Target Detection probability simulation in the homogeneous ground clutter environment

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Abstract

This paper describes target detection performance of millimeter wave radar that exits on non-stationary target detection schemes in the ground clutter conditions. The comparison of various CFAR process schemes such as CA(Cell-Average)-CFAR, GO(Greatest Of)/SO(Smallest Of)-CFAR, and OS(Order Statistics)-CFAR performance are applied. Using matlab software, we show the performance and loss between target detection probability and signal to noise ratio. This paper concludes the OS-CFAR process performance is better than any others and satisfies the optimal detection probability without loss of detection in the homogeneous clutter, When range bins increase.

Key Word : Target Detection, Radar Signal Processing, CFAR, Detection probability

Introduction

In the radar system for air-to-ground target detection such as power lines, non-stationary target signal detection in the environment of mountain condition may be a very difficult task. In such a condition, returned signal is composed of the target signal and environment clutter signal which is relatively larger than any other signals. In order to suppress the clutter, the various target detection schemes are reported by many authors[7][8][9][10][11]. These target detection schemes are mainly developed for microwave radar system, not for the millimeter wave radar system[1].

According to performing the target detection probability in the millimeter wave frequency, we need to have the millimeter wave clutter data. These are appropriate for the radar design and performance evaluation method. The Georgia Tech Research Institute has played an active role in clutter measurement data at millimeter wave frequency.

Atmospheric propagation effects dominate radar design performance relating to many MMW radar applications. Values of attenuation and backscatter due to atmospheric effects have been well established for frequency up to 100GHz. Of particular interest are effects near the attenuation minimum at 35, 94, 140 and 220GHz. So, it is important to consider these frequencies because Comparative observations on the effect of clear air, rain, and frozen hydrometers are required. Ground clutter has proven to impact significantly the effectiveness of MMW radar systems[4].

This paper shows how we define the MMW radar system parameters, according to the scenario of helicopter flight operation. These consist of the operation frequency, peak output power, detection distance, non-coherent receiver, antenna gain, target RCS(Radar Cross Section), noise figure, probability of false alarm rates, and range bin size. We explain to compare

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advantages/disadvantages between millimeter wave frequency and microwave frequency, when it adopts to design the radar system.

Returned signal in the receiver system exits on the various noise signals. We process to detect the target signal in the received signal. So, we introduce the CFAR process schemes in the homogeneous clutter environment and explain the CA(Cell-Average)-CFAR, SO(Smallest Of)-CFAR, GO(Greatest Of)-CFAR and OS(Order Statical)-CFAR process schemes.

According to definition of the radar parameters, we calculate the range cell size for helicopter mounted MMW radar system. In addition, we assume the output of envelop detector in the radar signal process has exponential distribution and homogeneous clutter background distribution in the range cell. Then, we simulate the detection probability on the various CFAR process under these assumptions and compare it between results of the optimum detection probability proposed by the P.P. Gandhi and S.A.Kassam[9] and simulation results in the various CFAR process schemes. We know that detection probability of OS-CFAR process satisfies the optimum detection probability very well.

MMW Radar System

The scenario proposed for this paper is a helicopter mounted MMW radar system that is attempting to detect the obstacles on the mountains. Fig. 1. shows the general geometry problem. A helicopter is flying over terrain with millimeter wave sensor scanning the ground ahead of obstacles. The problem has happened to detect the obstacles in the presence of atmosphere attenuation, rain attenuation, and ground clutters. At the MMW frequency, it is important to consider the environmental effects, clutter for the radar performance, and helicopter safety flight on the effects of clear air and rain. Ground clutter has proven to impact significantly the effectiveness of MMW radar systems. This frequency is advantages of high antenna gain with small aperture, high angular tracking accuracy, reduced electronic countermeasures vulnerability, reduction in multi-path and ground clutter at low elevation angle, improved multiple target discrimination and target identification, and mapping quality resolution possible. Disadvantages of component is high cost, low component reliability, low availability, short range propagation and higher attenuation[1].
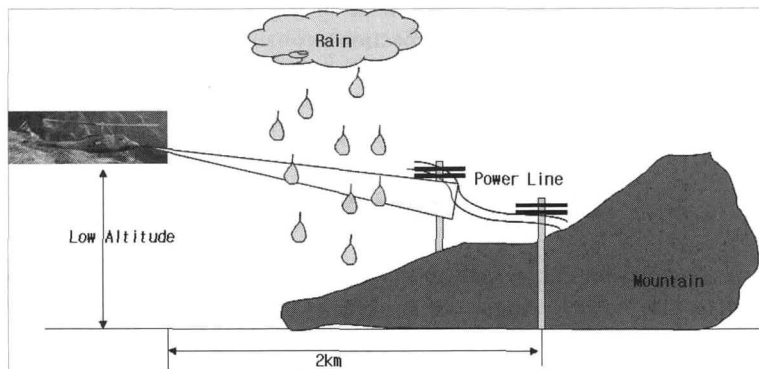

Fig. 1. Radar detection Scenario

We design the helicopter mounted millimeter wave radar system. This consist of the lens antenna, gimbal system, transmitter, non-coherent receiver, DSP(Digital Signal Processor) system, and cockpit display system. Table 1 summarizes the parameters of proposed MMW radar system. Frensnel Lens antenna used to be MMW radar system has the less side lobe than the reflector antenna. It is possible to use the 4 beam forming at the elevation angle. Antenna diameter limitation results in the aerodynamic and mounting the helicopter weight. Antenna scan rate must have azimuth -90°~+90° and elevation 26°. A raster scan pattern is envisioned in which antenna

scan from left to right. In order to transmit 2.5kW power, we use the E2V technology magnetron and solid-state modulators. Magnetron operates 2.5kW peak power at 35 ± 0.2GHz frequency. The modulator and high voltage power supply for radar transmitter are critical elements, and have to be properly specified and designed. Overall frequency stability for non-coherent systems is dependent on the performance of the modulator and power supply. Pulse width, PRF, operation voltage, current, size, and weight restricts modulator design[3].

Table 1. Radar Parameters [3]

Factors	Values	Remark
Frequency (f)	35GHz	Ka-band
Peak Power (P)	2.5kW	
Pulse Width	150nsec	
Antenna Gain (G)	>35dBi	
Beam Width	2°	
Azimuth Angle	-90° ~ +90°	
Bandwidth	7MHz	
RCS	5dBsm	Power Line
Detection Range	2km	
Probability of False Alarm Rate	10^{-6}	
Rain Attenuation	2.6dB/Km	10mm/hr
Noise Figure	<4dB	
ADC	>14bits	

Non-coherent receiver performs the single conversion system and provide the IF frequency (60MHz) to the signal process part. In the front stage of LNA (Low Noise Amplifier), STC (Sensitivity Time Control) is another gain control mode in which the gain of the receiver is varied as a function of time. SPS(Signal Processing Section) consists of 14bits ADC(Analog Digital Conversion) on PMC module, 4 Tiger SHARK DSP(Digital Signal Process)s that are performing the Non-Coherent Integration, CFAR(Constant False Alarm Rate) process, video output data, SBC module, and Digital I/O board. These are mounted in the 3U rack[2].

CFAR Process Scheme

Returned signal power from clutter and receiver noise is difficult to express mathematically . A fixed threshold detection scheme cannot be applied to the radar returned signal in individual range cells if the false alarm rate is controlled. An attractive class of schemes that can be used to overcome the problem of clutter are the constant false alarm rate (CFAR) processing schemes which set the threshold adaptively based on local information of total noise power.

Basically, the CA-CFAR processor sets the threshold by estimating the mean level in a window of N range cells. The CA-CFAR processor is the optimum CFAR processor in a homogeneous background when the reference cells contain independently. As N size increases, the detection probability approaches the optimum detector which is based on a fixed threshold.

The CA-CFAR procedure uses the maximum likelihood estimate of the noise power to set the adaptive threshold under the assumption that the underlying noise distribution has exponential distribution. This performance is affected when the assumption of homogeneous reference window is violated. This leads to serious degradation in detection probability. When a clutter edge exits on

the reference cell with target returns in the test cell, severe masking of targets results due to increase in threshold. However, if the test cell contains a clutter example, the threshold is not high enough to achieve the design of false alarm rate because the noise estimate also includes values from relatively clear background.

Modified CA-CFAR scheme has been proposed to overcome the problems associated with nonhomogeneous noise backgrounds. These split the reference window into leading and lagging parts symmetrically about the cell under test. The noise power is no longer estimated, therefore, some loss of detection in the homogeneous reference window is introduced to compare with the CA-CFAR processor. Hasen [7] has proposed the greatest of (GO) the sums in the leading and lagging windows, Moore & Laurence [8] have shown that during clutter power transitions, a mirror increase can be expected in the false alarm rate of GO-CFAR processor in the worst case. However, the GO-CFAR detector is incapable of resolving closely spaced targets.

In order to prevent the suppression of closely spaced targets, Trunk [10] proposes a SO-CFAR processing scheme, which sums the leading and lagging windows used to estimate the noise power.

Recently, OS (Ordered Statistics)-CFAR has been introduced to alleviate these problems to some degree. The ideas from the fact that OS schemes have proven very effective in rejecting impulsive noise and preserving edges in applications. The OS processor estimates the noise power simply by selecting kth largest cell in the reference window of size N. Rohling [11] has noted that the probability of false alarm of the OS processor is independent of the total noise power in the exponential noise model. The OS-CFAR processor is unable to prevent excessive false alarm rate at clutter edges, unless the threshold estimate incorporates the ordered samples near the maximum, that is unless k is very close to N, but in this case the processor suffers greater loss of detection performance.
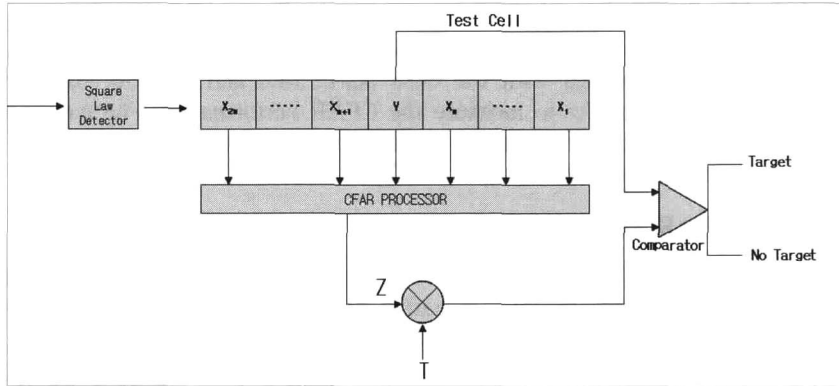

Fig. 2. Block Diagram of CFAR Process

The square-law detected video range samples are sent serially into a shift register of length N+1 = 2n+1 as shown in Fig. 2. The statistic Z proportional to the estimate of total noise power is formed by processing the contents of N reference cells surrounding the cell under investigation whose content is Y. A target is declared to be present if Y exceeds the threshold TZ. T is a constant scale factor used to achieve a desired constant probability of false alarm for a given window of size N, when the total background noise is homogeneous. In order to analyze the detection performance of a CFAR processor in homogeneous background noise, we assume that the square-law detector output for any range cell has exponential distribution with probability density function (PDF)

$$f(x) = (1/2\lambda)\exp(-x/2\lambda) \tag{1}$$

Under the null hypothesis H_0 of no target in a range cell and homogeneous background, λ

is the total background clutter-plus-thermal noise power, which is denoted by μ. Under the alternative hypothesis H_1 of present of a target, λ is λ=μ(1+S) , where S is the average signal-to-total noise ratio (SNR) of target.

We assume that a Swerling 1 mode for the radar returns from the target and Gaussian statistics for the background. We also assume that the observations in the N+1 cells, including the cell under test, are statistically independent. Therefore for the cell under test the value of λ is

$$\lambda = \begin{cases} \mu & H_0 \\ \mu(1+S) & H_0 \end{cases}$$ (2)

The optimum detector probability sets a fixed threshold to determine the presence of a target under the assumption that the total homogeneous noise power μ is known. In this probability of false alarm(P_{fa}) is given by[6]

$$P_{fa} = P[Y \rangle Y_0 | H_0] = \exp(-Y_0/2\mu)$$ (3)

Y_0 is the fixed optimum threshold. The optimum detection probability P_D^{opt} is given by

$$P_D^{opt} = P[Y \rangle Y_0 | H_1] = \exp(-Y_0/2\mu(1+s))$$ (4)

Substituting (3) into (4), we get[6]

$$P_D^{opt} = [P_{fa}]^{1/(1+S)}$$

There is an inherent loss of detection probability in a CFAR processor compared with the optimum detection performance in homogeneous noise background. The CFAR processor is able to set the threshold by estimating the total noise power within a finite reference window. The optimum processor is able to set a fixed threshold under the assumption that the total noise power is known. It is obviously of value to have some idea of the loss of detection power for a proposed CFAR processor relative to the optimum processor for a homogeneous noise background. This loss of detection probability varies with the false alarm rate and window size. There are two different methods that may employ to measure the CFAR performance. The conventional method is to compute the SNR needed for CFAR processing scheme beyond the optimum processor to employ a fixed detection probability.

CA(Cell-Average) CFAR Process Scheme

In the case of CA-CFAR processor from Fig. 3, total noise is estimated by the sum of N range cells in the reference window. This is sufficient statistics for the noise power μ under the assumption of exponentially distributed homogeneous noise background. We have

$$Z = \sum_{i=0}^{N} x_i$$ (5)

X_i is range cells surrounding the cell under test. We express exponential density to gamma density with α=1 in PDF.

$$f(y) = \beta^{-\alpha} y^{\alpha-1} \exp(-y/\beta)/\Gamma(\alpha)$$ (6)

The cumulative distribution function (cdf) corresponding to this pdf is denoted. The detection probability P_d for the CA-CFAR processor yields

$$P_D = [1 + T/(1+S)]^{-N}$$ (7)

The constant scale factor T is computed from (7) by setting S=0:

$$T = (P_{fa})^{-1/N} - 1$$ (8)

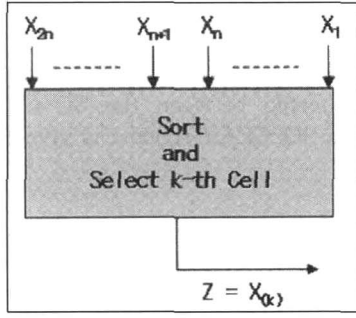It is obvious that above detection and false alarm probabilities are independent of μ.

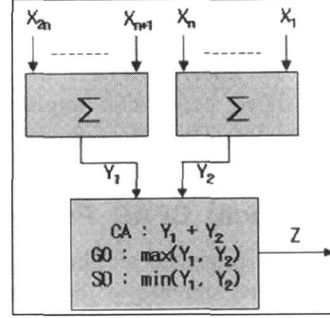**Fig. 3. Block Diagram of Mean Level CFAR**

Fig. 4. Block Diagram of OS-CFAR

GO(Greatest Of)/SO(Smallest Of) CFAR Process scheme

Excessive numbers of false alarms in the CA-CFAR scheme at clutter edge and degradation of detection probability in multiple target environments are the prime motivations for exploring other CFAR schemes that discriminate between interference and the primary targets. Two such techniques that are modifications of the CA-CFAR technique have been investigated . However, each of these schemes is capable of overcoming only one of the above two problems, with additional loss of detection power.

A modified detection scheme is proposed and known as the greatest of (GO) CFAR procedure. The total noise power estimation forms the larger of two separated sums computed for the leading and lagging window, as shown in Fig. 3.

Subheadings are in bold letters and placed flush on the left-hand margin of the column

$$Z = \max(Y_1, Y_2) \tag{9}$$

Where,

$$Y_1 = \sum_{i=0}^{n} x_i, \qquad Y_2 = \sum_{n+1=0}^{N} x_i \qquad n = N/2 \tag{10}$$

With n=N/2. In general, the pdf of Z is given by

$$f_z(z) = f_1(z)F_2(z) + F_1(z)f_2(z) \tag{11}$$

Where, f and F are pdf and cdf of random variable Y_1 and Y_2 ,respectively. For homogeneous background, the probability of false alarm is

$$P_{fa} = 2(1+T)^{-n} - s \sum_{i=0}^{n-1} \binom{n+i-1}{i}(2+T)^{-(n+i)} \tag{12}$$

Where, T is the constant multiplier which depends on the reference window size N and designs P_{fa}. The detection probability P_d is found by simply replacing T with T/(1+S) in (12).

The smallest of (SO) CFAR scheme has been introduced by alleviating the problems associated with closely spaced targets leading to two or more targets appearing in the reference cell. In the SO-CFAR scheme the noise power estimation is the smallest of the sums Y_1 and Y_2 in Fig. 3.

$$Z = \min(Y_1, Y_2) \tag{13}$$

In this case the pdf of Z is given by

$$f_z(z) = f_1(z)[1 - F_2(z)] + f_2(z)[1 - F_1(z)] \tag{14}$$

Therefore, we conclude the OS-CFAR scheme

$$P_{fa} = M_{Y1}(T/2\mu) + M_{Y2}(T/2\mu) - P_{fa}^{GO} \tag{15}$$

Where, $M_{Y1}(T)$ and $M_{Y2}(T)$ are the mgfs of Y_1 and Y_2. P_{fa}^{GO} is the GO-CFAR probability of false alarm. Above expression explains the relationship between the SO-CFAR and the GO-CFAR performance. The detection probability of the SO-CFAR scheme is given by replacing the T with $T/(1+S)$.

OS(Order Statistics) CFAR Process Scheme

Rohling[11] has proposed an alternative CFAR procedure in which the threshold is obtained from one of the ordered samples of the reference cell. The range samples are first order according to their magnitudes, and the statistic Z is given to kth largest sample.

Rohling [11] has shown that the OS scheme falls in the class of CFAR schemes for the exponential noise model. Therefore, without loss of generally we simply set $\lambda = \mu = 1/2$.

The detection probability of OS-CFAR can be expressed by

$$\begin{aligned} P_d(S) &= k\binom{N}{k} \int_0^\infty (1 - \exp(-z))^{k-1} \times \exp(-(N-k+1+T/(1+S))z)dz \\ &= \prod_{i=0}^{k-1}(N-i)/(N-i+T/(1+S)) \end{aligned} \tag{16}$$

The constant T is now a function of k. The P_{fa} is given by setting S=0 in (16). The value of T for a given k is computed by solving iteratively for fixed N and P_{fa}.

The ADT of the OS processor is given by differentiating the mgf with respect to T and expresses

$$ADT = T \sum_{i=0}^{k-1} 1/(N-i) \tag{17}$$

Where, N is number of range bins. T is the scale factor of the OS-CFAR scheme.

Result of Simulation

Based on the above calculations, we perform the simulation of the detection probability in (5), (8), (13), (16), and (17). In the simulation, the important parameter is the number of range bin.

Parameter		Operation Mode				Remark
		Mode 1 (Take-off)	Mode 2 (Cruise)	Mode 3 (Landing)	Mode 4 (Weather)	
System Parameters	Operation Freq.	35 GHz	35 GHz	35 GHz	35 GHz	
	Unamb. Range	31.25 km	31.25 km	31.25 km	125 km	c/2PRF [m]
	Detection Range	2 km	8 km	2 km	70 km	
	PRF	4.8 KHz	4.8 KHz	4.8 KHz	1.2 KHz	
	PRI	208.3 us	208.3 us	208.3 us	833.3 us	1/PRF
	Pulse-width	150 nsec	150 nsec	150 nsec	600 nsec	
	Range Resolution	22.5 m	22.5 m	22.5 m	90 m	cτ/2 [m]
	No. of Sample Data	89	356	89	778	Range / Range Resolution (총수신기)
	Sample Size	1424	5696	1424	3112	No. of Sample Data * No. of Integrated pulse (16개)
	Sampling Frequency	60MHz	60MHz	60MHz	15MHz	
	Range Accuracy	2.5 m	2.5 m	2.5 m	10 m	c/2f_{A/D}
	A/D Resolution	14 bit	14 bit	14 bit	14 bit	
	Range BIN	800	3200	800	7000	Range / ADC Range Accuracy
	Data Size	179,200 bit 22.4 KByte	716,800 bit 89.6 KByte	179,200 bit 22.4 KByte	1,568,000 bit 196 KByte	Range BIN * No. of Integrated pulse * A/D Resolution
	비고	- 4빔 - 각 빔마다 16 펄스 적분	- 4빔 - 각 빔마다 16 펄스 적분	- 4빔 - 각 빔마다 16 펄스 적분	- 1빔 - 16펄스 적분	A/D에서 DSP로 14 bit 데이터 전송에 걸리는 시간과 그 데이터를 처리하는 DSP의 계산시간이 가장 많이 소요될것으로 보임. 단, DSP에서 SBC로의 데이터 전송은 그래픽 경보 데이터로 1 range cell에 대한 결과만 전달되므로 전송속도 및 용량에는 문제없음.

Fig. 5. The number of range bin for flight status [2]

Fig. 5 shows the detail the range bin when we use to be 14bit-ADC and flight mode. We set the 1000 range bins.

From the Fig. 6, it shows the performance of detection probability in homogeneous region of CA, GO/SO, OS-CFAR schemes. And it performs the various schemes as function of primary target SNR at $P_{fa}=10^{-6}$ for different window size N.
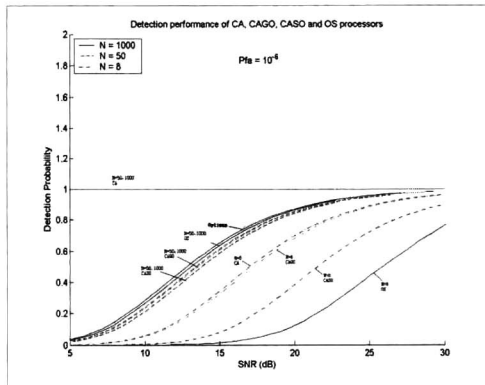

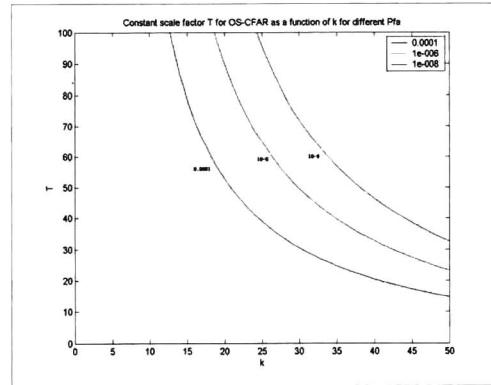**Fig. 6. Detection Probability of CA, GO, SO, and OS-CFAR**

Fig. 7. Constant Scale Factor T for OS-CFAR

As the result of simulation, the performance of OS-CFAR scheme is highly dependent on the range bin size. For small N , this scheme loss is quite large compared with CA, GO/SO-CFAR schemes. But decrease for increasing N. And other CFAR schemes except the OS-CFAR are constant value.

It is important to define the kth parameter in OS-CFAR scheme. Then, the Fig. 7 shows the value of T and ADT(Average Detection Threshold) as function of k for probability of false alarm rate. As k increases, T decreases accordingly. For higher k values, the noise estimation Z is one of the reference range samples that have relatively large magnitude.

It is clear the ADT exhibits a board minimum for larger values of k. Therefore, any reasonable k for which the ADT is relatively low may be chosen for estimating the noise power without loss of the detection performance in uniform noise background.

Conclusion

This paper performs non-stationary target detection under the homogeneous clutter, using the 1000 range bin sizes. We assume that target has swelling I mode and clutter has exponential distributions. Assumption to clutter distribution is based on the microwave measurement result. For next investigation, we will replace exponential clutter with the millimeter clutter distribution.

Considering the simulation results, we know the performance of OS-CFAR is better than any other CFAR schemes on 1000 range bins sizes. On future work, We will consider target detection in the non-homogeneous clutter background.

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