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MILLIMETER WAVE FRONT-END FIGURE OF MERIT, PART 1

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This report outlines a theoretical approach for defining and calculating a meaningful figure of merit for frequency modulated continuous wave radar systems with separate receive/transmit antennas.

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INTRODUCTION

This report presents a theoretical approach for defining and calculating a meaningful figure of merit (FOM) for frequency modulated continuous wave (FMCW) radar systems with separate receive and transmit antennas. The purpose for generating this FOM calculation was to estimate the systems's noise floor and dominant noise sources prior to hardware assembly, hence, enabling the designer to address the dominant noise sources early in their design. In the past, the noise floor was measured and addressed after the front-end was assembled, which usually resulted in redesign and a costly solution.

The FOM for FMCW systems is presented in two reports. This report, Part I, which is purely theoretical in nature, presents general definitions, descriptions, and e-quations for the FOM. The second report, Part II, will be practical in nature, providing a FOM calculator code written in MATLAB. The second report will be written in calendar year 1994.

FIGURE OF MERIT (FOM)

In a sensor development program, the Government Statement of Work usually specifies the primary target radar cross section (RCS), maximum and minimum ranges of engagement, maximum allowable false alarm rate per specified area, and counter-measure details. The remaining radar parameters are left to the discretion of the system designer. It is desirable to generate a front-end system specification which allows the radar designer as much latitude as possible. After performing simulations and determining the expected signal-to-clutter ratio (SCR) at the maximum range, based on the target RCS information and the clutter models (e.g., GTRI clutter models or measured clutter data), the designer should set the signal-to-noise ratio (SNR) greater than the signal-to-clutter ratio at the maximum detection range to assure a clutter limited system. A clutter limited system is desirable because it observes the world rather than internal system noise. The probability of false alarm (Pfa) and probability of detection (Pd) are functions of SNR. It is common to use Meyer and Mayer plots (ref 1) which tabulate and plot SNR for a range of Pfa and for four target fluctuation models. It should be noted that the Meyer and Mayer false-alarm-number is the number of detection opportunities in the interval with a given Pfa (ref 2). After determining the minimum required signal-to-noise ratio, the following radar range equation summarizes the known and unknown parameters

$$SNR = \left(\frac{\sigma \lambda^2}{(4\pi)^3 R^4} \right) \left(\frac{P_t G_r G_t}{F_n L} \right) \tag{1}$$

where

P$_t$ - Transmitter power at the transmit antenna terminals

G$_t$ - Gain of the transmit antenna

G$_r$ - Gain of the receive antenna

F$_n$ - Noise factor

L   - System losses (i.e., transmission line losses, mixer losses, etc.)

σ - Radar cross section of a target

λ - Wavelength

R   - Maximum range to the target

This equation can be divided into 2 sections. The first section is composed of the fixed parameters such as the target RCS and the range to the target which are dictated by the SOW. The wavelength is usually a function of the current technology and sensor size requirement.

The second section of equation 1 is left up to the system designer to specify. From the system point of view, the designer can specify a single value for the combination of the five parameters, which can be inserted directly into equation 1. The FOM is defined as the portion of the radar range equation which the designer has the flexibility to change. This is a valid approach which does not constrain the front-end design to a particular state-of-the-art technology, but allows any combination of these parameters as long as they meet the minimum specified level. The FOM in this report is defined in equation form as

$$FOM = \frac{P_t G_r G_t}{F_n L} \tag{2}$$

The difference between a good FOM and a poor FOM is presented in figure 1.

Consider a simple front-end block diagram (fig. 2) where all possible leakage paths are shown. From a practical point of view, the FOM can be written in the following form

$$FOM\{dBm\} = ERP\{dBm\} + G_{RF-IF}\{dB\} - N_{IF}\{dBm\} + 30 \tag{3}$$

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where

    ERP   - Effective radiated power

    $G_{RF\text{-}IF}$ - Radio frequency (RF) to intermediate frequency (IF) gain

    N_{IF} - IF noise power

    30   - conversion factor from dBW to dBm

The ERP, which is the effective power radiating from the antenna, consists of: transmitter output power, line loss between the transmitter and the antenna, and transmit antenna gain. It should be noted that the mismatch loss between the transmitter and the transmission line is embedded in the line loss, and the mismatch between the transmission line and the antenna is embedded in the antenna gain value. The expression for ERP in equation form

$$ERP\{dBm\} = VCO\{dBm\} + TX\_A\_G\{dBi\} - TX\_L\_L\{dB\} \qquad (4)$$

where

    VCO   - Voltage-Control-Oscillator (transmitter) power output

    TX_A_G - The gain of the transmit antenna which also includes the mismatch loss between the antenna and the transmission line

    TX_L_L - Transmission line loss between the transmitter and the antenna

The RF to IF gain can be expressed in equation form

$$G_{RF\text{-}IF}\{dB\} = RX\_A\_G\{dBi\} - Mx\_L\{dB\} + IF\_G\{dB\} - RX\_L\_L\{dB\} \qquad (5)$$

where

    RX_A_G - Gain of the receive antenna

    Mx_L   - Mixer RF-IF attenuation

    IF_G   - Gain of the IF amplifier

    RX_L_L - Transmission line loss of the receive channel

The IF noise power has three contributors: system noise, oscillator amplitude modulation (AM) noise, and phase noise. In equation form, the IF noise power can be described as

$$\text{IF Noise Power\{dBm\}} = 10\log(B_n(KT_s + AM\_N\_P) + Phase\_N\_P) \quad (6)$$

where

    K - Boltzmann's constant 1.38×10^{-23} J/deg

    T_s - System noise temperature in degrees kelvin

    B_n - Integrated bandwidth

    AM_N_P - AM noise power

    $Phase\_N\_P$ - Phase noise power

Blake (ref 3) defines T_s, the system temperature, as a combination of temperature contribution from the antenna, RF components between the antenna and the receiver (in figure 2 is a transmission line, mixer, and IF filter/amplifier), and receiver. For a radar system which points at the ground, the system temperature is

$$T_s = T_0 L_r F_n \quad (7)$$

and the system temperature for a radar pointing towards the sky (a cool background) is

$$T_s = T_0 L_r (F_n - 1) \quad (8)$$

where

    T_0 - Reference temperature (room temperature) 290 K

    L_r - Loss through the receive channel components (i.e. mixer, transmission line, and IF filter/amplifier)

    F_n - Receiver noise factor which is calculated using the Friis's equation

The receiver noise bandwidth B_n is defined as

$$B_n = \frac{\int |H(f)|^2 df}{|H(f_0)|^2}$$

(9)

where f_0 is the center frequency and $H(f)$ is the frequency response of the IF filter. The noise bandwidth B_n can usually be approximated by the half power bandwidth. The AM noise is defined as the spillover of the transmitted signal amplitude fluctuations into the receiver. The AM noise is usually an order of magnitude less than the frequency modulated (FM) noise; therefore, AM noise is treated as an insignificant contributor to the system noise in FMCW systems. Typical AM and FM GUNN oscillator power spectral noise densities are shown in figure 3. The open literature does not define AM noise in the form of an equation; however, one can measure the transmitter's AM noise and reduce it by the transmit/ receive path isolation. The AM noise in figure 2 can be expressed in the following form

$$AM\_N\_P = (AM\_N\_P\_M\_P) \cdot (IF\_G) \cdot (AM\_N\_P\_A\_P) \cdot (REC\_G) \quad (10)$$

where

      AM_N_P   - AM noise power spillover into the receiver {W/Hz}

      AM_N_P_M_P - Oscillator's AM noise power leakage through the mixer path {W/Hz}

      IF_G   - Gain of the IF amplifier

      AM_N_P_A_P - Oscillator's AM noise power leakage through the antenna path {W/Hz}

      REC_G   - The gain of the receive channel

The two leakage paths are shown in figure 2. The mixer leakage path, AM_N_P_M_P, consists of the transmit signal attenuated by the local oscillator (LO) coupler and the mixer's LO to RF isolation. Note, that the mixer LO to IF path is not included because the IF filter is usually designed to adequately attenuate energy outside the IF passband. The transmit-receive antenna leakage path include antenna gains and isolation between the receive and transmit antennas. The gain of the receive channel contains receive channel line loss, mixer RF to IF attenuation, and IF amplifier gain. However, the AM noise is not the dominant noise source in the FMCW systems. The phase noise, also occasionally referred to as FM noise, could be the dominant noise

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source in the FMCW radar systems if not carefully addressed in the transceiver's layout. Numerous books and articles have been written on this subject. Different oscillators produce unique phase noise characteristics where some of the contributors are: random walk FM noise, flicker FM noise, flicker phase noise, white FM noise, and white phase noise. In most cases, measurement is preferred over calculation for determining the phase noise; however, the model presented in reference 4, chapter 1, achieved adequate resemblance to measured data. This model represents an oscillator's phase noise as

$$TXPN = (\eta/2)^2 \qquad (11)$$

where

TXPN   - Oscillator phase noise

η - Modulation index (fd/fm - maximum frequency deviation over frequency modulation)

There are four paths from which phase noise can leak into the receive IF channel. The four paths are: normal transmit-receive path, direct transmit-receive antenna leakage path (surface waves and reflection from the radome), mixer LO-IF leakage path, and mixer LO-RF-IF leakage path. The phase noise contamination of the normal transmit-receive path can be ignored because the transmitter's waveform nonlinearity masks this path's phase noise. The mixer's LO-IF leakage path is also ignored because the frequency content of this path is well outside the IF filter pass band. The remaining two leakage paths are the phase noise contributors within IF filter pass band. However, the direct antenna leakage path is the bigger contributor since through this path the phase noise is amplified by both transmit and receive antenna gains. The resulting phase noise contamination at the IF receive channel due to the mixer and the antenna leakage paths is modeled in reference 4 by

$$\int_{f_{l0}}^{f_{hi}} 2\left[TXPN^n \cdot (MLP(1-Cos(w_m t_{dm})) + ALP(1-Cos(w_m t_{da})))\right] df_m$$

$$(12)$$

where

TXPN   - Oscillator's phase noise defined above [dBc/Hz]

n   - Filter's order of poles

MLP- Mixer leakage power

ALP - Antenna leakage power

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t_{dm} - Time delay through the mixer

t_{da} - Time delay through the antenna

f_{lo} - The lower limit of the IF bandpass filter

f_{hi} - The higher limit of the IF bandpass filter

CONCLUSION

The theoretical description of a FOM for an FMCW radar system with separate receive and transmit channels was presented in this report. The approach was to separate the radar range equation into two sections. One section incorporates all the system user specified parameters which are rigid, and the second section lumps the remaining parameters into a single value which the design has to exceed in order to meet the required performance. Therefore, the FOM is defined as the portion of the radar range equation which the designer has flexibility to specify. The FOM consists of the following five parameters: transmit power, transmit antenna gain, receive antenna gain, noise figure, and system loss. Any combination of these five parameters that will meet or exceed the minimum required FOM set by a system designer to achieve a clutter limited system is acceptable. This approach greatly differs from previous methods which used to reject systems based on poor performance of a single component that resulted in very challenging and costly designs. This is a more flexible approach which allows radar front-end designers more flexibility throughout the design cycle.

The second report on this FMCW FOM will present a MATLAB code and explain FOM from a practical implementation point of view. The second report will be written by the end of calendar year 1994.
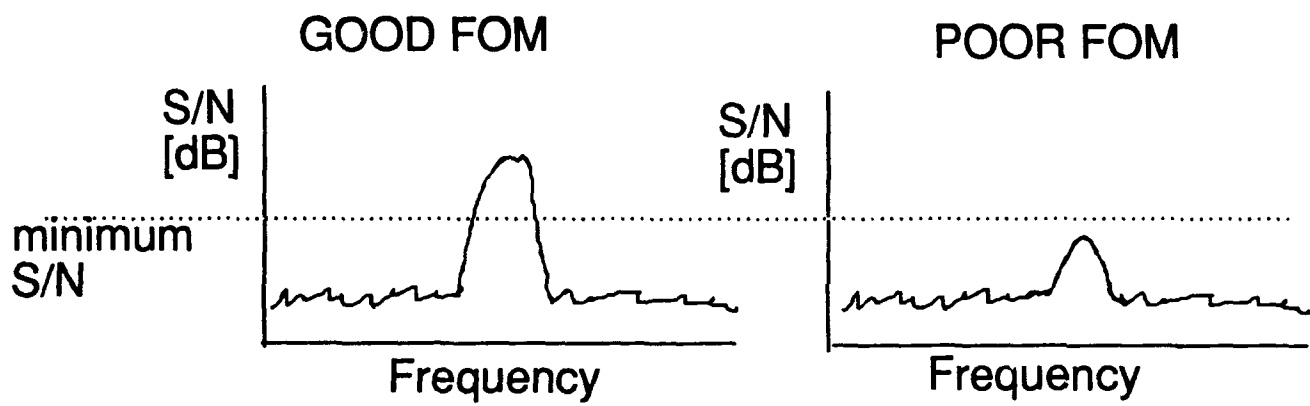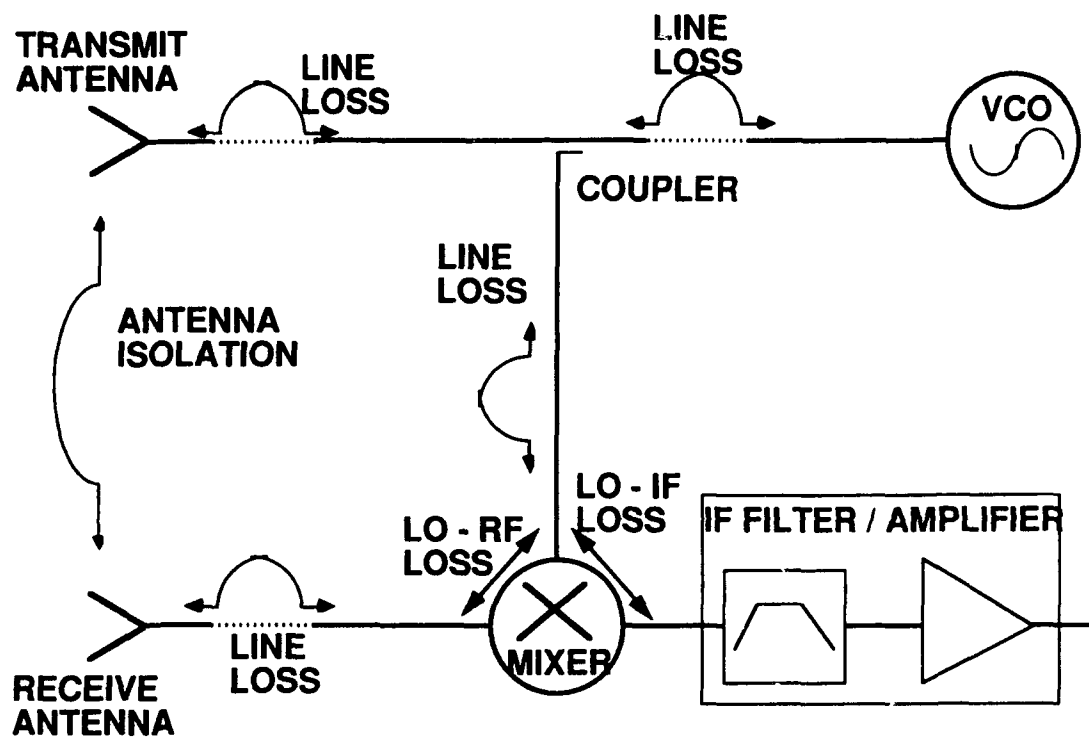
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TARGET RADAR RETURN

GOOD FOM

POOR FOM

Figure 1. Good and bad figure of merit

Figure 2.   Block diagram of a typical frequency modulated continuous wave

AM, FM GUNN Oscillator Spectral
Power Density

dBc/Hz

FM Noise

AM Noise

200K   1M

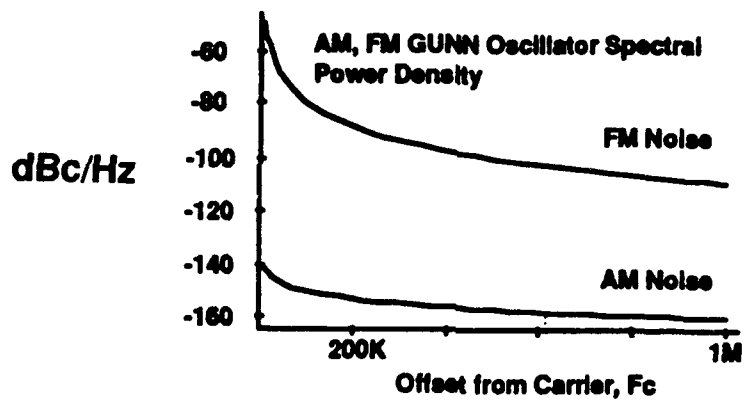Offset from Carrier, Fc

Figure 3. Typical Gunn amplitude modulation and frequency modulation power
            spectral densities

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