A MATLAB Radar Range Equation and Probability of Detection Evaluation Tool

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A MATLAB Radar Range Equation and Probability of Detection Evaluation Tool

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I have developed a graphical user interface (GUI) that makes the process of evaluating the radar range equation faster and more convenient. From this GUI, one can enter the input parameters necessary to compute the signal-to-noise ratio (SNR) and probability of detection ($P_d$) of a radar system as a function of range, and view the results graphically. The GUI and the SNR and $P_d$ computations are coded using the MATLAB programming language. I review the derivation of the equation used to evaluate the $P_d$ of a signal detected by a linear quadrature detector and provide examples of the GUI’s operation.
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1. Introduction

Evaluating the radar range equation and obtaining probability of detection \( P_d \) as a function of range are frequently useful when performing a radar systems analysis. A MATLAB graphical user interface (GUI) has been developed to do this conveniently and flexibly. Shown in figure 1, the GUI allows parameters to be entered from either the pop-up boxes, sliders, or editable text boxes. The values taken from the text boxes are used to calculate curves of signal-to-noise ratio (SNR) versus range from the radar range equation (fig. 1 (a)), and these curves are plotted as a function of range for three values of the radar cross section (RCS). A second plot of \( P_d \) (fig. 1 (b)) is generated based on the computed SNR values and a probability of false alarm \( P_{fa} \) entry. This evaluation tool, consisting of a MATLAB GUI and MATLAB code for computation, is intended to be used as a first cut for system design, since it does not have the level of detail to support an advanced study. Although it is flexible enough to support most surveillance radar designs, such as the Army Research Laboratory's (ARL's) low-cost enabling radar technology (LCERT) radar or the Yuma Proving Ground (YPG) instrumentation radar programs, it would have to be modified to address other types of radars. However, it would not be difficult to extend or modify the capabilities of this tool or to add features, such as a detailed system-loss budget including atmospheric attenuation or antenna shapes other than circular. Modifications could also be made to this MATLAB code to change the parameter computations or to read out intermediate results.
Figure 1. YPG point design results:
(a) signal to noise versus range and
(b) probability of detection versus range.
2. Graphical User Interface

The GUI is called with the command "rrefig" at the MATLAB prompt. The command "help rrefig" will print a synopsis of how to use the GUI. To use the GUI, enter the desired parameter values into either the sliders, pop-up boxes, or editable text boxes. After each entry, a new set of SNR and $P_d$ curves is computed. Since this computation takes about 3 s (almost entirely because of the $P_d$ computation), the response of the sliders may be somewhat slow. The values entered into the pop-ups or sliders are copied to the associated editable text boxes. Conversely, a value entered into an editable text box causes the associated pop-up to read "see edit box." However, a value entered into an editable text box does not cause any change in the position of the associated slider. The transmitted bandwidth and window function inputs are not used as inputs to the radar range equation. Rather, they are used to compute the theoretical range resolution that would be obtained. The example computation shown in figure 1 is based on a conceptual design for a projectile tracking instrumentation radar. The RCS values used are based on a range of generic artillery projectiles. Another example, shown in figure 2, is based on the LCERT system design.*

Figure 2. LCERT field test parameters: (a) signal to noise versus range and (b) probability of detection versus range.
3. Radar Range Equation

One can use a form of the radar range equation found in Skolnik's handbook* to obtain SNR as a function of range and RCS:

\[
SNR = \frac{P_t G_A^2 \sigma^2 G_{\text{tbr}} G_{\text{dop}}}{(4\pi)^3 kTBR^4 LN_f},
\]

(1)

where

- \(P_t\) = peak transmitted power,
- \(G_A\) = antenna gain,
- \(\sigma\) = radar cross section of target,
- \(\lambda\) = wavelength of transmitted carrier,
- \(G_{\text{tbr}}\) = time-bandwidth product gain,
- \(G_{\text{dop}}\) = Doppler processing gain,
- \(k\) = Boltzmann's constant,
- \(T\) = ambient temperature,
- \(B\) = modulation bandwidth of transmitted signal,
- \(R\) = range to target,
- \(L\) = system losses, and
- \(N_f\) = noise figure.

Although the equation is exact, the parameters used to obtain the SNR are often approximations or based on engineering judgment. Obviously, the user must apply knowledge of the problem and experience to obtain a reasonable result, and the value of this tool is that it makes this process more efficient. The details of the SNR computation may be found in the comments in the MATLAB code shown in the appendix of this report. The antenna gain is computed based on entering the diameter of a circular antenna with an efficiency of 60 percent.

---

4. Probability of Detection

In this section, I will discuss the derivation of the equation that I used to compute the $P_d$ as a function of SNR for a given $P_{fa}$. The derivations are based on course notes by Trunk* and a book by McDonough and Whalen.† I will consider the situation where an input signal $v(t)$ is processed through a linear quadrature detector, as shown in figure 3. The integral function in the quadrature detector represents a low pass filter. The output of the quadrature detector is

$$q = \left[ \left( \int_0^\tau v(t)\sin(\omega_c t)dt \right)^2 + \left( \int_0^\tau v(t)\cos(\omega_c t)dt \right)^2 \right]^{1/2}, \quad (2)$$

where $\tau = \text{measurement period}, 0 \leq t \leq \tau$, and $\omega_c = \text{carrier frequency}$. One can now postulate two possibilities for $v(t)$. It may consist only of white, Gaussian, zero-mean noise, or it may consist of a sinusoidal signal plus the noise. Thus I define two hypotheses:

$$H_0: \quad v(t) = n(t)$$
$$H_1: \quad v(t) = n(t) + A \sin(\omega_c t + \theta), \quad (3)$$

where $n(t) \sim G(0, \sigma_n^2)$,

- $\omega_c = \text{carrier frequency}$,
- $A = \text{amplitude (peak-to-peak)}$,
- $\theta = \text{random receive phase}$,
- $\sigma_n^2 = \text{variance of noise signal}$,
- $G(\cdot) = \text{Gaussian (normal) distribution}$,

and the signal-to-noise ratio of power is defined as

$$\text{SNR} = \frac{A^2}{2\sigma_n^2}. \quad (4)$$

---

(In eq (4), I define the SNR as power rather than as energy as in McDonough's definition (eq (7.32) and (7.54)). If \( r \) is normalized to equal 1 in equation (7.32), then the power for a complex signal is
\[
P = 2 \left( \frac{|A|}{2\sqrt{2}} \right)^2 + \frac{|A|^2}{2} \left( \frac{1}{2} \right)^2 ,
\]
where the factor of 2 outside the brackets is introduced for convenience, as it was in equation (7.25) of McDonough’s work.

The Neyman-Pearson criterion\(^\ast\) is typically used in radar detection problems to determine an expression for \( P_d \) for a given \( P_{fa} \). It specifies a procedure to test one hypothesis against another and is a most powerful test—\( P_d \) is maximized for a \( P_{fa} \) less than or equal to some value. To simplify the derivation, one can first assume continuous probability density functions (pdf's) for the distributions of interest. Then one can assume that the envelope of the input signal does not vary during the measurement period \( \tau \). If it had, one could still show that the test is uniformly most powerful for the amplitude and could proceed the same way. One could then compute the \( P_d \) for a target with Rayleigh fading, or for a Swerling II target when multiple coherent processing intervals (cpi’s) are integrated noncoherently. Finally, one assumes that although the phase angle \( \theta \) of the input signal is unknown, it has a uniform random pdf. Although the random variable in the signal makes \( H_1 \) a composite hypothesis, it can be integrated out, with no change in the form of the pdf for \( H_1 \), and now \( H_1 \) becomes a simple hypothesis.

One then defines the \( P_{fa} \) as the probability that a detection \( D_1 \) is declared when hypothesis \( H_0 \) in equation (3) is correct:
\[
P_{fa} = P(D_1 | H_0) = \int_T \rho_0(q) dq ,
\]
where \( T \) is defined as the detection threshold level and \( \rho_0(q) \) is the pdf associated with hypothesis \( H_0 \). Similarly, the \( P_d \) is defined as the probability that a detection \( D_1 \) is declared when the hypothesis \( H_1 \) in equation (3) is correct:
\[
P_d = P(D_1 | H_1) = \int_T \rho_1(q) dq ,
\]
where \( \rho_1(q) \) is the pdf associated with hypothesis \( H_1 \). The threshold \( T \) will be some function of \( q \) and is found by using the likelihood ratio test. This test states that you decide \( H_1 \) if
\[
\lambda(q) = \frac{\rho_1(q)}{\rho_0(q)} \geq T .
\]

To find the ratio in equation (8), one must determine the numerator and denominator pdf's. McDonough* derives the pdf of a linearly detected narrowband signal plus narrowband noise. It is known as the Rician density function, and for this problem is given by

\[ p_1(q) = \left( \frac{q}{\sigma_n^2} \right) \exp \left[ -\frac{(q^2 + A^2)}{2\sigma_n^2} \right] I_0 \left( \frac{Aq}{\sigma_n^2} \right), \]

where \( I_0 \) is Bessel function of the first kind order zero. If the signal \( q \) is equal to zero, then \( I_0(0) = 1 \), and the resulting density will be that of integrated noise, which is the Rayleigh probability density given by

\[ p_0(q) = \left( \frac{q}{\sigma_n^2} \right) \exp \left[ -\frac{q^2}{2\sigma_n^2} \right]. \]

The threshold can now be found by substituting equations (9) and (10) into equation (8):

\[ \lambda(q) = \frac{p_1(q)}{p_0(q)} = \frac{\left( \frac{q}{\sigma_n^2} \right) \exp \left[ -\frac{(q^2 + A^2)}{2\sigma_n^2} \right] I_0 \left( \frac{Aq}{\sigma_n^2} \right)}{\left( \frac{q}{\sigma_n^2} \right) \exp \left[ -\frac{q^2}{2\sigma_n^2} \right]} = \exp \left[ -\frac{A^2}{2\sigma_n^2} \right] I_0 \left( \frac{Aq}{\sigma_n^2} \right) \geq T. \]

In equation (11), only the term inside the argument of the Bessel function contains the term \( q \). So the threshold test reduces to

\[ I_0 \left( \frac{Aq}{\sigma_n^2} \right) \geq T, \]

where constants have been absorbed into \( q_t \). Since the Bessel function is a monotonically increasing function of \( q \), the ratio test can be performed as a linear function of \( q \) so that

\[ q \geq T. \]

From equation 13, one can set \( T = q_t \) and use equations (6) and (10) to find \( q_t \) in terms of a given value of \( P_{fa} \):

\[ P_{fa} = \int_{q_t}^{\infty} \left( \frac{q}{\sigma_n^2} \right) \exp \left[ -\frac{q^2}{2\sigma_n^2} \right] dq = \exp \left[ -\frac{q_t^2}{2\sigma_n^2} \right]. \]

By rearranging, one obtains

\[ \frac{q_t}{\sigma} = \left[ -2 \ln \left( P_{fa} \right) \right]^{1/2}. \]

---

Substituting equation (9) into equation (7), the $P_d$ is

$$P_d = \int_{q_1}^{\infty} \left( \frac{q}{\sigma_n^2} \right) \exp \left[ -\frac{(q^2 + A^2)}{2\sigma_n^2} \right] I_0 \left( \frac{Aq}{\sigma_n^2} \right) dq$$  \hspace{1cm} (16)

The substitution, $v = q/\sigma_n^2$, is now made in equation (16) to put the integral in the form of the Marcum Q function,* which is more convenient for calculating. Also, by using the expression for SNR in equation (4), equation (16) becomes

$$Q \left( \sqrt{\text{SNR}}, \frac{q}{\sigma_n^2} \right) = 1 - \int_0^{q_1} v \exp \left[ -\frac{(v^2 + \text{SNR})}{2} \right] I_0 \left( \sqrt{\text{SNR}} v \right) dv \hspace{1cm} (17)$$

This is the expression used to compute the $P_d$ for a given $P_{fa}$, where $q_1/\sigma$ is found from equation (15). The code used to evaluate equation (17) in terms of equation (15) is found in the appendix. It is important to note that the SNR as defined in equation (4) is lower than the definition in Skolnik† by a factor of 2 or 3 dB. The Skolnik definition is used in the MATLAB GUI so that the SNR calculated from the radar range equation matches his curves in figure 2.3 of his publication rather than McDonough’s curves in figure 7.3 of his publication. Also note that the SNR as defined above is in units of volts per volt, not decibels. In equation (1), the computation is performed in decibels. So one converts to the form used in equation (17):

$$\sqrt{\text{SNR}} = 10 \log_{10} \left( \frac{\text{SNR}_{db}}{20} \right)$$ \hspace{1cm} (18)

---


5. Conclusion

A MATLAB GUI has been developed that can be used to quickly and easily determine the SNR and $P_d$ as a function of the radar range equation parameters and the $P_{fa}$. I have used it to plot curves of SNR and $P_d$ versus range for two different radar examples: the YPG instrumentation radar and the LCERT. The equation used to compute $P_d$ as a function of SNR and $P_{fa}$ was derived using the Neyman-Pearson criterion and procedure. One could further develop the capabilities of this GUI by adding new functionality and features.
Appendix. Code for Radar Range Equation and $P_d$ GUI

% FILE: rre
% DATE: 7/19/98
%
% This function is the target of callbacks in the rrefig GUI. Radar range equation
% parameters and the Pfa are read from the editable text windows, and used to
% compute SNR and Pd as a function of SNR for the given Pfa. The values from the
% popups and sliders are read into the associated editable text boxes. After
% reading the parameters, the SNR as a function of range is computed for 3 RCS
% values. Then, the Pd as a function of range is computed based on the SNR values
% from the radar range equation. See technical report "A MATLAB Radar Range Equation
% and Probability of Detection Evaluation Tool".
% The MATLAB copy figure function does not copy the popups, sliders, or boxes.
% To copy everything in the GUI to a eps file with a tiff preview feature, use
% command "print -depsc2 -tiff <path.filename>".
%
%  trans_pwr        % Transmitter power in Watts.
%  antenna_diam     % Antenna diameter in meters
%  rf_loss          % RF system hardware loss
%  frequency        % Transmitter frequency in GHz (1 GHz = 1)
%  rcs_start        % RCS in dBsm
%  noise_figure     % Receiver LNA noise figure in dB
%  pulsewidth       % Pulsewidth in microseconds.
%  cpi_pulses       % Number pulses in coherent processing interval
%  window           % Rectangular for no window, or Hamming
%  snr              % Power signal-to-noise ratio, in dB.

% action == 1 reserved for initial conditions if required.

function rre(action)

%************ READ PARAMETER VALUES FROM GUI ********************************

% Execute this block from every action on the GUI callbacks. For popups
% and sliders, their callbacks put their values into the editable text block
% which is then read in this section.
if action ~= 1
  h = findobj('Tag', 'Freqe'); % Finds the object with the tag 'Freqe'.
  frequency = eval(get(h, 'String')); %In this case, eval is like str2num.
  % frequency = eval(get(gcbo, 'String')) used in Celsius example
  % Use code below to get value from popup; see p 3-22 of GUI manual
  % h = findobj('Tag', 'Freq');
  % value = get(h, 'Value');
  % string = get(h, 'String');
  % frequency = str2num(string(value));

  % If the action is from the frege editable text block, set the value of the
  % freq popup to "see edit box". Similarly for the other popups.
  if action == 3
    h = findobj('Tag', 'Freq');
    set(h, 'Value', 5) % Set the value of the popup, 'Freq', to 5, which is
    % "see edit box" in the string cell for 'Freq'
  end
end
Appendix

h = findobj('Tag', 'Powere');
trans_pwr = eval(get(h, 'String'));
if action == 4
    h = findobj('Tag', 'Power');
    set(h, 'Value', 6)
end

h = findobj('Tag', 'Diame');
antenna_diam = eval(get(h, 'String'));

h = findobj('Tag', 'RCSe');
rcs_start = eval(get(h, 'String'));

h = findobj('Tag', 'Losse');
rf_loss = eval(get(h, 'String'));

h = findobj('Tag', 'Nfe');
noise_figure = eval(get(h, 'String'));

h = findobj('Tag', 'Pwe');
pulsewidth = eval(get(h, 'String'));
if action == 5
    h = findobj('Tag', 'Pw');
    set(h, 'Value', 7)
end

h = findobj('Tag', 'Number');
cpi_pulses = eval(get(h, 'String'));
if action == 6
    h = findobj('Tag', 'Number');
    set(h, 'Value', 7)
end

h = findobj('Tag', 'Pfae');
pfa = eval(get(h, 'String'));
if action == 7
    h = findobj('Tag', 'Pfa');
    set(h, 'Value', 8)
end

h = findobj('Tag', 'Strt_rnge');
start_range = eval(get(h, 'String')) * 1.e3;

h = findobj('Tag', 'Stp_rnge');
stop_range = eval(get(h, 'String')) * 1.e3;

h = findobj('Tag', 'BWc');
bandwidth = eval(get(h, 'String'));
if action == 8
    h = findobj('Tag', 'BW');
    set(h, 'Value', 6)
end

h = findobj('Tag', 'Window');
value = get(h, 'Value');
string = get(h, 'String');
window = string(value);

end
% ******************* EVALUATE RADAR RANGE EQUATION *******************

c = 3e8; % Velocity of light (m/sec).
A = pi * antenna_diam ^2 / 4;
wavelength = c / (frequency * 1.e9);
antenna_gain = 10 * log10(0.6 * 4 * pi * A / wavelength ^ 2);

four_pi = 10 * log10((4 * pi)^3);

pt = 10 * log10(trans_pwr);
lambda_sq = 2 * 10 * log10(c / (frequency * 1.e9));
ktb = 10 * log10(1.38e-23 * 300 *(bandwidth * 1.e6));
t_bw_gain = 10 * log10(pulsewidth * bandwidth);
dop_gain = 10 * log10(cpi_pulses);

range = linspace(start_range, stop_range, 100);
tcs(1) = ccs_start;
delta_ccs = -10;
for ii = 1 : 3 % Loop over 3 RCS values
    snr(ii, :) = pt + lambda_sq + 2*antenna_gain + t_bw_gain + dop_gain + ccs(ii)...
        - four_pi - ktb - 40 * log10(range) - noise_figure - rf_loss;
    ccs(ii+1) = ccs(ii) + delta_ccs;
end

% ******************* EVALUATE RANGE RESOLUTION *******************

res = c /(2 * (bandwidth * 1.e6));
if window == 'hamming'
    res = res * 1.44;
end
h = findobj('Tag', 'Res');
set(h, 'String', res)

% ******************* EVALUATE Pd FUNCTION *******************

% Taken from McDonough and Whalen, "Detection of Signals in Noise", 2nd ed
% eqn 7.53

global alpha % Make alpha global to pass it to marcum_q_fn.
beta = sqrt(-2*(log(pfa)));

%snr1 = 5 : 15;
range = linspace(start_range, stop_range, 50);
rl = length(range);
for ii = 1 : 3
    for jj = 1 : rl
        alpha = 10.^(10 * (snr(ii, 2 * jj) + 3) / 20);
        % Add 3dB to SNR to match Skolnik, p2.20
        % Don't add 3dB to SNR to match McDonough, p 261.
        % Care should be taken in the use of tolerance for the integration. Larger toler-
        % will run faster, but will generate errors in Pd for small values of Pd. The
        % are not noticeable in the linear scale plots.
        pd(ii, jj) = 1 - quad('marcum_q_fn', 0, beta, [1.e-1 1.e-3]);
    end
end
Appendix

11 = sprintf('RCS = %3.0f dBsm', rcs(1)); % Use these in the legends.
12 = sprintf('RCS = %3.0f dBsm', rcs(2));
13 = sprintf('RCS = %3.0f dBsm', rcs(3));

haxes = findobj('Tag', 'Axes1');
set(haxes, 'nextplot', 'replacechildren'); % These two lines keep plots from printing
% to outer figure box.

axes(haxes)
x_lims = get(haxes, 'xlim'); % Use this to make xaxis in second plot consistent
plot(range, snr(1,:), 'k-', range, snr(2,:), 'k-.', range, snr(3,:), 'k-')
grid on; title('Signal-to-Noise vs. Range')
xlabel('Range (km)'); ylabel('Signal to Noise Ratio (dB)')
legend(11, 12, 13, 0)

haxes = findobj('Tag', 'Axes2');
set(haxes, 'nextplot', 'replacechildren');
axes(haxes)
plot(range1, pd(1,:), 'k-', range1, pd(2,:), 'k-.', range1, pd(3,:), 'k-')
axis([x_lims(1) x_lims(2) 0 1]) % Use x axis limits from first plot.
grid on; title('Probability of Detection (Pd) vs. Range (Skolnik p2.20)')
xlabel('Range (km)'); ylabel('Pd')
legend(11, 12, 13)

% FILE: marcum_q_fn.m
% DATE: 7/29/98

% Use this function as integrand to evaluate the Marcum Q
% function that provides the probability of detection for
% a single pulse out of a quadrature detector. Called from
% rre.m which calculates the radar range equation.

function f = marcum_q_fn(v)
global alpha
f = v .* exp(-(v.^2 + alpha.^2)/2).* besseli(0, alpha.*v);
Distribution

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**Authors:** Barry Scheiner

**Abstract:**
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