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Modelling and Performance Evaluation of Ground based Monostatic Radar Surveillance System

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ABSTRACT
The modelling and performance evaluation of ground based monostatic radar surveillance system presented in this paper is analysed in terms of system performance results, input data of the radar system and its operating mode. Radar equations are derived to obtain the minimum detection signal (P_{min}), system loss (L_{sys}), minimum signal-to-noise ratio $(SNR)_{min}$ and maximum detection range equation (R_{max}) respectively. Radar parameters such as transmit peak power (P_t), antenna gain (G), radar cross section (RCS), bandwidth (B), and other parameters are analysed in the radar equations. Radar system losses (L_{sys}) are accounted into the modified radar equations and calculated to be 21.1 dB. The modified radar equations with P_t = 15 kW, and R_{max} = 500 km, also gives a significantly lower value of SNR = 27.0 dB. Analysing the radar performance, MATLAB simulation program is used to evaluate the radar performance equations with different parameter values. Target detection radar signal is a difficult problem when the SNR is low, thereby causing the constant false alarm rate (CFAR) processor to adjust threshold. Simulation results are presented respectively.

Keywords
Radar System, System loss, Range and Signal to noise ratio.

1. INTRODUCTION
The concept and invention of radar, was discovered in the beginning of the 20^{th} century simultaneously in many countries such as Japan, Germany, United States, France, Italy, Netherlands and United Kingdom in the early 1920s [1]. Originally, radar was developed to meet the needs of the military services, and also the critical applications for national defence purposes [2]. Radar refers to radio detection and ranging. It is an electronic equipment that detects the presence and location of reflecting objects (targets) such as aircraft, ships, spacecraft, vehicles, people, iceberg and the natural environment by using reflected electromagnetic energy [3].

The basic radar concept is that radio frequency (RF) energy is generated by transmitting a particular type of waveform, radiated by the transmitting antenna, reflected by the target, collected by the receiving antenna and detects the nature of the returned echo signal in the radar receiver [4]. In addition, radar controls and guides, weapons, allows one class of target to be distinguished from another, aids in the navigation of aircraft and ships, and also assist in reconnaissance and damage assessment [2].

Readers can be classified as ground based, airborne, space borne or ship based and weather radar systems. They can also be classified into numerous categories based on the specific radar characteristics such as the frequency band, antenna types and waveform utilized [5,6,7]. Where a radar is based or located, will determine to a large degree the spatial coverage of the radar waves and the kind of targets it may observe or track [4]. The major categories where radar are based , are terrestrial, airborne, and space-based. In order to predict radar performance, detectable signal must be modified to include external factors. External factors affecting radar performance include: target characteristics; external noise that might enter via the antenna; unwanted clutter echoes from land, sea, birds, or rain; interference from other electromagnetic radiators; and propagation effects due to the earth's surface and atmosphere. The parametric factors affecting radar maximum equation range include noise factor, system losses, pulse integration, high pulse repetition frequencies and effect of earth reflection, atmospheric attenuation, refraction, diffraction, interference, clutter target size, receiver noise and free space loss [1, 6]. The major tool and the ability of a radar to detect the presence of a target is expressed in terms of the radar range equation with respect to its parameters.

2. REVIEW OF RELATED WORKS
Radar equation is derived from the authors [8] to obtain the equations for the minimum detection range (R_{min}) and maximum signal to noise ratio $(SNR)_{max}$ equations respectively. From the derived equations, high and low pulse repetition frequency accounted for and allocated in the radar equation. Analysing the radar performance using several choices parameters like transmit power (MW), radar cross section area (m^2), antenna gain (dB), coherent pulses (sec), duty cycle and other parameters were considered. The authors assumed and allocated values for each respective parameter with a SNR of <=80 dB, power of 65 MW, RCS 10 m^2 and minimum range of 50 km. Although system losses were not included, MATLAB simulation tool was used for analysing the radar performance for range, gain, SNR and power respectively.

Authors [9] derived radar equation to obtain equations for the R_{min} and maximum SNR respectively. Some assumed radar parameter values were allocated for P_t, radar cross section RCS and antenna gain (G) and other relevant parameters. The authors analysed the derived radar equations without accounting for any other parameters including system losses, and used MATLAB to evaluate the radar performance with respect to the parameters.

Both authors had it that the peak power has little effect on improving the detection range or SNR when compared with other radar parameters such as RCS and antenna gain, because the transmitted and received signal power is proportional to the fourth power of the range while in communication systems is proportional to square power of the range, that

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means the radar's received energy drops with the fourth power of the distance.

3. METHODOLOGY

The major tool and the ability of radar to detect the presence of a target are expressed in terms of the radar range equation. To evaluate the performance of a radar system, radar equation needs to be derived rather than just quoted because of the insight it gives into the way radar works. These equations are derived to include some main parameters such as transmitting and receiving powers, antenna gain, radar cross section, radar range and frequency from the ground based civilian monostatic aircraft radar. In this paper, Lagos, radar system parameter is considered.

3.1 Radar Performance Parameters

The radar parameters can be used to evaluate radar performance system. These parameters include: frequency (in hertz), transmit and receive powers (in watts), signal to noise ratio (in decibels), radar cross section (metres square), range (in nautical miles or metres), temperature (in Kelvin), bandwidth (in hertz), pulse width (in seconds) and antenna gain (in decibels).

The radar equation gives the range in terms of the characteristics of the transmitter, receiver, antenna, target and environments [9]. It is the basic tool for understanding radar operation. The radar has several different forms and will be derived accordingly from first principle. The radar aiming distance (R) is determined from the running time of the high frequency transmitted signal (t) and the propagation velocity (C_o) given as Equation 1 [3,4,5].

$$R = \frac{C_o \,.\, t_{delay}}{2} \qquad (1)$$

Where R is the range, distance or antenna – aim (km), t_{delay} is the two way path between the antenna and the target and C_o is the propagation velocity equals $3.0\text{x}10^8$ (m/s).

3.2 Derivation of Minimum Detectable Range and Maximum Range Equation

The detection range of a radar system is primarily a function of three parameters; transmitter power, antenna gain and receiver sensitivity [10]. Since the same antenna is used for transmitting and receiving, then we have that the gain of an antenna is also related to the capture area given by Equation 2 [4,11].

$$G_r = \frac{4\pi A_e}{\lambda^2} \qquad (2)$$

A_e is the effective antenna area as given in Equation 3

$$A_e = \frac{G_r\, \lambda^2}{4\pi} \qquad (3)$$

where λ is the wave length given as $\lambda = \frac{c}{f}$

The power density (in watt per square meter) at the distance R away from the target location from an isotropic antenna is given by

$$P_d = \frac{P_t}{4\pi\, R^2} \quad [\text{Wm}^2] \qquad (4)$$

For radar using a directive antenna with the gain of G_t, then the reflected power density of the target is given by Equation 5

$$P_d = \frac{P_t\, G_t}{4\pi\, R^2} \qquad (5)$$

The target reflects part of its energy, the measure of the amount of reflected incident power intercepted by the target and re-radiated back in the direction of the radar is denoted by the cross section (σ) [11].

$$\sigma = \frac{\text{power backscattered to radar}, P_r}{\text{power density at target}, P_d}\ (\text{m}^2) \qquad (6)$$

The reflected power from the target is given by Equation 7.

$$P_d = \frac{P_t\, G_t\, \sigma}{4\pi\, R^2} \qquad (7)$$

The power density (in watts per square meters) of echo signal back to the to the radar antenna location becomes.

$$P_d = \frac{P_t\, G_t\, \sigma}{4\pi R^2\, 4\pi R^2} \qquad (8)$$

The effective capture area of the receiving antenna is A_e, then power received becomes

$$P_r = \frac{P_t\, G_t\, \sigma\, A_e}{4\pi R^2\, 4\pi R^2} \qquad (9)$$

Putting Equation 3 into Equation 9 yields.

$$P_r = \frac{P_t\, G_t\, G_r\, \sigma\, \lambda^2}{(4\pi)^3 R^4} \qquad (10)$$

For monostatic radar the transmitting and receiving gains are equal (G_t = G_r), which implies G^2. Hence, Equation 10 becomes

$$P_r = \frac{P_t\, G^2\, \sigma\, \lambda^2}{(4\pi)^3\, R^4} \quad [\text{W}] \qquad (11)$$

Equation 11 is the minimum detectable signal radar in watts.

Figure 1 shows the radar detection performance parameters that gave rise to the Equation 11

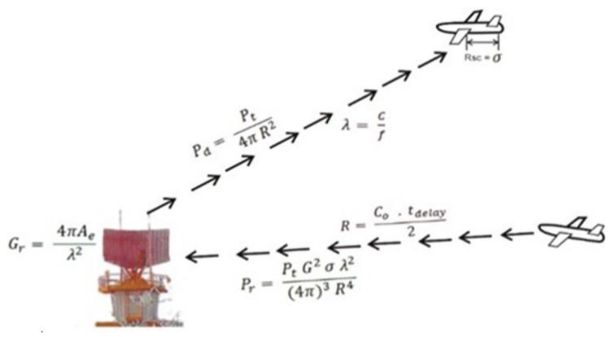

Fig 1: Radar system detection

R^4 is the distance of aim determined from the running time of the antenna high frequency transmitted signal and the propagation velocity C_o from Equation 1.

The minimum detectable signals or smallest received power that can be detected by radar is given as P_{min}. If $P_r = P_{min,}$ then the R_{max} which is the maximum distance which the target can be detected. Thus, minimum power to detect at R_{max} is given by the Equation 12.

$$R_{max} = \sqrt[4]{\left[\frac{P_t\, G^2\, \lambda^2\, \sigma}{(4\pi)^3\, P_{min}}\right]} \qquad (12)$$

Equation 12 is another form of the radar equation.. The maximum radar range is the distance beyond which the required signal is too small for the system operation [3, 5, 12].

The noise figure of a receiver is given by Equation 13. Where the receiver noise power is given as Equation 14

$$F = \frac{(SNR)_i}{(SNR)_o} = \frac{S_i/N_i}{S_o/N_o} \quad (13)$$

$$N_i = kT_sB \quad (14)$$

When $S_i = P_{min}$ and $\left(\frac{S_i}{S_o}\right) = \left(\frac{S_i}{S_o}\right)_{min}$, then minimum detectable signal, P_{min} is that value of corresponding to the minimum ratio of $(S/N)_{min}$ necessary for detection, then the minimum receive signal is thus given by Equation 20 [11,13].

$$P_{min} = kT_sBF\left(\frac{S}{N}\right)_{min} \quad (15)$$

Substituting this Equation 15 into the radar Equation 12, gives Equation 16;

$$R = R_{max} = \left[\frac{P_tG^2\lambda^2\sigma}{(4\pi)^3\, k\, BT_sF\left(\frac{S}{N}\right)_{min}}\right]^{\frac{1}{4}} \quad (16)$$

Where k is Boltzmann's constant *(1.38×10^{-23} J/K)*, T is absolute temperature in Kelvin, B is the bandwidth in hertz, F is the noise figure (unit less, linear form), and (S/N) is a minimum output signal to noise ratio in ratio.

The minimum signal to noise figure is obtained from Equation 16 to be given by Equation 17 as;

$$\left(\frac{S}{N}\right)_{min} = \left[\frac{P_tG^2\lambda^2\sigma}{(4\pi)^3R^4\, kBT_sF}\right] \quad (17)$$

3.3 Radar System Losses

Several losses of various types must be accounted for in real radar. Several radar systems experience most of these losses common to tracking system plus other losses common to only search system [14]. Losses which cannot be calculated include those due to field degradation and operator motivation [15]. These are values that are calculated to compensate for attenuation by precipitation, atmospheric gases, and receiver detection limitations.

The following losses are encountered during the radar system performance [16]: Atmospheric loss (L_a), beam shaped loss (L_{ant}), beam width factor (L_B), filter matching loss (L_m), antenna efficiency loss (L_{ef}), fluctuation loss (L_f), receive line loss (L_r), transmit line power (L_t), scanning loss (L_s), Propagation loss (L_p), Miscellaneous signal process loss (L_{sp}). The total system losses are given in Equation 18

$$L_{sys} = L_a + L_{ant} + L_B + L_a + L_s + L_f + L_t + L_r + L_m + L_{sp} + L_p + L_{ef} \quad (18)$$

The total system losses are obtained by adding the respective system losses as shown in Table 1

Table 1: Parameters system losses

Components	Symbol	Loss
Atmospheric loss	L_a	1.2 dB
Beam shaped loss	L_{ant}	1.3 dB
Beam width factor	L_B	1.2 dB
Filter matching loss	L_m	0.8 dB
Antenna efficiency loss	L_{ef}	1.2 dB
Fluctuation loss	L_f	6.4 dB
Receive line loss	L_r	1.0 dB
Transmit line power	L_t	1.0 dB
Scanning loss	L_s	2.0 dB
Propagation loss	L_p	2.0 dB
Miscellaneous signal process	L_{sp}	3.0 dB
Total losses	L_{sys}	21.1dB

3.4 Modified Radar Equation

The Equations 19 and 20 show the modified radar model equation, including system loss factor (L_{sys}).

$$R_{max} = \left[\frac{P_tG^2\lambda^2\sigma}{(4\pi)^3\, k\, BT_sF\left(\frac{S}{N}\right)_{min}L_{sys}}\right]^{\frac{1}{4}} \quad (19)$$

$$\left(\frac{S}{N}\right)_{min} = \left[\frac{P_tG^2\lambda^2\sigma}{(4\pi)^3\, R^4\, kBT_sF\;\, L_{sys}}\right] \quad (20)$$

Where T_s is the system temperature (K), S_o/N_o is minimum receiver output signal-to-noise ratio (unit less, linear form), λ is wavelength (m), P_t is transmit peak power (W), G is antenna gain (unit less), σ is radar cross section (m^2), L_{sys} is system loss in ratio (unit less, linear form) and R is the radar range (m)

Table 2 shows some of the allocated and calculated parameter values which is substituted into the modified radar Equations 19 and 20 used by MATLAB program [17] to obtain the respective radar analysis.

Table 2: AN2000STAR Primary radar performance parameters

Symbol	System Parameters	Values
S	Frequency	2.8 GHz
τ	Pulse width	7.5×10^{-6} s
σ	Cross sectional area	40 m^2, 60 m^2, 90 m^2, 100 m^2
P_t	Peak power	15 kW, 10 kW, 9 kW, 5 kW
F	System noise stability figure	15 dB
T_i	Beam time rate	3.3 ms
R	Radar distance	500 km
$(SNR_o)_{min}$	Signal to noise ratio	48.1 dB
$(SNR_o)_{min}$ + loss	Signal to noise ratio	27.0 dB

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L_{sys}	System losses	21.1 dB
G	Antenna gain	30 dB, 32 dB, 33 dB, 35 dB
B	Bandwidth	1.333 x 10^{-6} Hz
λ	Wavelength	0.1111 m
PRT	Pulse repetition time	1.0 x 10^{-04} μsec
A_e	Antenna effective aperture	1.95x10^{26} m^2
C	Speed of light	3.0x10^{08} m/s
T	Temperature	290 K
K	Boltzmann's constant	1.38 x10^{-23} J/K
	Probability of detection (Pd)	> 99 %
	False target report ratio	< 0.1 %
	Multiple target reports	< 1 per scan
	Azimuth accuracy	< 0.07°

4. RESULTS AND DISCUSION

The results of the simulated Equations 19 and 20 are as shown in the following Figures 2 to 5.

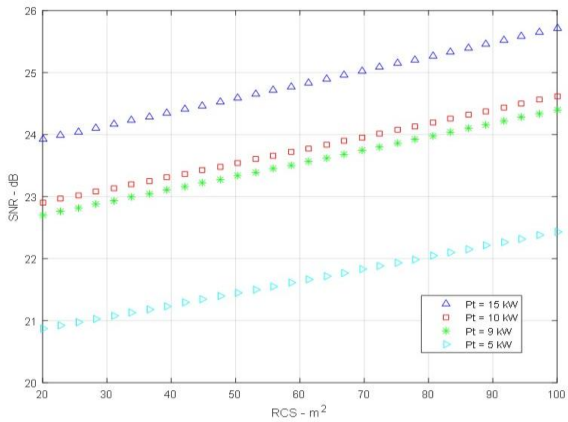

Fig 2: SNR versus detection range for different choices of transmit power

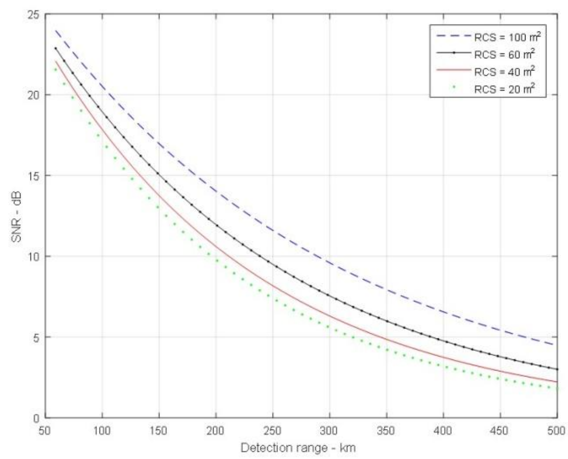

Fig 3: SNR versus detection range for several choices RCS

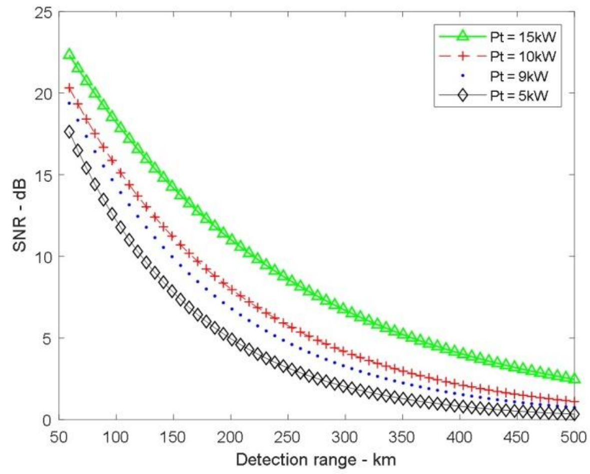

Fig 4: SNR versus RCS for several choices of transmit power

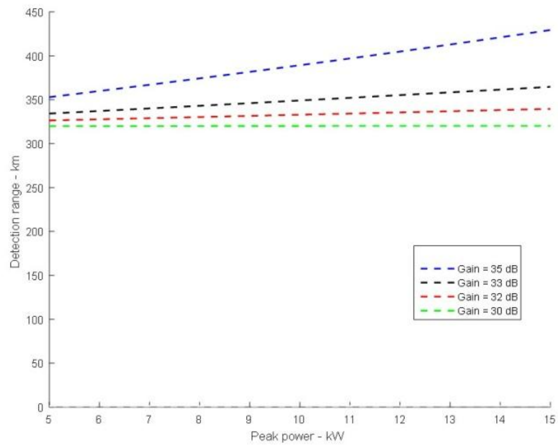

Fig 5: Detection range versus peak power with various choices of gain

Figure 2 shows the SNR plotted against detection range with different peak power. This gives an exponential increase in the detection range with increasing SNR while SNR decreases linearly with increasing detection range of different peak power values. When system loss is considered in the existing radar equation, SNR is reduced to a certain value in which, if the loss is excessive may affect the system performance. SNR is mostly a factor that affects radar performance if not properly determine. Thus affecting the probability of good detection.

Figure 3 shows an exponential increase in detection range for different RCS. With different RCS, SNR decreases exponentially with increasing detection range when plotted against detection range. In radar equation, SNR and range is a function of gain, RCS, wavelength and peak power, target (aircraft) with RCS (20 m^2) and minimum SNR of 15 dB value may still be detected with respect to the antenna gain, frequency and range.

Figure 4 shows a plot of SNR (dB) against RCS (m^2), using different peak power to determine the performance in terms of SNR. The RCS decreases linearly with a power increase as SNR increases. Considering 15 kW power as the default power for LMMIA, it shows that for a transmit power to reflect clear and strong reflected or received energy from a target under heavy atmospheric attenuation like snow or rain, the transmit power needs to be high even up to megawatt. Although power in kW still gives a strong effect on radar signal no matter the target RCS.

Figure 5 shows the detection range plotted against peak power with different values of gain. At the default gain of 35 dB, the is a clear and significant space between others, giving a better performance at a power of 15 kW as compared to other gain of 30 dB to 33 dB. But to have a significant minimum detection range the power may need to be in megawatt. Power in milliwatt is not required in radar signal transmission because low power may give low signal. Therefore, for a gain of 30 dB to 33 dB, detection power needs to be in kilowatt or megawatt.

5. CONCLUSION

MATLAB program was developed to determine detection range and SNR for the different parameters as a function of the radar range equation to analyse radar performance. The system loss L_{sys} = 21.1 dB has a significantly high value which may probably have an effect in slowing down the probability for better detection. Equation 20 has a significant effect on the radar performance with SNR_{max} = 27.0 dB. This SNR value is considered low. Hence, with the SNR low, target detection radar signals become a difficult problem. Constant false alarm rate processors are typically used in radar applications. CFAR processors are suitable for targets with large enough SNR. Consequently, for such targets the CFAR processor can set the detection threshold higher, and will miss low-SNR targets. Finally, there is the need to eliminate excessive losses from the radar system.

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