection, and Nonfluctuating Targets, for Five Values of P_{fa}**

There is no unique solution to this problem. A specific approach employing constrained but optimized frequency perturbation has been developed in a separate report [7]. Only the results will be presented here. The nominal sequence of agile frequency is obtained using a certain pseudo-random sequence. The frequency selections are then perturbed, subjected to the constraint that the final distribution of the frequency selections has a minimum squared deviation from a uniform distribution, so that the number of pulses directed at each azimuth over one azimuthal scan is very close to being uniform. Computer programs which implement these procedures have been developed.

In Figure 5, the detailed histogram of illumination resulting from a frequency selection obtained by the optimization program is presented. For clarity of presentation, only an azimuthal sector of 30 degrees is shown. Trace A shows the coverage before optimization, and Trace B shows the coverage after optimization. In the optimization program, the radar frequency was assumed to be continuously variable. In Figure 5, however, the performance was computed by quantizing the optimum sequence of agile frequency to 64 discrete levels. This result shows that the number of pulses received by each azimuth is within 1 pulse of that of the desired uniform value.

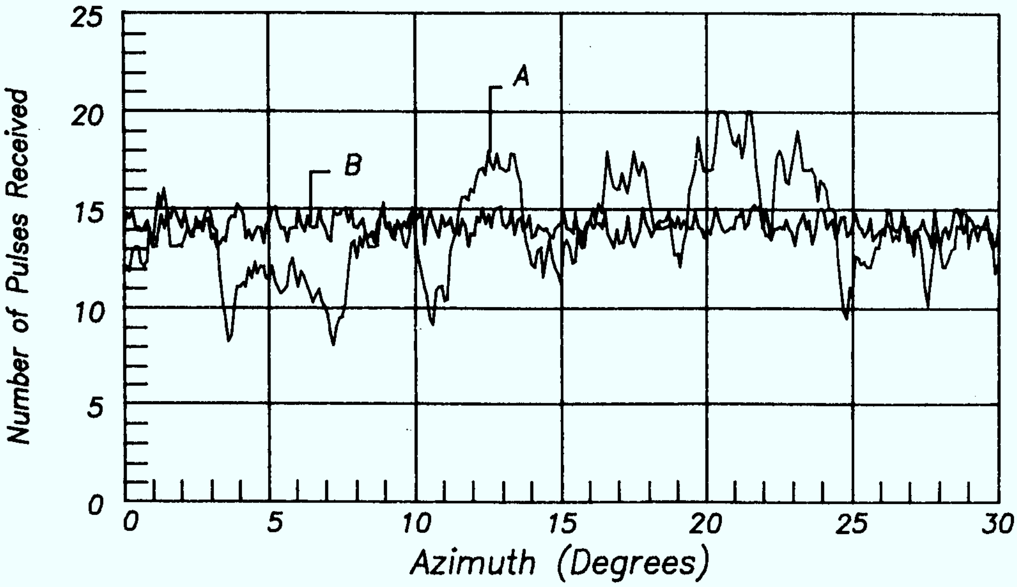

Figure 5 - **Histogram of Illumination of a Frequency Squinting Antenna with Optimized Agile Frequency Selection**

(b) Random ordering of returns from contiguous azimuths

There are several potential problems resulting from the random ordering of returns from contiguous azimuths:

(i) Complication in the implementation of certain automatic detection algorithm.

In modern radars, automatic detection is an important feature because of the requirement of tracking a large number of targets simultaneously. There are many automatic detection algorithms [8]. They generally require that the decision of target declaration be based on the observation of several returns. In the case of a conventional antenna, returns of a pulse train of varying radar frequency are essentially from the same azimuth. Consequently, a decision can be made as soon as the returns from the transmitted pulse train are received. In the case of a frequency squinting antenna, however, the returns of a pulse train of varying radar frequency will be from random azimuthal directions. Thus the returns from one azimuth are interlaced with the returns of many other azimuths. As a result, memory is required to store the intermediate results of the automatic detector while it awaits the arrival of the remaining returns from a specific direction. Since the squinting range of the sandwich wire antenna is in the order of 12 to 15 degrees, and each azimuth may have several hundred range cells, the memory requirement is substantial. It also complicates the design of the automatic detector. The memory requirement may be circumvented by restricting the application of frequency agility to the burst-to-burst mode. However, this reduces the flexibility of the radar operation and may result in a degradation of performance. On the other hand, the resulting longer interpulse period permits sea clutter to decorrelate further, thereby enhancing integration efficiency.

(ii) Complication in the presentation of information to radar operator

Another problem resulting from the random ordering of azimuthal returns is related to the presentation of information to the radar operator. The most common form of radar display is the plan position indicator (PPI). The centre of the display represents the position of the radar. An electronic beam is swept outward away from the centre once every pulse is emitted. The direction of the electron beam is synchronized to the antenna rotational movement. The intensity of the electron beam is modulated by the video signal of the returned echoes. For conventional antennas, the PPI display represents a logical image of the area around the radar. With a frequency-squinting antenna, the direction of the antenna beam is no longer constrained only by the mechanical antenna bearing. Consequently, the information displayed on the PPI will be scrambled in azimuth and will not be compatible with existing signal processing and display equipments.

There are two ways to overcome this problem. The first is to utilize random access memory (RAM) as a de-squinting processor. This approach may be considered as a pre-signal processing operation. The scrambled video data from the squinting antenna will be written into the RAM in such an order that when they are read out contiguously, the data will represent returns from contiguous azimuths. The advantage of this approach is that the de-squinter can be treated as a black box to be inserted between the radar receiver and the signal processing system. As a result, modification to existing signal processing equipment is minimized. In addition, there is also a possibility of integrating this de-squinter into existing signal processing memories. This particular aspect is included in a study undertaken by CMC [5].

The second approach may be considered as a post-signal processing operation. For certain radar systems which do not have sophisticated signal processors, the reordering of the video data may be accomplished by slightly modifying the deflection circuitry of the PPI display unit to conform with the random firing angle of the antenna beam. If the signal processing of the radar does not involve complicated coherent integration of samples from consecutive azimuths, then this approach can be very economical. One important signal processing function, which involves coherent integration of samples from contiguous azimuths, is MTI filtering. This, however, will not present any problems since, in order that MTI operation can be maintained, the radar frequency must remain the same for the duration of the pulse train required for MTI filtering.

(iii) Loss of non-coherent integration gain.

When frequency agility is applied in conjunction with a frequency squinting antenna, the time between returns from an azimuth is increased. For a conventional reflector type antenna, the pulses directed at a particular azimuth are separated in time by an amount equal to the pulse repetition interval(PRI), regardless of whether frequency agility is employed. With a frequency squinting antenna, consecutive pulses are not directed at the same azimuth when frequency agility is employed. Consequently, for a particular azimuth, the time between the arrival of consecutive pulses is greater than or equal to the PRI. Consider the following set of typical system parameters. Let the PRF be 740 Hz, so that the PRI is 1.351 msec. The total time for a typical burst of 14 pulses directed at an azimuth would be 1.351 x 14 = 19 msec. Fourteen is the approximate number of hits per 3 dB beamwidth for an antenna with a 2 degree beamwidth rotating at a rate of 20 rpm. Assume that the agile frequency bandwidth is 500 MHz and the frequency squinting sensitivity of the antenna is 12 degrees/500 MHz. If a radar pulse employing the lowest frequency of the agile frequency band is directed at a certain azimuth at time $t=t_0$, the same azimuth can still be reached by a radar pulse employing the highest frequency of the agile frequency band at a time t_1 when the antenna has rotated 12 degrees. At the assumed rotational rate, it would take the antenna 100 msec to traverse 12 degrees. This means that, in the worst case, the total time for emitting 14 pulses at the vicinity of a single azimuth could be as long as 100 msec. For targets with very high velocity, more than one cell may be traversed in such a time. The result could be a loss in non-coherent integration gain. Similarly, the phosphor of a PPI display performs the axiliary function of non-coherent integration of video signal. The effectiveness of this integration is a function of the persistence of the phosphor. Consequently, there is the question of whether the non-uniform rate of integration resulting from the random azimuthal returns will degrade the display quality to such an extent that it is unacceptable to human operators. This should be taken into account in the system design. However, for sophisticated radar systems, it is unlikely that non-coherent integration will be the main signal processing technique.

2.1.2 Pulse compression and MTI performance

Pulse compression can be realized either with frequency modulation or phase coding of the radar pulse.

(a) Linear FM pulse compression

In the case of linear FM pulse compression, the radar frequency changes linearly with time. Consequently, one would expect a squint of the beam direction for a frequency-squinting antenna when such a waveform is employed. Two possible effects may result. The first is a loss of signal energy reflected from potential targets as the antenna beam squints by them. The second is a possible change in the reflected clutter spectral characteristics. The first effect is not likely to cause serious problems for typical signal bandwidths. However, the significance of the second effect is not obvious.

The spectral characteristics of radar clutter plays an important role in the effectiveness of certain signal proceesing components such as MTI filter and Doppler Processor. These devices are employed in radar systems to enhance the probability of detecting moving targets in clutter environments. The effectiveness of Doppler processing depends on the target speed and the clutter spectral spread. Generally, the PRF employed in surveillance radar systems is not high enough to cover the entire range of possible Doppler frequencies resulting from moving targets of various speeds, which may range from zero to Mach 3 or 4. Consequently, targets with a Doppler frequency higher than that of the radar PRF would appear as slower targets. This is called the aliasing effect [9]. Steps must be taken to resolve this Doppler ambiguity. Multiple or staggered PRFs [10] are often employed for this purpose. Radar clutter appears as low frequency components in the total radar signal. Due to the aliasing effect, these components also appear at frequencies near the multiple of the radar system PRF, giving rise to the so-called blind speed regions. If the clutter spectrum is widespread, then the blind speed region would occupy a significant fraction of the Doppler bandwidth. These clutter components will reduce the ability of the radar to detect targets with Doppler frequencies near zero and multiples of the system PRF. The result would be a more complicated signal processing design. For example, it may require a larger number of PRFs to resolve the Doppler ambiguity.

For a conventional reflector type antenna, the direction of the antenna beam varies slowly due to the mechanical rotation. It is well known[8] that mechanical antenna scanning will introduce antenna scanning modulation. The signal spectrum appears wider when viewed by a rotating antenna than by a stationary antenna. The result is a degradation in Doppler processor performance. It is not obvious whether the intra-pulse beam squint would produce a similar effect.

The spectral characteristics of a signal is related intimately to its time varying behaviour. If two signals have very close time varying behaviours, then their spectral characteristics will also be very similar. Consider an area 'A' illuminated by a radar employing linear FM pulse compression. This area extends in range from $R=r_1$ to $R=r_2$ and in azimuth from $\theta=\theta_1$ to $\theta=\theta_2$. This situation is depicted in Figure 6. The time-variation characteristics of the signal resulting from sampling the returns corresponding to a patch-area located at azimuth θ_0 and range r_0, using a conventional and a frequency squinting antenna are compared. Both

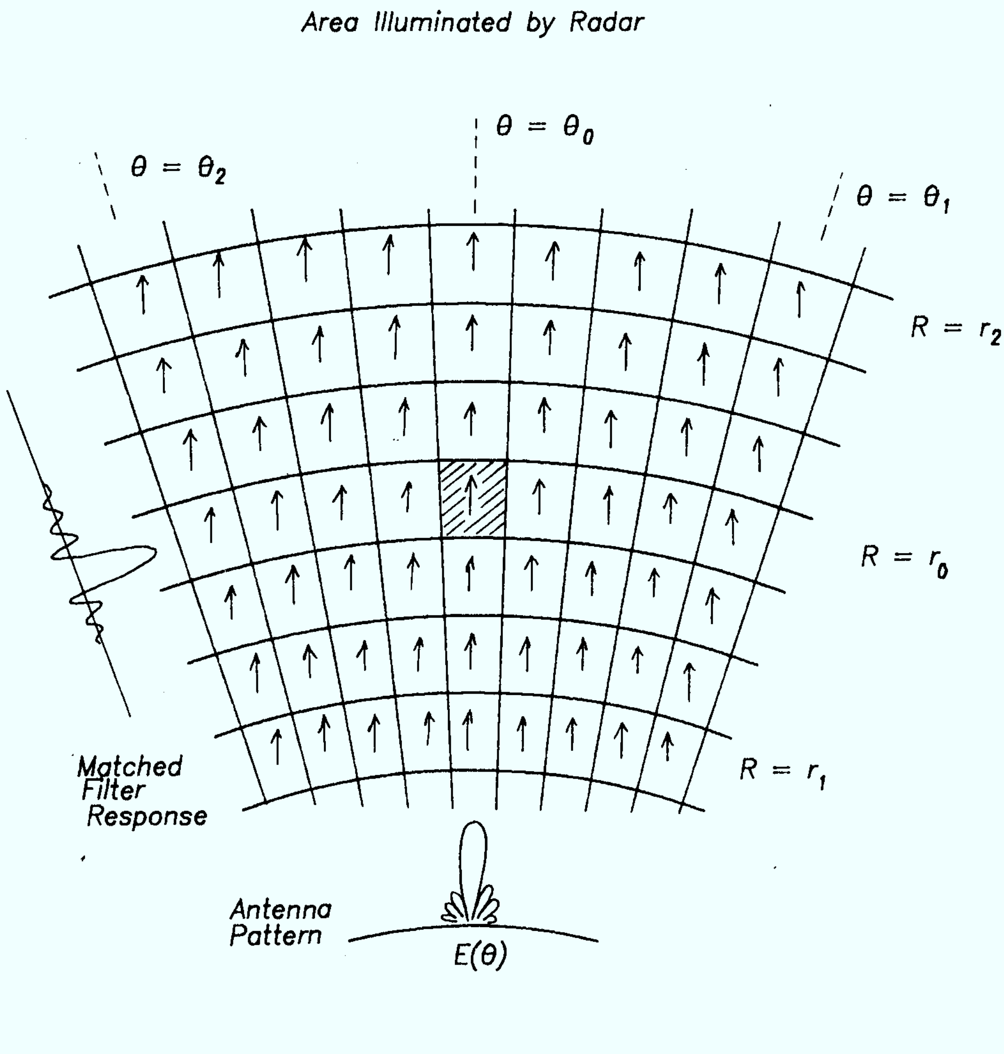

Figure 6 - **Geometry of a Surveillance Cell for a Pulse Compression Radar**

signals are processed by a filter matched to the transmitted waveform before being sampled. Because of the finite resolution of the antenna and the matched filter response, all scatterers located within area A will have some contribution to the sampled video value even though this sample is considered to be from the point (θ_0, r_0). It is assumed that the two antennas have identical radiation patterns. Consequently, any difference in the time varying behaviour of the two signals is due to the matched filter response to the return signals.

Let the matched filter responses be $M(\tau)$ and $M'(\tau)$ for signals received by the conventional and the frequency squinting antennas respectively. The linear FM pulse is given by:

$$S(t) = \cos(\omega t + \pi\mu t^2) \qquad (2)$$

$$0 \leq t \leq T$$

where

$$\mu = \frac{f_2 - f_1}{T}$$

f_1 = carrier frequency at the beginning of pulse
f_2 = carrier frequency at the end of pulse
T = pulse duration

The matched filter response, assuming no Doppler shift in the return signal, is given by the autocorrelation function of $S(t)$:

$$a(\tau) = \int_{-\infty}^{\infty} S(t)\, S(t-\tau)dt \qquad (3)$$

Consider the radar return from a ground patch centred about a point defined by $(\theta=\theta_o,\ r=r_o)$. For a non-frequency-squinting antenna, the amplitude of a pulse received at a fixed azimuth will remain constant throughout the entire pulse. Hence the matched filter response to a linear FM signal received by the conventional antenna is given by:

$$M(\tau) = \int_{-\infty}^{\infty} \cos(\omega t + \pi\mu t^2)\cos[\omega(t-\tau) + \pi\mu(t-\tau)^2]dt \qquad (4)$$

Using the trigonometric identity

$$\cos D \cos E = \frac{1}{2}[\cos(D-E) + \cos(D+E)] \qquad (5)$$

and letting $D = \omega t + \pi\mu t^2$, $E = \omega(t-\tau) + \pi\mu(t-\tau)^2$, we have:

$$M(\tau) = \frac{1}{2}\int_{-\infty}^{\infty} \cos(\omega\tau + 2\pi\mu t\tau - \pi\mu\tau^2)dt$$

$$+\frac{1}{2}\int_{-\infty}^{\infty}\cos[2\omega t + 2\pi\mu t^2 - \omega\tau - 2\pi\mu t\tau + \pi\mu\tau^2]dt \qquad (6)$$

It can be shown that the second integral, being a function of the doubled carrier frequency, will vanish for narrow-band signals. This is due to the fact that, for narrow band signals, the time variation of all other terms is negligible compared to that of the term involving $2\omega t$. Hence, over a complete cycle, they may be considered constant. Integration of a sinusoidal function over a complete cycle will yield a value of zero. Since the pulse length T usually spans a large number of complete cycles, the contribution of the integral involving $2\omega t$ terms will be negligible. The first integral in Eqn.(6) is easily integrated, yielding:

$$M(\tau) = \frac{\sin[\pi\mu\tau(T-|\tau|)]}{2\pi\mu\tau}\cos[(\omega + \pi\mu T)\tau]$$

$$|\tau| \leq T \qquad (7)$$

Equation (7) may be considered as the real part of a complex sinusoidal function having a complex envelope and a complex carrier, i.e.,

$$M(\tau) = \mathrm{Re}\{\, e(\tau)\exp[j(\omega + \pi\mu T)\tau]\}$$

where

$$e(\tau) = \frac{\sin[\pi\mu\tau(T-|\tau|)]}{2\pi\mu\tau} + j0$$

and (8)

$$\exp[j(\omega + \pi\mu T)\tau]$$

are the complex envelope and complex carrier, respectively.

For the frequency squinting antenna, the returned pulse will be different. Depending on the azimuthal location, the instantaneous amplitude of the pulse received by a scatterer will be modified by the antenna pattern. For small squinting angles, this amplitude change may be approximated linearly. The qualitative difference between the pulse shapes transmitted by the two antnenas and observed at a fixed azimuth is depicted in Figure 7.

Let the amplitude of the transmitted pulse be A at the beginning of the pulse. Because of the frequency squint of the antenna, the amplitude will change approximately linearly with time with a slope b. The received signal will be subjected to the same amplitude change with frequency. Consequently the matched filter response to the returned pulse will be given by:

$$M'(\tau) = \int_{-\infty}^{\infty} (A+bt)\cos(\omega t+\pi\mu t^2)\ [A+b(t-\tau)]\cos[\omega(t-\tau)+\pi\mu(t-\tau)^2]dt$$

$$= \int_{-\infty}^{\infty} [(A^2-Ab\tau) + (2Ab-b^2\tau)t + b^2t^2].$$

$$\cos(\omega\tau + \pi\mu t)^2\cos[\omega(t-\tau) + \pi\mu(t-\tau)^2]dt \qquad (9)$$

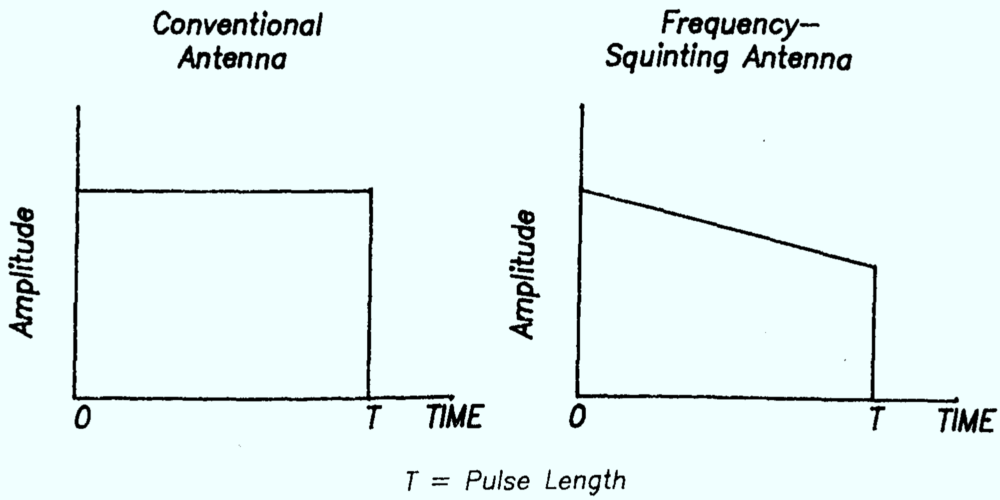

Figure 7 - **Comparison of Observed FM Waveform at a Fixed Azimuth Between a frequency-Squinting and a Conventional Antenna**

Again using Eqn(5) and the fact that terms involving $2\omega t$ will have negligible contribution to the integral, we have:

$$M'(\tau) = \frac{A^2-Ab\tau}{2} I_1 + \frac{2Ab-b^2\tau}{2} I_2 + \frac{b^2}{2} I_3$$

where

$$I_1 = \int_{-\infty}^{\infty} \cos(\omega\tau + 2\pi\mu t\tau - \pi\mu\tau^2)dt$$

$$I_2 = \int_{-\infty}^{\infty} t\cos(\omega\tau + 2\pi\mu t\tau - \pi\mu\tau^2)dt$$

and

$$I_3 = \int_{-\infty}^{\infty} t^2\cos(\omega\tau + 2\pi\mu t\tau - \pi\mu\tau^2)dt$$

(10)

Integral I_1 can be obtained from Eqn (7). Integral I_2 may be integrated by parts. For an FM pulse of finite duration T and for positive value of τ, the integration limits are (τ,T). For negative values of τ, the integration limits are $(0,T-|\tau|)$, yielding:

$$I_2 = \frac{T+\tau}{2\pi\mu\tau} \sin[\pi\mu\tau(T-|\tau|)] \cos[(\omega+\pi\mu T)\tau]$$

$$+\left\{\frac{T-|\tau|}{2\pi\mu\tau} \cos[\pi\mu\tau(T-|\tau|] - \frac{2}{(2\pi\mu\tau)^2} \sin[\pi\mu\tau(T-|\tau|\right\}$$

$$\sin[(\omega+\pi\mu T)\tau] \quad |\tau| \leq T \tag{11}$$

Similarly I_3 can be integrated by parts to yield:

$$I_3 = \left\{\left[\frac{T^2+\tau^2}{2\pi\mu\tau} - \frac{4}{(2\pi\mu\tau)^3}\right] \sin[\pi\mu\tau(T-\tau)] + \frac{2(T-\tau)}{(2\pi\mu\tau)^2} \cos[\pi\mu\tau(T-\tau)]\right\}$$

$$\cos[(\omega+\pi\mu T)\tau] + \left\{\frac{T^2-\tau^2}{2\pi\mu\tau} \cos[\pi\mu\tau(T-\tau)] - \frac{2(T+\tau)}{(2\pi\mu\tau)^2} \sin[\pi\mu\tau(T-\tau)]\right\}$$

$$\sin[(\omega+\pi\mu T)\tau] \text{ for } \tau > 0 \tag{12}$$

$$I_3 = \left\{\left[\frac{(T-|\tau|)^2}{2\pi\mu\tau} - \frac{4}{(2\pi\mu\tau)^3}\right] \sin[\pi\mu\tau(T-|\tau|)] + \frac{2(T-\tau)}{(2\pi\mu\tau)^2} \cos[\pi\mu\tau(T-|\tau|)]\right\}$$

$$\cos[(\omega+\pi\mu T)\tau] + \left\{\frac{(T-|\tau|)^2}{2\pi\mu\tau} \cos[\pi\mu\tau(T-|\tau|)] - \frac{2(T-|\tau|)}{(2\mu\pi\tau)^2} \sin[\pi\mu\tau(T-|\tau|)]\right\}$$

$$\sin[(\omega+\pi\mu T)\tau] \text{ for } \tau \leq 0 \tag{13}$$

Integrals I_1, I_2 and I_3 may be considered as three complex envelope functions on a complex sinusoidal carrier $\exp\{j(\omega + \pi\mu T)\tau\}$. Figures 8, 9 and 10 show the complex envelope functions I_1, I_2 and I_3, respectively, for a linear FM pulse with a BT product of 250(Bandwidth = 5 MHz; Pulse length = 50 μsec.). It can be seen that the imaginary part of I_2 and I_3 is not identically zero as is in the case of I_1. The matched filter output for an FM pulse whose amplitude changes linearly with time over the pulse length is a linear combination of integrals I_1, I_2 and I_3. The effect of the frequency squint on the clutter signal now becomes apparent. The returns from scatterers as received by a frequency squinting antenna undergo a phase shift relative to the returns received by a non-squinting antenna. This phase shift is a function of τ and b(the slope of the amplitude change caused by the frequency scanning of the antenna pattern). If successive pulses by a mechanically scanned antenna causes this slope to change significantly, then the signal components from

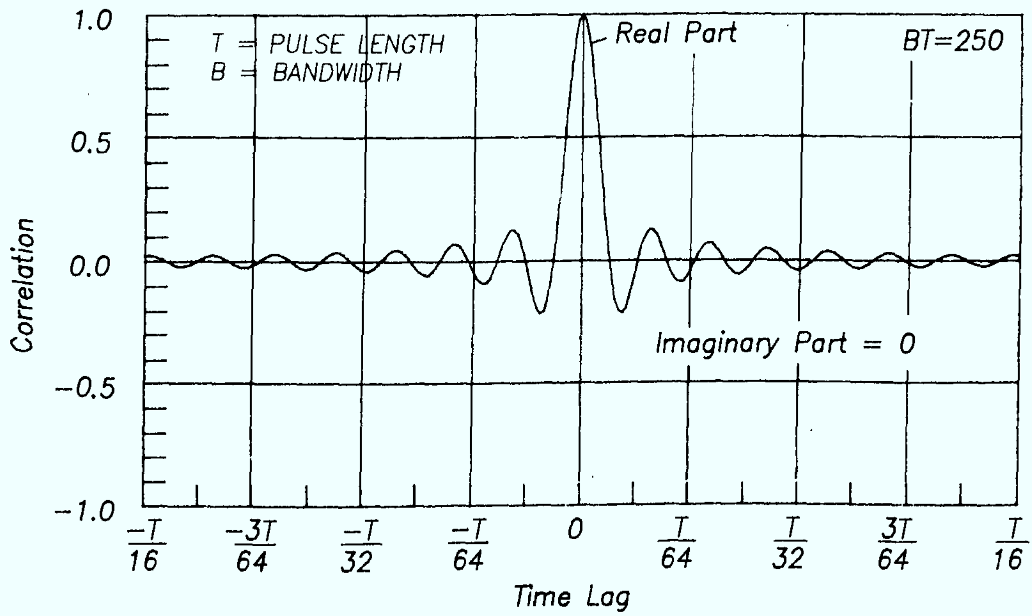

Figure 8 - **Complex Envelope Function of Integral I_1**

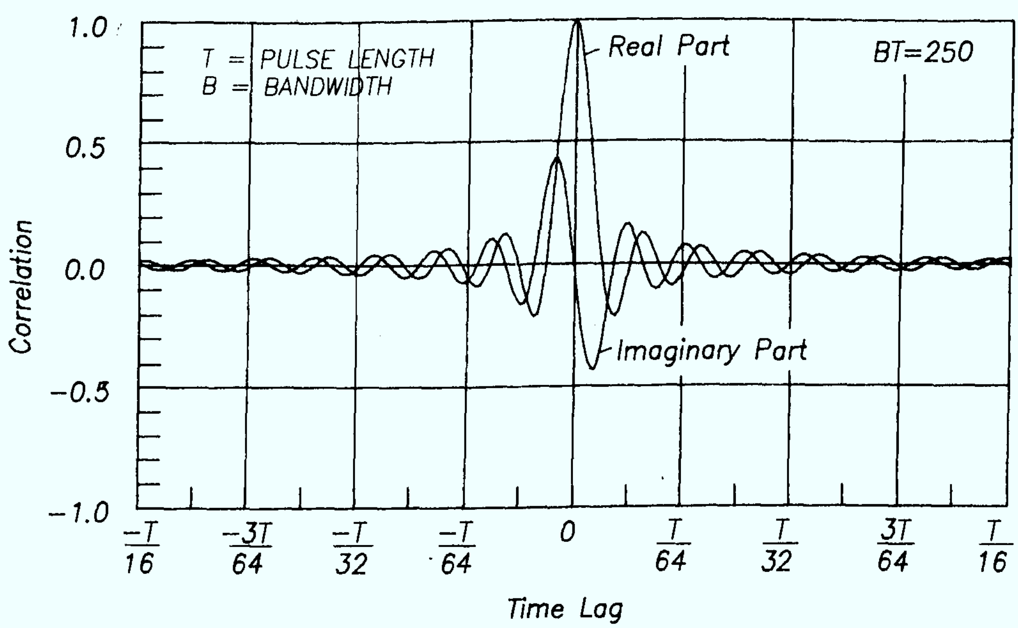

Figure 9 - **Complex Envelope Function of Integral I_2**

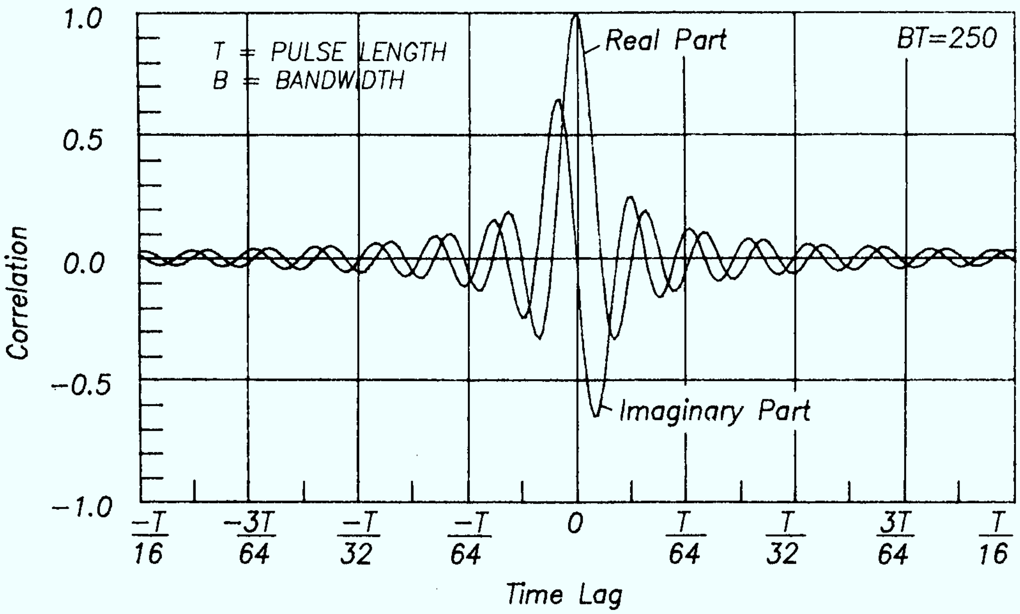

Figure 10 - **Complex Envelope Function of Integral I_3**

some scatterers will undergo time varying phase shift from one pulse to another. This will be reflected in the composite radar signal as higher frequency components.

Now that the effect of the frequency squint on clutter signals has been isolated, it is possible to assess its impact on a typical radar using such a frequency squinting antenna. To simplify the calculation, it is assumed that the frequency squinting antenna has a modified Gaussian shape one way voltage pattern given by :

$$E(\theta) = \exp\left\{-\frac{\theta^2}{k\sigma_\theta^2}\right\}$$

where $\sigma_\theta = \frac{1}{2}$ (3dB antenna beamwidth)

$k = 2.8854$ so that when

$\theta = \sigma_\theta \qquad E(\theta) = 0.707$ (3 dB point)

The following are also assumed:

antenna beam squint sensitivity = 0.024 degrees/MHz
FM pulse bandwidth = 5 MHz
Uncompressed pulse length = 50 micro-second
Antenna one way beamwidth = 2.3 degrees (σ_θ = 1.15°)
PRF = 740 Hz

Since the beam squinting sensitivity is 0.024°/MHz, the antenna beam will scan the azimuth by an amount of 0.12° during the pulse transmission. For each azimuth, the slope of the amplitude change, b, can be calculated. For a scatterer located at an azimuth θ measured from the electrical boresight of the antenna, the amplitude of the pulse would be proportional to $E(\theta)$ at the beginning of the pulse. At the end of the pulse, the amplitude of the pulse would be proportional to $E(\theta+\Delta\theta)$. Thus the slope b of the amplitude change can be approximated by:

$$b = \frac{E(\theta + \Delta\theta) - E(\theta)}{T} \tag{14}$$

where $\Delta\theta$ = the azimuthal squint caused by the linear FM pulse.

For scatterers located near the electrical boresight of the squinting antenna, the amplitude change caused by the squint should be very small. Away from the electrical boresight, there should be a gradual increase in the slope. For example, at $\theta = 3\sigma_\theta$, $E(\theta+\Delta\theta) \simeq 0.8E(\theta)$. This means that the pulse amplitude at the end of the pulse drops about 20% compared to the value at the beginning of the pulse. The value of b computed by using $\theta=3\sigma_\theta$ is substituted into Eq(9) to obtain the matched filter response for scatterers located in that azimuth. The complex envelope function of the matched filter response to returns from scatterers located at this azimuth is plotted in Figure 11. It can be seen that the largest phase shift caused by the frequency squint occurs near $\tau=0$ and is rather moderate. This means that only returns from scatterers located in the vicinity of the observed range cell would experience any noticeable degree of phase shift.

Based on the above analysis, it can be concluded that, for small signal bandwidth, the frequency squint will have negligible effect on the clutter spectrum. The reason is that, for the clutter spectrum observed by a frequency-squinting antenna to have a significantly wider spectral width than the one observed by a non-squinting antenna, the returns from the scatterers must have noticeably large phase shift from one pulse to another. At a typical antenna rotational rate of 20 rpm(120°/sec), and a PRF of 740 Hz, the antenna pattern would have moved merely 120°/740Hz = 0.1622°. Consequently, the slope of the antenna pattern is not much different from one pulse to another.

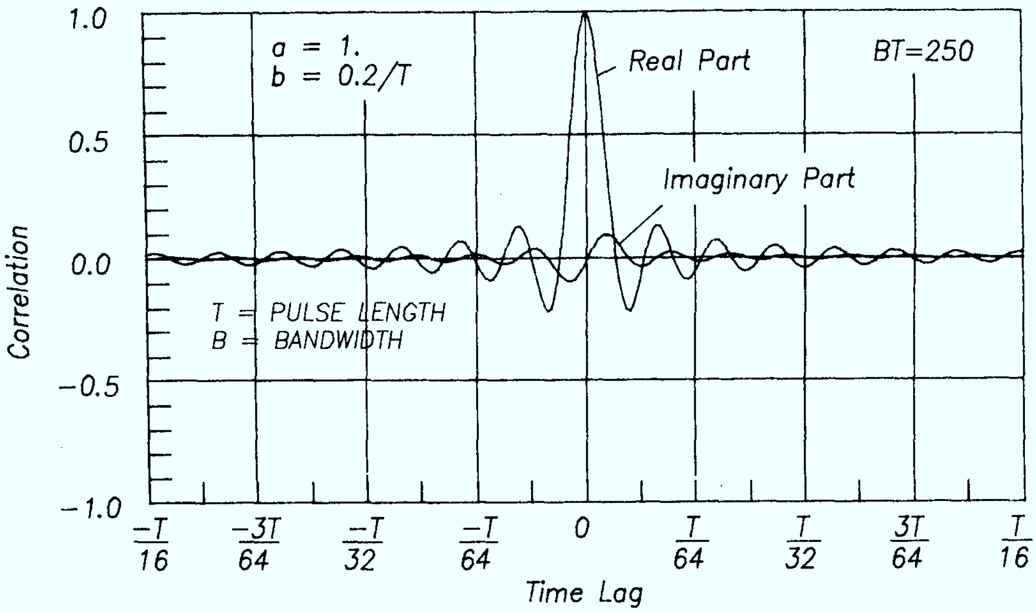

Figure 11 - **Complex Envelope Function of a Returned FM Pulse Received by the squinting Antennna and Processed by a Matched Filter**

For extremely large signal bandwidths, say several hundred MHz, the entire matched filter operation must be reconsidered. Under this condition, the beam-squint within one pulse will span a large azimuthal sector. The returned signal contains both azimuthal and range information, thereby producing a range-azimuth ambiguity. Consequently, conventional matched filters will not be compatible with extremely large bandwidth FM pulse compression signals.

b. PN phase coded pulse compression

Another form of pulse compression is the so-called PN coded pulse compression. A long pulse is divided into a large number of segments. The phase of each segment is switched according to some pseudo-random sequence. An example of such a code is the Barker[11] code. The returned echoes are demodulated and correlated with a stored replica of the transmitted code. The correlation gain is a function of the number of segments in the pulse. For a reflector type antenna, the signal is fed from a feed horn to a reflector. The location of the feed horn normally will be at the focal point of the reflector. Consequently, signals from all points of the antenna aperture arrive at the same time, and there is no significant deviation of the signal phase from the design value along the antenna aperture. For the serial fed frequency squinting antenna such as the sandwich wire antenna, the signal must propagate from one end of the aperture to the other. As a result, the phase transitions between phase segments within a pulse will also propagate across the aperture. The resulting antenna pattern will be completely different from the normal antenna pattern, when there is a phase reversal of the signal between one part of the aperture and another. For example, when the phase of one half of the aperture is 180 degrees out of phase from the other half, there will be a null at the angle where the main beam is supposed to be.

Consider some typical parameter values. Let the length of an S-band sandwich wire array be 4 metres. Assume a PN coded pulse of 50 micro-seconds with 100 segments. Thus each phase segment will be 500 nano-seconds long. The phase transitions will take approximately 13.33 (i.e., $\frac{4}{3x10^8}$) nano-seconds to propagate across the aperture. This is still only a small fraction of the length of a phase segment. Consequently, for small bandwidth PN coded pulses, there is not likely to be significant degradation in performance due to the employment of a frequency-squinting antenna.

c) MTI Performance

No difficulty in MTI operation will result since a constant frequency is employed in MTI filtering.

2.1.3 Constant false alarm rate (CFAR) processor

There are many variations in the so-called CFAR processor. They may be loosely divided into two main categories, namely, a parametric-CFAR[12] and a non-parametric-CFAR[13]. A parametric-CFAR assumes that the general form of the clutter statistics is known and attempts to estimate the parameter values from the samples of the clutter process. Threshold values are set according to the estimated parameters and the required probability of false alarm. Non-parametric-CFAR, on the other hand, does not assume any knowledge of the statistical properties of the clutter process. It transforms the clutter data through some algorithm into a new data set with known statistics. Threshold values are set according to the transformed data. As with most modelling problems, the performance of parametric-CFAR is superior when the clutter statistics closely approximate those of the assumed model. The non-parametric-CFAR is more robust when it is operating in a clutter environment with unknown statistical properties.

In setting the threshold value for the detector, a CFAR processor employs either time averaging or range averaging to obtain the sample mean, and occasionally the sample variance, of the clutter samples from a particular range cell. The time-averaging technique utiizes information in samples from a particular range cell to determine the proper threshold value for that range cell. The range-averaging technique assumes that the statistical properties of the samples from a number range cells are identically and independently distributed. For an ergodic [14] process, time average and ensemble average are interchangeable. The sample mean and variance of the clutter data from a particular range cell are estimated from clutter samples of a number of neighbouring range cells.

For range-averaging-CFARs, there are no apparent detrimental effects of the squinting antenna on CFAR operation because it utilizes information contained in one single sweep. For time-averaging-CFARs, there may be complications because the frequency of successive pulses are different.

2.1.4 Coherent sidelobe canceller (CSLC)

A detailed analysis of the performance of a coherent sidelobe cancellation system with a frequency squinting antenna would require precise definition of the system and noise characteristics. This is beyond the scope of the present study. Nevertheless, some general conclusions can be made based on the fundamental operating priciples of coherent sidelobe cancellers.

A coherent sidelobe canceller may be considered as a special case of a more general problem of adaptive array processing. This problem was first addressed by Widrow[15] in the mid-sixties and has since become a significant branch of system science. The functional block diagram of a general adaptive array processor is depicted in Figure 12. The input signal $\underline{x}(t)$ is, in general, a complex vector quantity. The scalar product formed from vector $\underline{x}(t)$ and a weight vector $\underline{W}(\theta)$ represents the output signal $S(t,\theta)$. The argument θ signifies the angular or spatial dependence of the output signal. The output signal is compared with a reference signal $z(t)$, producing an error signal $e(t)$. The error signal is used to actuate some adaptive algorithm which in turn controls the value of the weight vector $\underline{W}(\theta)$. The objective is to obtain an optimum value for the weight vector with respect to some performance criterion such as signal-to-interference ratio. The solution to this problem can, in principle, be obtained if the covariance of the input signal and the cross-covariance between the input signal, $\underline{x}(t)$, and the reference signal, $z(t)$, are known. However, this usually will not be the case in practice. It may be possible to obtain an estimate of these two quantities from the input signal, but it would require a large number of input samples. If the dimension of the input signal vector is large, the solution may require the inversion of a covariance matrix of large dimension.

Most adaptive algorithms are developed to circumvent these difficulties. The Least Mean Square(LMS) algorithm developed by Widrow is basically the steepest descent method[16] used in numerical optimization problems. To evaluate the impact of the frequency squint on coherent sidelobe cancellers, a specific example may be used. A simple single-loop coherent sidelobe canceller may be considered as an application of the adaptive array processor. The functional block diagram of this system is depicted in Figure 13. The signals from the main antenna and the auxiliary antenna represent the first and second components of the input signal

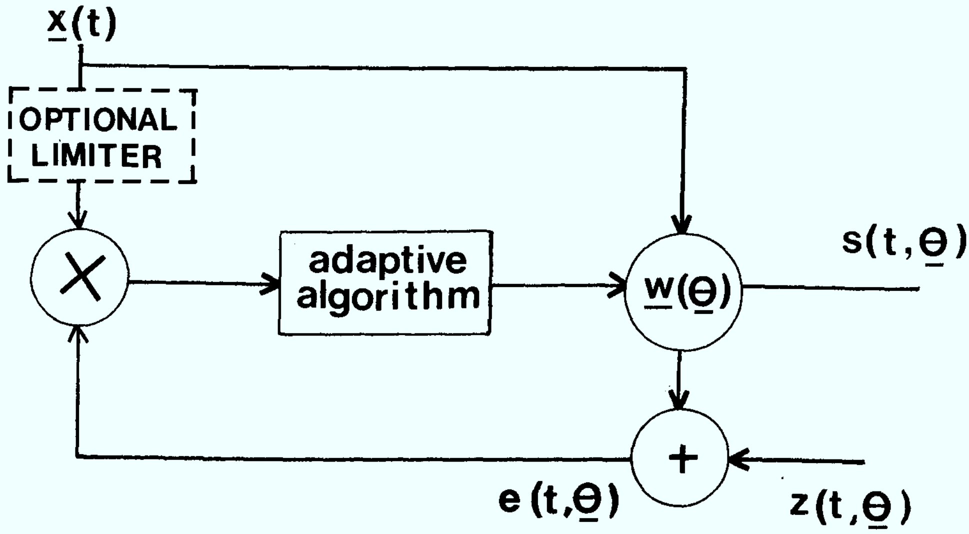

Figure 12 - **Functional Block Diagram of an Adaptive Array Processor**

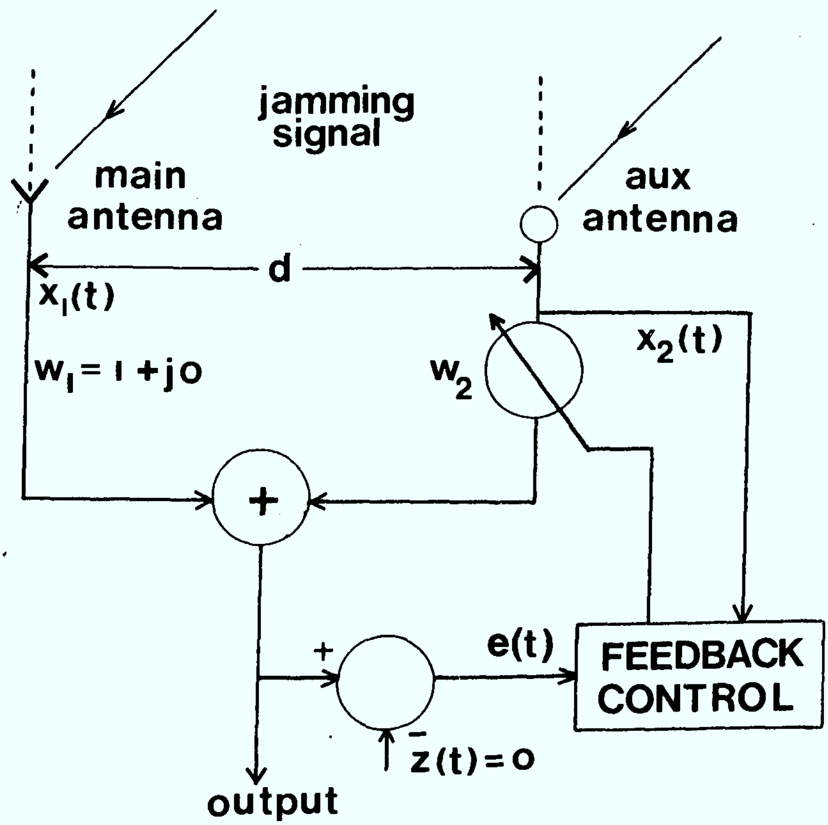

Figure 13 - **Functional Block Diagram of a Single Loop Coherent Sidelobe Canceller**

vector x(t), respectively. The weight vector $W(\theta)$ also has two components, W_1 and W_2. In this particular case, W_1 equals unity, and W_2 is an adjustable complex quantity.

The schematic diagram of the system described in the previous section is shown in Figure 14. The signal received at the main antenna, $x_1(t) = V_m \cos\omega_c t$, provides the phase reference. The signal received at the auxiliary antenna, $x_2(t)=V_A\cos(\omega_c t+\phi)$, will have a phase shift ϕ relative to the phase of $x_1(t)$. In the case of a strong jamming signal which dominates other signal or noise components, the phase angle is a function of the jammer bearing θ:

$$\phi = 2\pi\, d \sin(\theta)/\lambda \qquad (15)$$

where d = distance separating the main and auxiliary antennas
λ = wavelength of radar
θ = jammer bearing

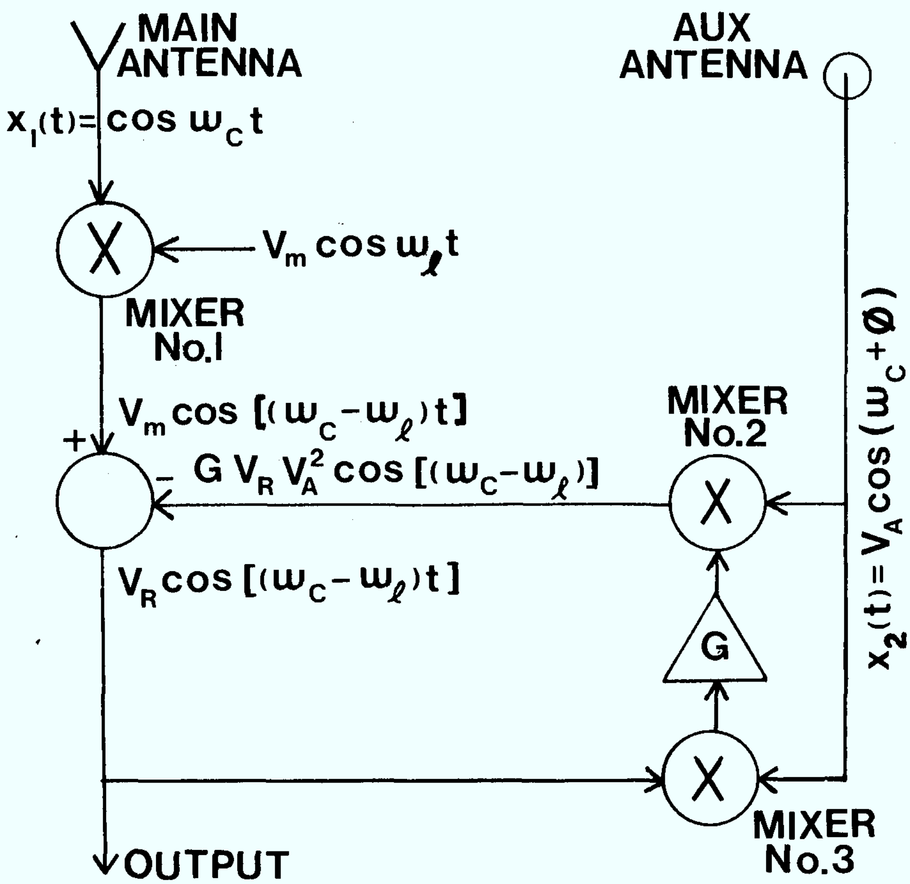

Figure 14 - **Schematic Diagram of a Single Loop Coherent Sidelobe Canceller**

The objective is to scale $x_2(t)$ properly and subtract it from $x_1(t)$ so that the jammer component in $x_1(t)$ will be removed. This requires two operations. The first is to obtain the component of $x_2(t)$ which correlates with $x_1(t)$. The second is to adjust its magnitude properly. These two operations may be performed either in complex baseband or at a suitable intermediate frequency (i.f.). The system shown in Figure 14 performs the correlation and scaling operations at i.f.

Mixer No. 1 is used to translate singal $x_1(t)$ down to a suitable i.f., $(\omega_c-\omega_\ell)$, where ω_ℓ is the angular frequency of the local oscillator signal. The output of this mixer will be a signal proportional to $V_m\text{Cos}[(\omega_c-\omega_\ell)t]$. A feedback control loop which performs both the amplitude and phase adjustments is comprised of mixers No. 2 and 3, and a narrow band amplifier with gain G. Mixer No. 3 and the narrow band amplifier form a correlator extracting the signal component in $x_2(t)$ which correlates with $x_1(t)$. The output of mixer No.3 has a frequency identical to that of the output of mixer No.1, but its amplitude is controlled by the signal at the output of the narrow band amplifier. The output of the narrow band amplifier has a carrier frequency equal to the local oscillator, ω_ℓ; however, its phase is shifted by an angle ϕ. This signal is mixed with the auxiliary antenna signal $x_2(t)$, producing a signal centred at frequency $(\omega_c-\omega_\ell)$. The phase angle ϕ is removed from the resulting signal, $GV_RV_A^2\cos[(\omega_c-\omega_\ell)t]$. This signal, which is in phase with the output of Mixer No.1, represents the error signal. This error signal is subtracted from the signal at the output of Mixer No.1, producing the output signal $V_R\cos[(\omega_c-\omega_\ell)t]$. Since the magnitude of the signal at the output of the narrow-band amplifier is directly proportional to the amount of correlation between the output siganl and the signal from the auxiliary antenna, this system constitutes a feedback control system which tends to reduce the signal component in $x_1(t)$ which is correlated with $x_2(t)$. Since the jamming signal is highly directional, the jamming signal component received by both the main and the auxiliary antennas are highly correlated. On the other hand, the main antenna has very high gain in the look direction, whereas the auxiliary antenna is usually omni-directional with a gain similar to that of the main antenna sidelobes. Consequently, the correlation between the signals in the two antennas is dominated by the jammer components.

The effect of the frequency squint of the sandwich wire antenna can now be evaluated in terms of coherent sidelobe canceller operations. The look direction of a frequency-squinting antenna will change when a new radar frequency is employed. As a result, the relative angular position of the sidelobes with respect to the jammer location will be changed. The net result is a change in the signal amplitude V_m. The phase angle ϕ will be changed when a new frequency is applied. These changes do not affect the basic operation of the feedback loop. The reason is that, in a practical system, the adaptation period usually begins at the end of the last pulse interval to stabilize the weighting ajustment. It is conceivable that there may be a difference in the length of the adaptation period due to the difference in the antenna pattern. The more abrupt change in the sidelobe level in the direction of the jammer may cause a higher level of transient noise in the servo loop, thereby degrading the performance slightly. Other than that, there appears to be no fundamental problem for the operations of a coherent sidelobe canceller employing a frequency-squinting antenna as the main antenna.

2.2 ECCM aspects

The ECCM performance of a radar system may be assessed in terms of jamming resistance and probability of intercept. The probability of a radar transmission being intercepted by an enemy electronic support measure (ESM) receiver is a complicated function of many factors which are either incompletely known or beyond the control of the radar analyst. For example, the signal density of the operating environment is seldom adequately defined. The characteristics and capabilities of enemy ESM receivers are never known exactly in tactical situations. It is reasonable to assume that the enemy will not initiate jamming action until it has determined the existence of a hostile radar. With regard to the sandwich wire antenna, a natural question which arises is whether the frequency squint of the antenna beam will significantly change the probability of intercept of a radar system employing such an antenna.

2.2.1 Probability of intercept

Before investigating the probability of intercept of a radar system employing a frequency-squinting antenna, it would be instructive to put it into the proper perspective. In the past, analyses of intercept receivers have usually been posed as coincidence problems between transmitter and receiver antenna beam directions and their respective passbands. This is partly due to the extreme complexity of the problem and partly to the limitations of the older generation of ESM receivers. With the advent of modern receiver technology, some of the restrictions on intercept receivers have gradually been relaxed or even removed. A survey of the literature indicates that the most common types of intercept receiver are the following:

- Frequency channelized super-het receivers
- Scanning super-heterodyne receivers
- Micro-scan receivers
- Instantaneous frequency measurement(IFM) receivers
- Optical receivers (Bragg cell)
- Crystal video receivers

The operational and technical features of these intercept receivers may be found in Van Brunt[17]. To obtain an evaluation of the probability of intercept for a particular radar, the operational characteristics of the radar and the intercept receiver, the signal density of the environment in which they both operate must be taken into account.

Consider a typical one-on-one situation involving a naval surveillance radar and an intercept receiver on board an aircraft with an average radar cross section of $\sigma = 10\ m^2$. Assume a radar receiver sensitivity of -105 dbm, which represents a radar receiver of reasonably low noise figure. The maximum detectable range of the aircraft can be found from the radar range equation:

$$R_{max}^4 = \frac{(P_t G_t^2\ \sigma\lambda^2)}{(4\pi)^3 P_{min}}$$

where R_{max} = maximum detectable range (16)

P_t = peak transmit power
G_t = radar antenna gain
σ = target radar cross section
λ = radar wavelength
P_{min} = minimum detectable signal power

Ignoring any atmospheric propagation and component losses and assuming the following set of radar parameter values:

P_t = 20 KW
G_t = 30 dB
λ = 10 cm
σ = 10 m^2

the maximum detectable range for a target of 10 m^2 radar cross section is:

$$R_{max}^r = \left[\frac{(20000)(1000)^2(10)(0.1)^2}{(4\pi)^3\ 3.162\text{x}10^{-14}} \right]^{1/4} = 75.14 \text{ km} \quad (17)$$

The intercept range for an ESM receiver with a minimum detectable signal of -70 dBm would be:

$$R_{max}^i = \left[\frac{P_t\ G_t\ G_r\ \lambda^2}{(4\pi)^2\ S_{min}}\right]^{\frac{1}{2}} \quad (18)$$

where G_t = average radar antenna sidelobe gain
G_r = antenna gain of ESM receiver
S_{min} = minimum detectable signal of ESM receiver

$$R_{max}^i = \left[\frac{(20000)(0.2)(10)(0.1)^2}{(4\pi)^2\ 10^{-10}}\right]^{\frac{1}{2}} = 159.1 \text{ km}$$

In the above computation, it is assumed that the signal can be received from the sidelobes of the transmit antenna which has an average gain of G_t = 7dB below that of an equivalent isotropic radaiator. The receiver antenna has a moderate gain of G_r = 10dB. Thus a modern intercept receiver would have a substantial range advantage over the radar. It can detect the presence of the radar long before a good size target can be detected by the radar.

In the absence of detailed system parameters, the effect of the frequency squint on the probability of intercept can only be assessed qualitatively. The major effect of the frequency squint is to alter the antenna beam pointing direction. Since, for modern intercept receivers, the interception of radar pulses is not dependent on main beam coincidence, the probability of intercept will change only if there is a substantial difference in the sidelobe characteristics between the two antennas. Consequently, it is reasonable to conclude that the frequency squint will not have a significant effect on the intercept probability of modern intercept receivers.

2.2.2 Jamming resistance

Intercepting a radar transmission is only part of the requirements for effective jamming. The ESM receiver is also required to analyze the signal parameters of the radar transmission such as frequency, waveform, etc. The logical questions which might be asked are: Will there be any potential weaknesses in the frequency-squinting antenna in terms of the ability of an enemy ESM receiver to analyze and determine the nature of the signal emitted by the antenna? Would an antenna possessing frequency squint be more jamming resistant? The answers to these questions are mixed. Most ESM receivers obtain their information from the sidelobes of the transmit antenna. It is rather difficult to distinguish between the cases of a frequency-squinting antenna with frequency agility and a non-squinting antenna with frequency agility, based solely on the signal received from the sidelobes. However, it is possible for an ESM receiver with a certain memory capability to detect the frequency dependent nature of the beam direction for the sandwich wire antenna, by correlating the main beam direction with frequency. This is a potential disadvantage of the frequency-squinting antenna. Because of the limited squinting range of this antenna, the ability of the sandwich wire antenna to backscan is limited. This means that when the antenna mechanical boresight has rotated away from a certain azimuth, the choice of radar frequencies which can be employed to direct the beam back to that azimuth will decrease with time. For an enemy jammer whose objective is to jam the radar in a limited azimuthal sector, the knowledge of the frequency squint may allow the jammer to reduce the bandwidth of its transmitted noise to match the reducing frequency range, resulting in a greater effective jammer energy.

On the other hand, the frequency squint provides a limited degree of freedom in the azimuthal dimension in that the antenna beam can return to a moderately wide azimuthal sector almost instantaneously. It is, therefore, conceivable that some gain in jamming resistance may be obtained by devising some new signal processing techniques. This aspect of jamming resistance will be examined in more detail in Section 3. For conventional signal processing systems, it is unlikely that the frequency-squinting antenna would provide any additional jamming resistance to the radar.

3. EVALUATION OF THE SANDWICH WIRE ANTENNA IN NEW MODES OF OPERATION FOR POSSIBLE IMPROVEMENT OF RADAR SYSTEM PERFORMANCE

In this section, several unconventional modes of operation, designed to take advantage of the extra degree of freedom provided by the frequency squint of the sandwich wire antenna, will be examined. The frequency squint raises some interesting possibilities, such as:

- Simultaneous beam forming with multiple frequency channels
- Wide-band FM modulation or time multiplexed, multiple-frequency beams
- Look back and burnthrough capabilities
- Efficient use of surveillance time
- Pseudo-mono-pulse operation providing improved azimuthal resolution
- Ultra-low sidelobe with the sandwich wire antenna operating in the tilted or cocked antenna modes

The feasibility of these modes of operation in a naval surveillance radar is evaluated.

3.1 Simultaneous beam forming

Since the beam pointing direction of the sandwich wire antenna is frequency dependent, it should be possible for the antenna to form beams in multiple directions when signals of differing frequencies are applied simultaneously. This would provide a much more efficient azimuthal coverage than in the conventional single beam case. How well this can be realized depends on the basic properties of the antenna. In order that the beams in different directions have sufficient energy, the antenna must be able to handle the sum total of the energy in all beams. Summing RF pulses of different frequencies results in a pulse of non-constant envelope. Microwave output devices used in radar systems are usually operated in the saturation mode for optimum efficiency. Because of nonlinearity this mode of operation is not compatible with non-constant envelope pulses. Consequently, it is necessary to have parallel output channels for each beam. Modern solid-state RF output modules offer good performance and reliability. They may be employed if such a system is implemented.

Data processing rate is an important aspect which must be examined in a multiple-beam system. The data rate will be multiplied by the number of beams. For example, with a 12 degree squinting range and an azimuthal beamwidth of 2 degrees, 6 simultaneous beams may be employed. Assuming a 5 MHz signal bandwidth for each channel, the effective signal bandwidth will be 30 MHz. This will add considerable costs to the signal processing system.

3.2 Wide-band FM or time-multiplexed, multiple-frequency beams providing wide azimuthal coverage

The application of wide-band FM pulses in a radar system employing a frequency-squinting antenna results in a main beam which sweeps through a wide azimuthal sector(sweep beam mode). Similarly, a long pulse may be coded with segments of sine waves of differing frequencies, thus producing time-multiplexed beams(step-beam mode) pointing at different directions. There are several problems associated with these modes of operation.

First, the energy intercepted by a potential target per pulse transmitted will be reduced because the beam is directed to each azimuth in only a fraction of the total pulse length. To maintain the same level of signal energy required for detection, the transmit power must be increased accordingly. This means that the sandwich wire antenna must be able to handle peak power levels several times that of a single direction transmission.

Second, a conventional pulse compression receiver alone is not enough to process all the information. Unlike a non-squinting antenna, the return from a frequency-squinting antenna employing wide-band FM pulses contains both azimuthal and range information. Consequently, there is an azimuth-range ambiguity. For example, a target at long ranges in the azimuth corresponding to the beam pointing direction at the beginning of the pulse would produce a similar response as that of a target at shorter ranges in the azimuth corresponding to the beam pointing direction at the end of the pulse. This ambiguity may be resolved with frequency discrimination using parallel frequency channels, but at a considerable added cost. Theoretically, signal energy may be increased by lengthening the transmit pulse. However, there is a practical limit to the pulse length which can be employed. The radar receiver cannot begin to receive until the transmitted pulse is terminated. If the transmit pulse length is too large, there will be a large range interval which is not covered. Auxiliary coverage must be provided to augment this loss of information.

Third, the resulting data from a sweep-beam or a step-beam subsystem will be increased many fold. Consequently, the signal processing system must be redesigned in order to handle the increased data rate.

3.3 Look-back and burnthrough capabilities

The frequency-squint property of the sandwich wire antenna enables the radar to return to a desired azimuth even though the antenna mechanical boresight has already gone passed it. There are two possible applications, namely, look-back and burnthrough. The antenna may be used in conjunction with some form of sequential detection scheme, whereby a small number of pulses is initially transmitted in various azimuths. A preliminary detection process will either confirm or dismiss targets in azimuths where conclusive decisions can be made. More pulses can then be transmitted in azimuths where the preliminary detection is inconclusive.

Burnthrough is a technique used to improve detection performance under masking jamming conditions. Masking jammers include barrage noise jammers, spot jammers and swept jammers. They are usually operated in continuous mode so that any target returns will be totally submerged in jammer noise. Their effectiveness depends on several factors. It depends on whether the jammer has sufficient power to penetrate the radar antenna sidelobes. For spot jammers, it also depends on whether the jammer can effectively track the radar frequency which may change from pulse to pulse. Modern jammers transmit wide-band noise of moderately high microwave power. Microwave devices achieving over 10% bandwidth are not uncommon. Barrage jammers do not utilize available power efficiently because the power is distributed over a very wide frequency bandwidth. Other limitations include interference from friendly radars and constraints caused by ESM operations. One of the characteristics of masking jamming is that it discloses the azimuth of the jammer; however, the radar will be denied range information. One advantage of a frequency-squinting antenna is the possibility of increased dwell time on a single azimuth by employing the proper frequency increment in the transmitted pulses to offset the mechanical rotation. It is, therefore, possible that detection performance can be improved under masking jamming by employing this so-called burnthrough technique.

To obtain a quantitative measure of possible improvement in detection performance with the burnthrough technique, the following set of system parameters is used:

Antenna rotational rate = 20 rpm (120 degrees/sec)
Antenna squinting range = 12 degrees/500 MHz
Radar PRF = 740 Hz

At a rotational rate of 120 degrees/sec, it will take 100 msec for the antenna to traverse an azimuthal sector of 12 degrees. Consequently, at a PRF of 740 Hz, 74 pulses may be directed to a single azimuth per scan. Again referring to Figure 4, for a probability of false alarm of 10^{-6}, an SNR of 5 dB is required for a probability of detection of 90% with 10 non-coherently integrated pulses. With 80 non-coherently integrated pulses, the SNR requirement is about -0.7 dB. Thus an improvement of 5.7 dB in detection performance is possible. However, this improvement is achieved at the expense of ignoring all other azimuths within the 12° degree azimuthal sector. The merit of this application in the context of overall system performance must be investigated.

3.4 Efficient use of surveillance time.

Under certain conditions, the available surveillance time of the radar may be optimized with the help of the frequency squint property of the sandwich wire antenna. One example is the mode of operation in which the radar is transmitting short pulses to obtain coverage of short ranges. This comes about because of the relatively long pulse length employed in pulse compression system. For example, for an uncompressed pulse length of 50 micro-seconds, the minimum range is at 7.5 km. Since the unambiguous range is short, the radar PRF can be increased. With a conventional antenna, this will introduce multiple-time-around interference since the look direction of a reflector type antenna is constrained by its mechanical boresight. Thus all the extra pulses are directed to the vicinity of a single azimuth. With the frequency-squinting antenna, however, pulses of differing frequencies can be transmitted to obtain information of many more azimuths within the short range, for the same amount of surveillance time and problems of multiple-time-around clutter interference are avoided.

3.5 Pseudo-monopulse operation providing improved azimuthal resolution

The ability of the squinting antenna to scan a target within a pulse length may be used to advantage in a mode of operation similar to the amplitude monopulse operation. By transmitting an FM pulse and sampling the target return with parallel frequency channels, a more precise estimate of the target azimuth may be obtained than would be possible with a conventional reflector type antenna. In this case, the bandwidth of the pulse need not be very large. The objective is to squint the antenna beam across an azimuthal sector of approximately one beamwidth. Consider a frequency squinting antenna having a 3 dB beamwidth of θ_{3dB} at a nominal radar frequency f_o. A linear FM pulse having a signal bandwidth Δf is transmitted and the return from a point target received by this antenna. Because of the frequency dependent squint, the signal strength of the transmitted pulse directed at the point target will vary with time due to the changing frequency within the pulse. A number of channels, each having a bandwidth $\Delta F/N$, are used in the receiver. The center frequencies of bandwidth of the transmit pulse. The samples taken at the output of each receiving channel will trace out the antenna pattern around the main beam. The relative magnitude of these samples is used to obtain a more refined estimate of the azimuthal location of the point target. The effectiveness of this mode of operation is a function of SNR. Since receiver noise is Gaussian distributed, the samples from each receiving channel, when a target is present, will be Rician distributed[18] given by:

$$p(r) = \frac{r}{\sigma^2} \exp\left(- \frac{S^2 + r^2}{2\sigma^2}\right) I_o\left(\frac{Sr}{\sigma^2} \right) \qquad (19)$$

where r is the amplitude

S^2 is the signal power from a non-fluctuating target
σ^2 is the noise power
and $I_0(x)$ is the zeroth order modified Bessel Function of the first kind.

With very high SNR, the estimate should be very accurate. For low SNR, such as in the case of a weak target signal, the accuracy of the estimate will be degraded.

A simple simulation will be used to obtain some quantitative indication of the performance of this mode of operation. The one-way antenna pattern is assumed to have Gaussian shape given by Eq.(13). Thus the sample taken at the receiving channels are samples of the two-way antenna pattern. The azimuthal position of the point target is estimated by a quadratic fit of the sample with the maximum magnitude and the two samples on each side. The standard deviation of the estimate as a function of SNR is shown in Figure 15. The SNR figure is for single pulse. By non-coherent integration of several pulses, improved performance may be obtained. It can be seen that for moderate SNR, an estimate giving 0.2 beamwidth accuracy is feasible.

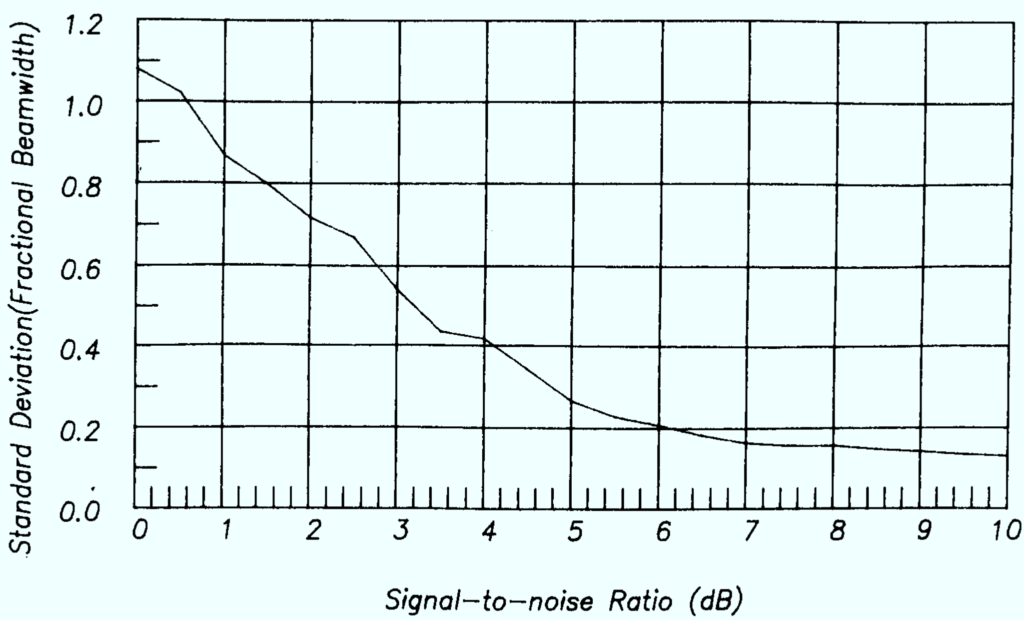

Figure 15 - **Standard Deviation of Azimuthal Estimate as a Function of SNR for a 9-Channel Pseudo-Mono-Pulse System**

In this mode of operation, the FM pulse is not used in the pulse compression mode. This means that range resolution would have to be obtained by employing short pulse length. However, for a fixed signal bandwidth the pulse length is determined by the required time bandwidth product. Consequently any possible gain in azimuthal resolution could be offset by a loss in range resolution.

3.6 Ultra-low sidelobe antennas

Aside from the frequency squint and light-weight properties, the sandwich wire array antenna also possesses the compactness and low cost properties compared to conventional array antennas. For conventional phased arrays comprising separate radiating elements, the elements must be controlled by microwave attenuators and phase shifters. This adds a tremendous amount of complexity and increases the cost significantly. Thus the sandwich wire array would have significant cost and weight advantages over conventional phased arrays when the number of radiators is large and maneuverability is important. A sandwich wire array will not have the flexibility in controlling its antenna pattern under changing radar environment as that of a fully phased array. There are certain applications which require the radiation pattern of a phase array but do not require its full adaptivity. One such application is the so called ultra-low sidelobe antennas.

In military radar applications, ECCM capability is an important facet. Good ECCM characteristics include low probability of intercept and high jamming resistance. In both instances and also as a counter-anti-radiation missile measure, an antenna with very low sidelobe levels is required. Conventional approaches to obtain low sidelobes have required large antennas which possess good sidelobe characteristics in all directions. While such an approach is theoretically possible, physical limitations have prevented radar designers from achieving the sidelobe levels necessary for the desired ECCM performance. Factors such as the precise control of the amplitude and phase of current flow over a large aperture and the close tolerance in radiator alignments all place a lower limit on the achievable sidelobe level.

Recently, however, there has emerged another school of thought on the solution to the radar ECCM problem. The main argument behind this alternative approach is that, while it is next to impossible to produce an antenna which possesses extremely low sidelobes everywhere, it is relatively easy to obtain very low sidelobes in certain directions. By a proper orientation of the antenna aperture, the relatively high sidelobes may be made to point to directions where enemy jammers or ESM receivers are least likely to be located. This concept has recently been demonstrated in a newly redesigned air defence radar employing the so-called tilted antenna[19]. A variation of the tilted antenna, called the cocked antenna, can also be used to achieve similar results. The sandwich wire antenna, being low cost and light weight, appears to be a good candidate for such applications. In the next section, the feasibility and limitations of employing the sandwich wire antenna in these two modes of operation will be explored.

A simulation study[20] of the performance requirements of the tilted and cocked antenna concepts has been carried out. The results of that study will be used to determine the feasibility of employing the sandwich wire antenna in the tilted antenna and cocked antenna modes.

For an array antenna operating in the tilted or cocked antenna modes to be effective, there are several basic requirements. These are:

(i) The aperture size of the array in both horizontal and vertical dimensions must be fairly large in terms of wavelength. The exact dimension depends on the desired beamwidth as well as the angular extent of the sidelobes.

(ii) Accurate current distribution weightings must be maintained in order to realize ultra-low sidelobes off the principal axes.

(iii) The antenna must be able to operate with a relatively large (30°-45°) backscan to enhance the curvature of the principal sidelobe structure.

These requirements can be met by conventional discrete element phased arrays, but the cost would be very high. Computer simulated results indicated that the sidelobe levels off the principal axes would rise significantly if close tolerances could not be maintained in the magnitude and phase of the aperture current. For example, the theoretical first sidelobe level of an aperture with Hamming weighting is -42 dB relative to that of the main lobe, while the theoretical sidelobe levels off the principal axes could be below -80 dB. However, if there is a random error in the aperture current magnitude of more than a few dBs, or a random phase error of several degrees, the sidelobes off the principal axes could rise to levels similar to those on the principal axes. To prevent the sidelobes off the principal axes from rising to the levels of those on the principal axes, the tolerance in aperture current magnitude should be kept within 1 dB of the design value, and the phase error should be kept within 1 percent of a wavelength. Results from the Cyrus Research study[21] indicated that the above figures of tolerance would be difficult to realize in practice for a sandwich wire antenna.

The back-scan capability of the sandwich wire antenna also appears to be limited. Results from the CMC and Cyrus Research studies showed that the frequency squint range of the sandwich wire is typically 12 to 15 degrees. This would limit the ability of the antenna to scan in elevation if the antenna were used in the cocked mode. Consequently, the sandwich wire antenna will not be a suitable antenna to be employed in the tilted-antenna or the cocked-antenna modes.

4. SUMMARY AND CONCLUSIONS

4.1 Summary

The two objectives put forward at the outset of this study have been accomplished. In this section we will summarize the results of the analyses and draw some conclusions on the feasibility of employing the sandwich wire antenna in maritime surveillance radar systems.

4.1.1 Conventional modes of operation

The first objective of this study is to determine the feasibility of employing the sandwich wire antenna in existing naval surveillance radar systems. An analysis assuming a baseline signal processing capability of a naval surveillance radar system has been carried out. This baseline system includes the following signal processing functions:

(i) Frequency agility
(ii) Pulse compression
(iii) MTI filter
(iv) CFAR processor
(v) Coherent sidelobe canceller

In addition, a theoretical and experimental study has been carried out by Cyrus Research Limited on the basic properties of sandwich wire antennas. The results of these studies are summarized below:

(a) The substitution of the sandwich wire antenna in place of a conventional reflector type antenna presents some operational problems. These problems primarily result from the employment of frequency agility. The azimuthal coverage of the sandwich wire antenna when in the frequency agile mode is non-uniform unless the frequency selection is optimized. A solution to this problem has been developed. The random frequency also creates a random beam pointing direction. This random beam pointing direction could present complications in the implementation of automatic detection algorithms. In addition, the returns from contiguous pulses will be scrambled in azimuth and are incompatible with existing signal processing equipment. These problems can be solved using random access memory as a de-squinter. There is also a potential degradation in non-coherent integration gain for targets with very high velocities.

(b) There are no apparent difficulties in pulse compression operations provided that the signal bandwidth is moderate. There is also no degradation in MTI filtering performance. This is due to the fact that coherent MTI filters operate under fixed frequency conditions and therefore, beam squinting will not occur. For a CFAR processor employing range-averaging for the determination of the detection threshold, there is no apparent problems in its operation. No serious problems are anticipated in the operation of coherent side-lobe cancellers.

(c) In terms of ECCM performance, no significant change in the probability of intercept of the radar is anticipated. There is, however, a possible degradation in jamming resistance, compared with random agility, if the frequency dependent squint of the antenna is known to the enemy jammer.

(d) An important element in the feasibility study of employing the sandwich wire antenna in radar system is the basic properties of the antenna itself. Cyrus Research Limited has completed an extensive theoretical as well as experimental study[21] of the antenna. It has developed a computer-aided design procedure for sandwich wire antenna line sources of required sidelobe levels. Based on the findings of the basic property study, a sandwich wire line source having a first sidelobe of -30dB to -32 dB may be achievable in practice. It is doubtful, however, that a substantially lower sidelobe than the above figure can be realized because of the lack of direct control over the aperture current distribution. Cross-polarization performance of the sandwich wire antenna has been investigated. It is found that the cross-polarization sidelobe performance of a single sandwich wire line source is very poor. However, by pairing together two line sources having mirror image geometries and feeding with signals of opposite phase, the cross-polarization response due to the undulating line may be reduced to negligible levels. Other elements contributing to cross-polarization sidelobes are the feed point and the load geometries. Their effects may be reduced by employing shielding in those parts of the line source. Experimental results indicate that sidelobe levels equal to or better than those of a typical reflector type antenna can be designed and fabricated.

4.1.2 Possible new modes of operation

The second objective of this study is to identify and evaluate new modes of operation for the sandwich wire antenna for possible improvement of radar system performance. Several modes of operation have been identified, and an initial assessment of these has been carried out. Most of these modes of operation require radical changes and redesigning of the radar transmitter, receiver and signal processing systems.

The mode of simultaneous multiple-frequency beam forming requires parallel microwave output channels and a signal processing system capable of processing data at a rate several times that of a conventional single beam system. It therefore requires radical changes in the transmitter, receiver and the signal processing system. The extent of simultaneous azimuthal coverage is limited by the sandwich wire antenna's back-scan capability, which is approximately 12 degrees. Consequently, the possible improvement in azimuth coverage does not justify the added cost of developing new transmitters and signal processing systems. The same comments apply equally well to the wide-band FM sweep-beam mode of operation.

The look-back and burnthrough modes of operation offer only limited benefits. The rather moderate back-scan capability of the sandwich wire antenna places an upper limit on the number of pulses which can be noncoherently integrated for a given direction. Typically, a noncoherent integration gain of about 5 dB can be expected. Since in the look-back and burnthrough modes, pulses are directed to a single azimuth, the integration gain is obtained at the expense of reduced surveillance time for other azimuths.

For surveillance of a small area around the radar, the frequency squint of the sandwich wire antenna may be used to minimize the surveillance time by employing different frequencies in a pulse train, thereby permitting the monitoring of different azimuths. Multiple-time-around echos have much less effect on a frequency squinting antenna than on a conventional antenna because they will be suppressed through frequency as well as spatial filterings.

The Pseudo-monopulse mode may be employed in conjunction with the sandwich wire antenna to obtain a finer azimuthal resolution than provided by the intrinsic antenna beamwidth. However, it requires that the receivers be channelized and calibrated accurately so that the target position can be interpolated from the response of the channels. The disadvantages are a possible degradation in range resolution and complicated receiver and signal processing system designs.

Ultra-low sidelobe modes of tilted and cocked antennas, are unsuitable for the sandwich wire antenna because of the rather limited frequency squinting range and the stringent magnitude and phase control requirements of the aperture current.

4.2 Conclusions.

Based on the analyses in preceding sections and the results obtained from the investigation performed by Cyrus Research Ltd, conclusions can now be drawn with regard to the feasibility of employing the sandwich wire antenna in naval surveillance radar systems. The conclusions are the following:

(a) It is feasible to employ a sandwich wire array antenna in naval radar systems. However, several modifications to the signal processing system must be implemented. A de-squinter comprising a large random access memory with associated control circuitry is required to sort the random azimuthal returns back in natural order. The agile frequency selection must be optimized to provide uniform azimuthal coverage. The antenna must be designed properly to minimize cross-polarization response.

(b) A slightly improved azimuthal sidelobe performance may be realized in the sandwich wire array, however, it is not expected that the over-all radar system performance could be significantly better than that of a radar using a conventional reflector antenna. It is also possible that the sandwich wire array could have a weight advantage over conventional reflector antennas. This advantage, however, could be offset by the requirements of structural reinforcement and a radome in order to provide the antenna with sufficient rigidity and protection from the elements.

(c) The frequency squint of the sandwich wire antenna makes possible several unconventional modes of radar operation. However, the potential benefits from these modes appear to be limited and do not justify the expected high cost of research and development in new transmitter, receiver and signal processing system designs.

(d) In the final analysis, the employment of the sandwich wire antenna in existing naval surveillance radar system should be based on a cost and benefit analysis. It should be evaluated as a tradeoff between a slight performance improvement against the added cost of implementing the digital desquinter, the antenna radom structure, the development cost and its marketing potential.

Overall, it is concluded that the potential of utilizing the sandwich wire antenna in high performance radar operations is rather limited. The development of this antenna for conventional naval surveillance radars is feasible and has some attraction, mainly because of its light-weight and low-cost attributes. However, a thorough cost and marketing analysis should be undertaken to determine the competitiveness of a naval surveillance radar system employing such an antenna. On the other hand, the use of printed circuit techniques in the fabrication of radar antennas generally seems to be an economical way of obtaining light-weight and high performance in non-military applications. Further study to evaluate the feasibility of employing this technology in other corporate fed array configurations may offer a means of producing high performance, light-weight array antennas at low cost which are most suited to military applications.

5. ACKNOWLEDGEMENTS

This work was supported by the Department of National Defence, Canada. The author wishes to thank Mr. Gordon Marwood for the many useful discussions and the reviewing of the manuscript.

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A SYSTEM PERFORMANCE FEASIBILITY STUDY FOR A SANDWICH WIRE FREQUENCY SQUINTING RADAR ARRAY ANTENNA (U)

4. AUTHORS (Last name, first name, middle initial. If military, show rank, e.g. Doe, Maj. John E.)

CHAN, H.C.

5. DATE OF PUBLICATION (month and year of publication of document) June 1987	6a. NO. OF PAGES (total containing information. Include Annexes, Appendices, etc.) 45	6b. NO. OF REFS (total cited in document) 21

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Sandwich Wire Antenna Arrays are attractive for its light-weight and low-cost attributes. However, this class of antennas have not been used in radar systems due to its moderate power handling capability and a lack of satisfactory design procedures for low-sidelobe applications. Recently, there has been interest in employing the Sandwich Wire Antenna in surveillance radar system on small naval vessels. Design studies for sandwich wire antennas have been undertaken. Being a travelling wave antenna, the main beam of this antenna possesses a frequency dependent squint. There is concern that this squint may have adverse effect on the signal processing system designed for radar systems employing conventional antennas. In this report, a feasibility study is carried out to evaluate the effects of the frequency squint on existing radar signal processing performance. In addition, new modes of operation designed to exploit the frequency squint are also identified and evaluated.

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--A system performance feasibility study for a sandwich wire frequency squinting radar array antenna

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