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A GLOBAL APPROACH TO OBJECTIVE EVALUATION AND COMPARISON OF POTENTIAL PERFORMANCES OF RADAR SYSTEMS

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ABSTRACT: The classical approach to objective evaluation of radar performance utilizes appropriate forms of radar range equation to compute the radar range versus different detection probabilities for a given false-alarm probability. This approach implies full prior knowledge of radar system parameters, losses, and signal processing as well as accurate specification of the environment, whether it is a clear or an ECM one. The classical approach involves heavy computations and analysis and the evaluation is environment dependent. The present paper generalizes an approach started by Nengjing in 1985 for deriving formulas for calculation of radar anti-clutter, anti-jamming, and generalized ECCM capabilities. This new approach avoids most of the problems encountered by the classical one and facilitates comparison of radars with different structures but are candidates for same application. The present paper provides more comprehensive objective evaluation of the potential radar performance with better precision of the expressions for the quality levels. A procedure for assigning technical weights to radars in competition is suggested. Examples are given to show the potential of the proposed global approach.

I-Introduction

During the last 25 years, radar systems have been subjected to continuous improvement of the technologies applied in their production and to continuous upgrading of their functions and capabilities. Therefore, radar system evaluation has become extremely important to radar designer, radar manufacturer, radar procurer, and radar-threat evaluator. Like any system evaluation, radar system evaluation comprises technical performance evaluation and reliability evaluation. The latter is function of the technologies applied, the radar system configuration, and the measures adopted for total quality management TQM. During the design phase reliability evaluation is an estimate based on a reliability model devised by a radar system analyst. Exact reliability evaluation implies recording the radar system failures over very large number of operating hours. Although reliability evaluation is very important to radar system procurer, it is of no concern to radar-threat evaluator.

There are two types of technical performance evaluation: objective evaluation and subjective evaluation. The latter is based on testing the radar system performance in clear and ECM environments. It is usually carried out by the radar system procurer and by the manufacturer for radar proto-types only. Although most radar system procurers prefer subjective evaluation to objective evaluation, the former has some shortcomings. It is always scenario (test procedure) dependent. In order to derive reliable conclusions, it is necessary to run many scenarios (tests) whose costs are often unaffordable by the procurer or the manufacturer. Moreover, subjective evaluation is inappropriate for both radar designer and radar-threat evaluator. On the other hand, objective evaluation is always based on calculating or measuring several performance indices. It

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is always carried out by skilled radar system analysts and is appropriate for the designer, the manufacturer, the procurer and the threat evaluator. Although objective evaluation is far more difficult than subjective evaluation, it is far cheaper.

This paper is concerned with the objective performance evaluation of military radar systems. The classical approach to this task [1]-[5] assumes full prior knowledge of radar system parameters, losses, and signal processing as well as accurate specification of the environment whether it is a clear or an ECM one. Appropriate forms of radar range equation are utilized to compute the radar range versus different detection probabilities for a given false alarm probability. This classical approach has obvious problems: (i) a large amount of data needs to be known apriori, (ii) heavy computations and analysis are necessary in the case of dense environment and sophisticated signal processing, and (iii) the evaluation is environment dependent.

An ECCM improvement factor EIF was introduced by Johnston [6] as a measure representing the performance of an ECCM technique in the analysis of radar performance in an EW environment. EIF is defined as the ratio in dB of the ECM signal required to cause a desired effect on the radar using ECCM to the ECM signal level causing the same effect without ECCM. Substituting EIFs for different ECCM techniques reduces the computations and the analysis implied by the classical objective evaluation. Generally, EIF has the advantage of being available for different types of ECM and ECCM, but it can only measure the effectiveness of an ECCM device or a string of ECCM devices and can not measure the ECCM capability of the whole radar system. Some of the radar technical parameters such as transmitted power and antenna gain are important for determining the ECCM capability of the whole system although they are not regarded as radar ECCMs. Moreover, in modern radars the implementation of ECCMs is not only explicit in the form of separate fixes (devices) like in early radar designs but also implicit in the form of certain design features provided in different parts of the radar and for which the calculation of EIFs is not a straight forward task.

To avoid the above problems of classical approach to objective evaluation of radar performance, the radar designers started another approach based on defining for every radar application a set of design features, determining for every design feature its first order dependence on the radar system parameters and finally extracting from these dependencies a set of figures of merits [7, Tables 4-2, and 4-5], [8]. This facilitates the comparison of radar sets with different structures but assigned to the same application. Within the frame of this second approach Nengjing [9] derived formulas for calculation of radar anti-clutter, anti-jamming and generalized ECCM capabilities. The fundamental part of these formulas consists of the technical parameters of the radar set and represents the radar potential ECCM capability. The supplementary part of these formulas, expressed in terms of characteristic specifications of the radar ECCM devices, represents the quality levels of these devices. Thus ECCM capabilities of different types of radar sets or different designs of a radar can be compared. In the process of design and/or technical upgrading the cost-effectiveness ratio of adding ECCM devices can be analyzed with the aid of the formulas in [9]. Johnston [10] appreciated Nengjing's idea of making a comparison of the total ECCM capabilities of different radar sets. Yet, Johnston [10] presented a large number of comments on [9] which can be divided into three groups. The first group of comments is most probably motivated by the fact that Johnston was completely biased to the classic approach to objective evaluation of radar performance. The second group of comments point out several important issues ought to be addressed by Nengjing. In the last group, Johnston shows that some of the expressions derived in [9] for quality levels of the supplementary ECCM devices are imprecise.

The present paper is a generalization of Nengjing's paper [9] but provides more comprehensive objective evaluation of military radar performance with better precision of expressions of quality levels. It addresses most of the issues pointed out by Johnston [10].

II- Modified Figures of Merits for Intrinsic Anti-Passive and Anti-Active ECM Capabilities

In [9], it is implicitly assumed matched Doppler filtering and mechanical antenna scanning are used. It is shown that in the presence of interference from chaff (passive ECM), the output signal-to-clutter ratio $(S/C)_o$ can be expressed as.

$$(S/C)_o = K_1(T_0 B_s G), \tag{2-1}$$

where K_1 is a coefficient determined by the target cross-section and the chaff environment, T_0 is the dwell time on the target, B_s is the radar receiver bandwidth, and G is the radar antenna gain. It is pointed out in [9] that the radar range and Doppler resolutions are respectively measurable by B_S and T_0 whereas the spatial (directional) resolution is measurable by G. For example, the larger T_0, the better is the Doppler resolution. It follows from (2-1) that a figure of merit for the radar intrinsic anti-clutter capability is the product $T_0 B_s G$. Note that (2-1) is valid for spot chaff, but for chaff cloud or corridor it should be modified as

$$(S/C)_O = K_1(T_0 B_s G \overline{Q}), \tag{2-2}$$

where $\overline{Q}$ is the average side-lobe gain defined as the inverse of the average side-lobe level (normalized to peak directive gain). Hence the figure of merit for the anti-clutter capability should be $T_0 B_s G \overline{Q}$. It is also shown in [9], that in the presence of main lobe spot noise jamming on the considered radar, the output signal-to-noise jamming ratio can be expressed as

$$(S/J)_o = K_2(\overline{P} T_0 B_s G), \tag{2-3}$$

Where K_2 is a coefficient determined by the target cross-section, range and noise jamming and $\overline{P}$ is the average transmitted power. Clearly, a figure of merit for the radar anti-jam capability is the product $\overline{P}T_0 B_s G$.

In [8], it is shown that a performance figure of merit for electronically scanning search radars, in heavy barrage noise jamming, is the average power-sidelobe gain product. Likewise, for a track system the figure of merit is the average power-antenna gain-sidelobe gain product. Therefore, for a radar which must provide good search and track performance in heavy jamming, average power $\overline{P}$ should be maximized, average sidelobe level should be minimized, and the antenna gain should be maximized. The last two conditions imply the use of the largest physical aperture and the highest frequency possible.

In [7, pp. 423-425], it is shown that for effectiveness of repeater deception against a victim radar, two inequalities should be simultaneously valid

$$G_{rep} \geq \frac{4\pi\,\sigma L_p^2}{\lambda^2\,\beta^2}\,, \tag{2-4}$$

$$\frac{P_T\,G\,L_p\;\alpha\,\sigma}{4\pi\;R^2\;G_{JT}\;\beta^2\;L_T} \leq P_{rep\,max}\,, \tag{2-5}$$

where G_{rep} is the repeater gain, α is a constant dependent on both the adopted deception technique and the radar type, ($\alpha\;\approx 7-10$ dB), σ is the average radar cross-section of the protected target, λ is the wavelength, L_p is a loss factor due to polarization mismatch between the radar set and the repeater antennas, β is the repeater duty cycle of gated repeater, P_T is the peak transmitted signal power, L_T is the radar system loss on transmission, R is the range of the protected target from the radar, G_{JT} is the repeater transmitting antenna gain and $P_{rep\,max}$ is the power output of a saturated repeater. Inequality (2-5) can be rearranged as

$$R^2 \geq \frac{\sigma}{P_{rep\,max}\;G_{JT}\;B^2}\cdot\frac{\alpha\,L_p}{4\pi\,L_T}\cdot\frac{\overline{P}\,G}{\delta}\,, \tag{2-6}$$

where $\overline{P} = P_T\,\delta$ and δ is the radar transmitter duty cycle. It follows from (2-4) and (2-6) that a figure of merit for the radar immunity to repeater deception is $\overline{P}G/\delta$. Inequality (2-6) indicates that radar set with pulse compression (large δ), are easier to be deceived by repeaters than radar sets without. In [7. P.293], it is mentioned that radar sets with linear FM pulse compression are vulnerable to repeater deception. Adding an appropriate fixed frequency shift to the repeated waveform causes the compressed pulse to be advanced so that it occurs before the actual target pulse.

Let us now study the immunity of a radar to interception. Assume that the maximum range at which the radar can detect the platform (aircraft) carrying the ESM system is R_r. In this case, we have

$$P_{min-r} = \overline{P}\,G^2\,\sigma\;\lambda^2\,/(4\pi)^3\;R_r^4\;\delta\;L_T\;L_r\,, \tag{2-7}$$

where P_{min-r} is the radar receiver operational sensitivity and L_r is the radar system loss on reception. Likewise, let R_{ESM} be the maximum range at which the ESM system can detect the radiation of the radar set. Hence we can write

$$P_{min-ESM} = \overline{P}\,G\,G_{ESM}\;\lambda^2/(4\pi)^2\;R_{ESM}^2\;\delta\;L_T\;L_p\,, \tag{2-8}$$

where $P_{min-ESM}$ is the ESM receiver operational sensitivity. From (2-7) and (2-8) we deduce that

$$R_r = \sqrt[4]{\overline{P}\,G^2\sigma\,\lambda^2\;/\;(4\pi)^3\delta\;L_T\;L_r P_{min-r}}\,, \tag{2-9}$$

$$R_{ESM} = \sqrt{\overline{P}\, G G_{ESM} \lambda^2 \; / \; (4\pi)^2 \delta\, L_T\, L_p P_{min-ESM}} \;. \tag{2-10}$$

For the radar to detect the aircraft first, it is necessary that $R_r > R_{ESM}$, or equivalently

$$\frac{\overline{P}\, G^2 \sigma \lambda^2}{(4\pi)^3\, \delta\, L_T\, L_r\, P_{min-r}} > \frac{\overline{P}^2\, G^2\, G_{ESM}^2\, \lambda^4}{(4\pi)^4\, \delta^2\, L_T^2\, L_p^2 \left(P_{min-ESM}\right)^2}, \tag{2-11}$$

$$\overline{P} < (4\pi\, L_p^2\, L_T / L_r)\, (P_{min-ESM} / G_{ESM})^2\, (\delta / \lambda^2\, P_{min-r}). \tag{2-12}$$

Thus for a given average transmitted power of the radar, a figure of merit of its immunity to ESM is $\delta \big/ \left(\lambda^2\, P_{min-r}\right)$. The radar has the advantage of decreasing P_{min-r} through matched filtering and coherent integration. Generally, P_{min-r} can be expressed as

$$P_{min-r} = K\, \tau_o\, B_n (S/N)_{min}\, F_n \;, \tag{2-13}$$

where K is the Boltzman's constant, τ_0 is absolute room temperature in degrees Kelvin, B_n is equivalent noise bandwidth of the receiver $(\approx B_s)$, $(S/N)_{min}$ is minimum operational signal-to-noise ratio and F_n is the receiver noise figure. Notice that $K\, \tau_0 = 4.10^{-21}$ Joule and for convenience we may take $(S/N)_{min} = 1$. Hence the figure of merit for immunity to ESM reduces to $\delta / \left(\lambda^2\, B_s\, F_n\right)$.

It follows from the above discussion that a figure of merit of the anti-passive ECM capability should be a least common multiple of $(T_0\, B_s G\, \overline{Q})$ and $(\delta \,/\, \lambda^2 B_s F_n)$. Thus we can write

$$AP - ECM = T_0\, G\, \overline{Q}\, \delta / \, F_n \;. \tag{2-14}$$

Similarly the anti-active ECM capability should be a least common multiple of $(\,\overline{P}T_0 B_s G \overline{Q})$, $\left(\overline{P}\, G / \, \delta\right)$ and $\left(\delta / \, \lambda^2\, B_s\, F_n\right)$; i.e.

$$AA - ECM = \overline{P}\, T_0\, G\, \overline{Q} / \, F_n \;. \tag{2-15}$$

Adopting the constant side and backward lobe level of a Chebyshev antenna design as an estimate of $\left(\overline{Q}\right)^{-1}$ in non-Chebyshev antenna design of same azimuth beamwidth θ_b and d / λ ratio, (d is the antenna linear dimension in azimuth) we derived the following simple estimate of $\overline{Q}$ as a straight line approximation of the curve presented in [11, p.325, Fig. 7.52], where θ_b to be substituted in degrees,

$$\overline{Q} = 1.25[\theta_b (d/\lambda) - 36.4], \quad [dB]. \tag{2-16}$$

III Quality Factors Associated with Design Features of a Single Radar Transmit-Receive Channel

Expressions (2-14) and (2-15) account for the theoretical radar anti-passive and anti-active ECM capabilities. Yet, the way the radar set is designed influences its final performance. In this section we enumerate radar design features, not considered in (2-14) and (2-15), and define appropriate quality factors in order to have more comprehensive evaluation of the radar performance.

It is well known that the detection performance of a radar is strongly dependent on the system losses both on transmission L_T and on reception L_r. The anti-clutter performance improves as the carrier frequency instability Δf decreases [7, p.266, Table 4-2]. The image frequency rejection IMR in the mixer as well as the single signal spur-free dynamic range DR should also be considered. A typical value of the former is 80 dB and of the latter is 70 dB. Thus an appropriate definition of the mixer quality factor is

$$q_{mix} = (IMR - 80) + (DR - 70), \qquad [dB]. \tag{3-1}$$

An MTI quality factor is defined in [9] as

$$q_{MTI} = I - 25, \qquad [dB]. \tag{3-2}$$

where I is the MTI improvement factor (incorrectly defined in [9] as the subclutter visibility). If we consider both ground and weather clutter, the typical average value of I is 25 dB. Comparing the performances of coherent and non-coherent integration techniques it is convenient to define an integration quality factor q_{int} which takes on a value of one for non-coherent integration and a value of two for coherent integration.

In section II, it has been shown that a figure of merit for radar immunity to repeater deception is $\overline{PG}/\delta$. The way the radar set is implemented allows further discrimination between short pulse, FM pulse compression, and phase coded pulse compression radars regarding their immunity to repeater deception. For this purpose we proceed in a qualitative way. Consider the comparisons presented in Tables 1 and 2 where the initials LPI stand for low probability of intercept, "1" denotes affirmation and "0" denotes negation. The entries provided in Tables 1 and 2 (first three rows) are based on the information provided in [7] about pulse compression and LPI radars. From Tables 1 and 2, we can define a quality factor q_{rep} expressing the relative differences in immunity to repeater deception as indicated in Table 3.

Regarding radar antenna design, we have already pointed out in section II the importance of the average side lobe gain $\overline{Q}$. Antenna polarization is also an important design feature which should be considered. Changing the antenna polarization from linear to circular enhances the signal-to-precipitation (or chaff) ratio by about 10-35 dB but causes a signal detection loss SDL of about 2.5 dB [3, pp. 504-506]. Therefore, it is convenient to associate with the type of antenna polarization two factors :

linear polarization : $q_p = 0$ dB, SDL $= 0$ dB, (3.3 a)

circular polarization : $q_p = 22.5$ dB, SDL $= 2.5$ dB. (3.3 b)

Another important antenna polarization parameter, particularly in angle tracking radars, is the level of the cross polarization pattern with respect to the antenna main polarization pattern. A good measure of the radar immunity to cross polarization jamming [7, pp. 152-154, 248] is the cross polarization gain factor q_{cp}, defined as the inverse of the cross polarization level (normalized to peak directive gain of the main polarization antenna pattern). A typical value of q_{cp} is 30 dB. Type of scanning is a third antenna design feature. In [7, p.274], it is mentioned that if the radar beam is frequency scanned the enemy can precisely determine the radar's transmission frequency from a knowledge of the radar beam location. This leads to a spot jamming ECM situation, which favors the jammer over the radar. The phase scanning approach (which is compatible with frequency agility) is preferred to the frequency scanning approach in several of the more modern designs. It is appropriate to define a quality factor q_{scan} which equals one for mechanical and phase scanning types and $1/q_A$ for frequency scanning type where q_A is the quality level of immunity provided by carrier frequency agility (section IV). Expressions (2-14) and (2-15) can be modified as

$$AP-ECM=\left(\delta T_0\ G\ \overline{Q}/F_n\right)\left(q_{mix}\cdot q_{MTI}\cdot q_{int}\cdot q_p/L_r\Delta f\right), \quad (3\text{-}4)$$

$$AA-ECM=\left(\overline{P}\ T_0\ G\ \overline{Q}/F_n\right)\left(q_{mix}\cdot q_{rep}\cdot q_{int}.SDL.q_{cp}/L_T L_r\right). \quad (3\text{-}5)$$

IV- Quality Factors Associated with Supplementary ECCM Devices

A- Carrier frequency agility:

The frequency agility of a radar can be countered by a barrage noise jammer, a responsive jammer or an ELINT device. A barrage noise jammer transmits a broadband noise whose spectrum is even spread over the span B_I of radar carrier frequency agility. Some times the span B_I is shared between two or more noise jammers. A responsive jammer intercepts the radiation from the radar and is expected to measure the radar carrier frequency within a fraction of the interval T_f during which the carrier frequency is temporarily fixed, and quickly re-centers the spot noise jam spectrum to be effective within the rest of the interval T_f. The shorter T_f, the tougher are the speed requirements on the responsive jammer. By recording the radar transmission over a long time interval, an ELINT device might acquire the sequence according which the value of the carrier frequency is changed. If this happens, the ELINT device is able to correctly predict the next value of the carrier frequency and to synchronize the jammer accordingly. There is no loss of generality to assume that the above three types of ECMs are equally probable. Before presenting a new ad-hoc expression for the quality level of immunity provided by frequency agility, we point out that if the pulse-to-pulse carrier frequency difference is always $\geq B_s$, the signal detection is enhanced due to 7 dB saving in the required SNR [12, p.24.]. Now we can write :

(i) Immunity to barrage jamming $= n_A = \min\left(N_A\,,\ B_I/B_s\right)$, (4-1)

where N_A is the number of selected (active) values of agile carrier frequency.

(ii) Immunity to responsive jamming $=\min[n_A(\Delta_{rj}/T_f)+1-(\Delta_{rj}/T_f),\ n_A]$, (4-2)

where Δ_{rj} is the time needed by the responsive jammer to measure and retune to the radar carrier frequency which periodically changes every T_f. If $\Delta_{rj} < T_f$, the best strategy for the responsive jammer is to radiate barrage noise during Δ_{rj} and accurate spot noise during $T_f - \Delta_{rj}$. If $\Delta_{rj} > T_f$ the responsive jammer will be radiating barrage noise all the time.

(iii) Immunity to an ELINT device $=\min[n_A(L/MD)+1-(L/MD),\ n_A]$, (4-3)

where $L = N_c\,T_f$, N_c is the number of frequency changes in a code sequence , and MD is a single mission duration of the radar. If L<MD the best strategy for the jammer is to radiate barrage noise jamming during the interval L in which the ELINT device is recording the code sequence, and to radiate during MD-L a spot noise whose frequency is changed according to the acquired code. Combining (4-1)-(4-3) we finally obtain

$$q_A = \frac{\psi}{3}\left\{n_A + \min\left(n_A \frac{\Delta_{rj}}{T_f} + 1 - \frac{\Delta_{rj}}{T_f},\ n_A\right) + \min\left(n_A \frac{L}{MD} + 1 - \frac{L}{MD},\ n_A\right)\right\}, \tag{4-4}$$

$$\begin{aligned} \psi &= 4 \text{ for pulse- to- pulse carrier frequency difference} \geq B_s, \\ &= 1 \text{ otherwise}. \end{aligned} \tag{4-5}$$

B- PRF stagger (PRI agility):

The PRI agility of a radar can be countered by a random repeater, a smart noise jammer, or an ELINT device. A random repeater re-radiates the intercepted radar pulses after random delays such that the separation between two successive pulses in the resultant pulse stream will be a random variable uniformly distributed between PRI_{min} and PRI_{max}. A smart noise jammer scans the intercepted pulses, identifies pulses belonging to same radar and measures the PRI from the last two of these pulses. Then it estimates the time of arrival of the next radar pulse to synchronize the radiation of a cover pulse of noise jamming. An ELINT device can from a long record of radar transmission acquire the code sequence governing the change of the radar PRI. If it succeeds in doing so, it will be able to correctly synchronize the false target generator. An ad-hoc expression for the quality of the immunity provided by PRI agility can be constructed in a manner very similar to that followed with carrier frequency agility. Therefore we write :

(i) Immunity to random repeater $= n_{stag} = \min\left(N_{stag},\ \frac{PRI_{max} - PRI_{min}}{pw}\right)$, (4-6)

where N_{stag} is the number of selected values of agile PRI and pw is the pulse width.

(ii) Immunity to smart noise jammer $= n_{stag} \mid N_{fPRI} + 1 - \frac{1}{N_{fPRI}} = 1 + (n_{stag} - 1) / N_{fPRI}$, (4-7)

where N_{fPRI} is the number of successive occurrences of same PRI.

(iii) Immunity to an ELINT device $= \min\left(n_{stag} \frac{L_{stag}}{MD} + 1 - \frac{L_{stag}}{MD},\ n_{stag}\right)$, (4-8)

where L_{stag} is the duration of the code governing the change of PRI. From (4-6)-(4-8) we deduce that

$$q_{PRI} = \frac{1}{3}\left\{n_{stag} + \frac{n_{stag} - 1}{N_{fPRI}} + 1 + \min\left[n_{stag} \frac{L_{stag}}{MD} + 1 - \frac{L_{stag}}{MD},\ n_{stag}\right]\right\}. \tag{4-9}$$

C- Simultaneous carrier frequency and PRI agilities:

In this case whenever a PRI change occurs, Δ_{rj} increases by no more than PRI_{max} - PRI_{min} only for a single measurement of the carrier frequency and returns to its original value in the following N_{fPRI} -1 measurements. Thus an average Δ'_{rj} can be expressed as

$$\Delta'_{rj} = \Delta_{rj} + (PRI_{max} - PRI_{min}) / N_{fPRI} , \qquad (4\text{-}10)$$

and should be substituted for Δ_{rj} in (4-4). Similarly, due to carrier frequency agility, the PRI measurements will be delayed by Δ_{rj} in a single measurement every T_f. Thus on the average PRI measurement is increased by a factor $\left(1+\frac{\Delta_{rj}}{T_f}\right)$. Consequently the term $(n_{stag} - 1) / N_{fPRI}$ in (4-9) should be multiplied by $\left(1+\frac{\Delta_{rj}}{T_f}\right)$.

D- Constant false alarm rate CFAR processing :

CFAR processing is not of the same category as other ECCMs that can enhance the signal - to - interference ratio [3, p.550]. It does not permit detection of any more targets. Although it is commonly agreed that the primary benefit of CFAR processing is in reduction of scope clutter and in reduced false targets passed to the computer [3], [10], we point out that a properly designed CFAR processor can slow down the degradation of the radar detection performance in an ECM environment. In this sense, CFAR processing can be regarded as a survivability enhancement ECCM technique. Evaluation of ECCM quality of a CFAR processor is not a straightforward task. We processed as follows :

(1) We note that inclusion or exclusion of CFAR processing affects the false - alarm rates of receiver at different levels of mean power of input noise. Hence, it is not possible to apply the Neyman - Person criterion for comparing the detection probabilities of the receiver, with and without CFAR, at different levels of input noise. We can adopt instead a decision reliability measure,

$$R = 10\log_{10}\frac{PD(1-PFA)}{(1-PD)PFA}, \quad [dB] \qquad (4\text{-}11)$$

where PD and PFA are respectively the detection and the false-alarm probabilities. The term decision reliability appeared for the first time in the context of optimum binary decision fusion [12]. An alternative performance measure which is also suitable for our case is the decision contrast

$$C = 10\log_{10}\frac{PD-PFA}{\sqrt{PFA-(PFA)^2}} . \qquad (4\text{-}12)$$

(2) Assume that there are nominal (or reference) operating conditions in which the conditional densities of the observations under both hypotheses (noise - alone and signal - plus - noise) are completely known and so is the desired false alarm probability PFA_0. Hence, in this case a statistically optimum receiver can easily be defined. For this receiver we can measure the detection probability PD_o and the ratio $\gamma_{no\ CFAR}$ which is the relative increase of input noise power level which causes 10 dB decrease of R (or C).

(3) For the CFAR receiver we determine first the CFAR loss L_{CF} which is the additional signal power, needed in nominal operating conditions to achieve a detection probability PD_o versus desired false alarm probability PFA_o. Then starting from reference operating conditions but with signal power increased by the factor L_{CF} we measure the ratio γ_{CFAR} which is the relative increase of the input noise power level which causes 10 dB decrease of R (or C).

(4) The quality of a CFAR processor can be evaluated as

$$q_{CFAR} = 10\log_{10}(\gamma_{CFAR} / \gamma_{noCFAR}) - L_{CF}. \quad [dB] \tag{4-13}$$

A typical value of q_{CFAR} is 6 - 8 dB.

E. Sensitivity Time Control STC:

Sensitivity time control is mainly intended to compensate the dependence of the target echo power on the target range. We are going to show that this compensation results in average improvements of the anti-passive ECM capability by 7 dB and the anti-active ECM capability by 1 dB. Indeed, in absence of STC the minimum number of chaff which a chaff dispenser should throw in order to simulate a false target at a distance R from the radar is expressed as

$$N_{min}(R) = K' P_{min-r} R^4, \qquad \forall R, \tag{4-14}$$

where K' is a constant easily determined from the two way radar equation. Now if STC is implemented up to range R_{STC}, (4-14) should be modified as

$$\begin{aligned} N_{min}(R) &= K' P_{min-r} R^4_{STC}, \qquad 0 < R \le R_{STC}, \\ &= K' P_{min-r} R^4, \qquad R > R_{STC}. \end{aligned} \tag{4-15}$$

Let $\overline{N}_{min}$ denote the average value of $N_{min}(R)$ over the range interval $0<R\le R_{STC}$. We easily deduce that :

$$\frac{\overline{N}_{min} \mid \text{with STC}}{\overline{N}_{min} \mid \text{without STC}} = \frac{K' P_{min-r} R^4_{STC}}{K' P_{min-r} R^4_{STC} /5} = 5, \tag{4-16}$$

which indicates 7 dB improvement of the anti-passive ECM capability.

Let us now study the dependence of the range measurement resolution on the range in absence or presence of STC. Consider two identical targets closely spaced in range and having same azimuth, elevation, and radial velocity relative to the radar. Let the responses of the matched filter to the signals reflected from the considered targets be $E(\tau)y(t-\tau)$ and $E(\tau+\Delta)y(t-\tau-\Delta)$ where $|y(t)| \le y(0), \forall t, y(0) = 1$, τ is the time-delay of the first target echo and $\tau+\Delta$ is the time delay of the second target echo. For $\Delta \ll \tau$ we can assume that $E(\tau) \approx E(\tau+\Delta)$. Let λ be the threshold with which the matched filter output is compared. The sum of the two responses is represented by the dashed curve in Fig. 1. Evidently, for the two responses to be resolvable in time-delay (range) at the matched filter output, it is necessary that

$$2E(\tau)y(\Delta/2) \le \lambda. \tag{4-17}$$

There is no loss of generality to assume that the detection threshold $\lambda=E(\tau_{max})$. From the two way radar equation and assuming no STC we have $E(\tau_{max}) / E(\tau) = x^2$ where $x = \tau / \tau_{max}$. Moreover $y(\Delta/2) \approx 1 + \ddot{y}(0)\Delta^2/8$ where $\ddot{y}(0)$ is the value of the second derivative of y(t) at t=0. Thus from (4-17) we deduce that the time delay resolution Δ can be expressed as

$$\Delta(x) = \sqrt{-8/\ddot{y}(0)}\sqrt{1-x^2/2}, \qquad 0 < x \le 1 \tag{4-18}$$

Now if STC is on, (4-18) should be modified as

$$\Delta(x) = \sqrt{-8/\ddot{y}(0)}\sqrt{1 - x_{STC}^2/2}, \qquad 0 < x \le x_{STC} \tag{4-19a}$$

$$\Delta(x) = \sqrt{-8/\ddot{y}(0)}\sqrt{1 - x^2/2}, \qquad x_{STC} < x \le 0 \tag{4-19b}$$

let $\bar{\Delta}$ denote the average value of $\Delta(x)$, defined by (4-19), over the interval $0 < x \le 1$. It can be shown that

$$\frac{\bar{\Delta}}{\Delta_{min}} = \frac{x_{STC}}{\sqrt{2}}\sqrt{1 - \frac{x_{STC}^2}{2}} + \frac{\pi}{4} - \mathrm{Sin}^{-1}\left(\frac{x_{STC}}{\sqrt{2}}\right) + \frac{1}{2}, \tag{4-20}$$

where $\Delta_{min} = 2\Big/\sqrt{-\ddot{y}(0)}$. Note that if $x_{STC} = 0$, the STC is off and if $x_{STC}=1$, the STC is active in the whole radar detection range. From (4-20) we deduce that

$$\frac{\bar{\Delta}\big|x_{STC} = 0}{\bar{\Delta}\big|x_{STC} = 1} = 1.285 \approx 1 \text{ dB}. \tag{4-21}$$

which indicates a one dB average time delay (range) resolution improvement.

F- Beamforming:

The processing gain achieved by any adaptive beamformer depends on several factors such as the angular locations and the number of interferences sources, the mutual coherence (correlations) among the desired and interference signals, the geometry and the number of elements of the array, the used adaptation algorithm, and the type of implementation (analog or digital) [8], [13], [14], [15]. It is far beyond the scope of this paper to study all these details. Based on practical data, we assign the following average quality levels q_{BF} to the adaptive beamforming capability of the considered radar. Let N_{BF} be the number of degrees of freedom of the adaptive beamformer. This is the maximum number of interference sources the adaptive beamformer can deal with. Now we write

$q_{BF}[dB] = 0,$	no beam forming.
$= 10\ N_{BF}$	no immunity to signal- coherent interferences but immune to N_{BF} noncoherent interferences.
$= 10\ N_{BF}+10$	Immunity to interferences of which 1-2 interferences are signal coherent and the rest is noncoherent. (4-22)

Before terminating this section, we point out that (3-4) and (3-5) should be modified as

$$AP-ECM = \left(\delta T_0\ G\ \bar{Q}/F_n\right)\left(q_{mix} \cdot q_{MTI} \cdot q_{int} \cdot q_p / L_r\ \Delta f\right)\left(q_{CFAR} \cdot q_{STC-AC} \cdot q_{STC-res}\right), \tag{4-23}$$

$$AA-ECM = \left(\bar{P}\ T_0 G\ \bar{Q}/F_n\right)\left(q_{mix} \cdot q_{rep} \cdot q_{int} . SDL. q_{cp} / L_r\ L_T\right)\left(q_A \cdot q_{PRI} \cdot q_{CFAR} \cdot q_{STC-res} \cdot q_{BF}\right). \tag{4-24}$$

V- Global Performance Quality Factors of the Radar

In Tables 4 and 5, we present suggested quality levels to be assigned to different global system functions as well as to display system features. The main objectives of Tables 4 and 5 are: (1) to enumerate the different possible global system functions and display system features, (2) to indicate a certain preference pattern among them and (3) to define a procedure for evaluation of total qualities. The suggestions made are based on the authers' expertise in the field.

The potential anti-passive ECM capability of the j-th transmit-receive channel is evaluated as

$$AP-ECM_j=\left(\delta T_o\, G\, \bar{Q}/F_n\right)\left(q_{mix}\cdot q_{MTI}\cdot q_{int}\cdot q_p/L_r\ \Delta f\right)\left(q_{CFAR}\cdot q_{STC-AC}\cdot q_{STC-res}\right)\left(q_{EM}\cdot q_{display}\right). \quad (5\text{-}1)$$

The potential anti-active ECM capability of the j-th transmit-receive channel is evaluated as

$$AA-ECM_j=\left(\bar{P}\, T_0\, G\, \bar{Q}/F_n\right)\left(q_{mix}\cdot q_{rep}\cdot q_{int}\cdot SDL.q_{cp}/L_r\ L_T\right)\left(q_A\cdot q_{PRI}\cdot q_{CFAR}\cdot q_{STC-res}\cdot q_{BF}\right)$$
$$\times\left(q_{EM}\cdot q_{Track}\cdot q_{JA}\cdot q_{display}\right). \quad (5\text{-}2)$$

The potential ECCM capability of the j-th transmit-receive channel is evaluated as the least common multiple of (5-1) and (5-2). Hence we write

$$ECCM_j=\left(\bar{P}\, T_0\, G\, \bar{Q}/F_n\right)\left(q_{mix}\cdot q_{MTI}\cdot q_{rep}\cdot q_{int}\cdot q_p\ .SDL.q_{cp}/L_r\ L_T\ \Delta f\right)\left(q_A\cdot q_{PRI}\cdot q_{CFAR}\cdot q_{STC-AC}\cdot q_{STC-res}\cdot q_{BF}\right) \quad (5\text{-}3)$$
$$\times\left(q_{EM}\cdot q_{Track}\cdot q_{JA}\cdot q_{display}\right).$$

The global performance quality factors of the considered radar are evaluated as

$$AP-ECM(\varepsilon)=\Sigma_j\, AP-ECM_j f_j^2(\varepsilon)\ , \quad (5\text{-}4a)$$

$$AA-ECM(\varepsilon)=\Sigma_j\, AA-ECM_j f_j^2(\varepsilon)\ , \quad (5\text{-}4b)$$

$$ECCM(\varepsilon)=\Sigma_j\, ECCM_j\ f_j^2(\varepsilon)\ , \quad (5\text{-}4c)$$

where ε is the elevation angle in degrees and $f_j^2(\varepsilon)$ is the antenna elevation power radiation pattern of the j-th channel. Below we present good analytic approximations to $f^2(\varepsilon)$ and G. Let ρ be the antenna efficiency and θ_{BW} be the azimuth beam width in degrees. Let us now consider the following cases :

1) The beam does not scan in elevation and its lower and upper edge angles are respectively ε_l and ε_u:

(a) If $\varepsilon_u-\varepsilon_l\le 5\,\theta_{BW}$, then

$$f^2(\varepsilon)=\exp\left\{-2.77\left[\frac{\varepsilon-(\varepsilon_u-\varepsilon_l)\ /2}{\varepsilon_u-\varepsilon_l}\right]^2\right\}\quad,\ \varepsilon_l\le\varepsilon\le\varepsilon_u \quad (5\text{-}5)$$

$$G=41252.96\ \rho\ /\left[\theta_{BW}(\varepsilon_u-\varepsilon_l)\right] \quad (5\text{-}6)$$

(b) If $\varepsilon_u-\varepsilon_l>5\,\theta_{BW}$ and $\varepsilon_u/5\le\varepsilon_l$, then

$$f^2(\varepsilon)=\mathrm{cosec}^2(\varepsilon)\ /\ \mathrm{cosec}^2(\varepsilon_l)\qquad \varepsilon_l\le\varepsilon\le\varepsilon_u \quad (5\text{-}7)$$

$$G=720.\rho\ \mathrm{cosec}^2(\varepsilon_l)\ /\ \left[\theta_{BW}\left(\mathrm{cosec}(\varepsilon_l)-\mathrm{cosec}(\varepsilon_u)\right)\right] \quad (5\text{-}8)$$

(c) If $\varepsilon_u-\varepsilon_l>5\,\theta_{BW}$ and $\varepsilon_u/5>\varepsilon_l$, then

$$f^2(\varepsilon)=1\qquad \varepsilon_l\le\varepsilon\le\varepsilon_u/5 \quad (5\text{-}9a)$$

$$=\mathrm{cosec}^2(\varepsilon)/\mathrm{cosec}^2(\varepsilon_u/5)\qquad \varepsilon_u/5\le\varepsilon\le\varepsilon_l \quad (5\text{-}9b)$$

$$G=\frac{41252.96\ \rho}{\theta_{BW}(\varepsilon_u-\varepsilon_l)}\ \frac{0.0035\,\varepsilon_u}{\left\{0.0035\,\varepsilon_u+\left[\sin(\varepsilon_u/5)^2\right]\left[\cot(\varepsilon_u/5)-\cot(\varepsilon_u)\right]\right\}} \quad (5\text{-}10)$$

(2) The beam scans in an elevation sector with lower and upper edge angles LEA and UEA [deg] respectively. Let ε_{BW} be the elevation beamwidth.

$$G=41252.96\,\rho/\theta_{BW}\varepsilon_{BW}, \tag{5-11}$$

(a) for mechanical scanning in elevation

$$f^2(\varepsilon)=1\,,\qquad \text{LEA}\le\varepsilon\le\text{UEA} \tag{5-12}$$

(b) for electronic (frequency or phase) scanning in elevation

$$f^2(\varepsilon)=\cos\varepsilon,\qquad \text{LEA}\le\varepsilon\le\text{UEA}\,, \tag{5-13}$$

By plotting the decibel values of the three functions defined by (5-4a, b, c) we obtain the global performance quality curves GPQCs which help the user investigate the suitability of the considered radar set to the intended application. Furthermore, for comparison of different radar sets that are candidates for a particular application it is possible to proceed as follows: (1) Study each radar set separately and decide about its suitability for the intended application. For this purpose, the procedure presented in this paper is helpful. Operational constraints should be considered too. (2) Exclude the radar set(s) that is (are) unsuitable. (3) Find the maxima of the GPQCs of the radar sets still in competition and determine the largest maximum. (4) Divide the GPQCs of the competing radar sets by the largest maximum then plot them. (5) Find the largest elevation coverage. Evaluate the averages of the normalized GPQCs over the largest elevation coverage. That is the averages are calculated as the results of dividing the areas under the normalized GPQCs by the largest elevation coverage. (6) Select the radar set with highest average to-price ratio.

Three air-defense surveillance radar systems are taken as examples. Radar A is a modern 3D radar with 6 antenna beams stacked in elevation, similar to the USA radar AN/TPS-43E [5, p. 173], [9], [7, p.210]. Radar B is also a modern 3D radar with a transmitting beam frequency scanning in elevation within a pulse duration and 8 receiving channels, similar to UK radar AR-3D [5, p. 178], [9]. Radar C is an old fashioned 2D radar with 6 independent beams (with different frequencies) stacked in elevation to form a cosec² fan beam [9]. Utilizing the derived formulas, the final results are presented in Fig. 2 and Table 6. Radar B has an elevation coverage of 32° which gives it an advantage over the other two radars whose elevation coverage stops at 20°. If the user is interested in elevation coverage up to 32°, the relative comparison weights of the three radars are given in Table 6 (2-nd block of results). If the user is not interested in elevation coverage from 20°-32°, the relative weights are modified as shown in Table 6 (3-rd block of results). The results in Table 6 indicate that radar B is technically the best, radar A is the second and C is technically the worst one. This conclusion differs from that derived in [9] which ranks radar A highest. The conclusion derived in this paper is more reliable because of the more comprehensive objective evaluation and the better precision of the expressions for the quality levels. In [9], the performance dependence on the elevation coverage of the radar is ignored and only potential performances of single channels from the radars under consideration are compared.

References

[1] D. K. Barton and W. F. Barton, Radar Evaluation Software: User's manual, Anro Engineering Consultants, Inc., Artech House, 1991.

[2] D. K. Barton, C. E. Cock, and P. Hamilton, Radar Evaluation Handbook, Artech House, Inc., 1991.

[3] Skolnik M. I., Introduction to Radar Systems, 2nd edition, McGraw-Hill, Inc., 1980.

[4] S. A. Hovanessian, Radar System Design and Analysis, Artech House, Inc., 1984.

[5] Eli Brookner, Aspects of Modern Radar, Artech House, Inc., 1988.

[6] S. L. Johnston, " ECCM Improvement Factors (EIF), " Electronic Warfare Magazine, Pt. 6, vol. 3, pp. 41-45, 1974.

[7] D. C. Schleher, Introduction to Electronic Warfare, Artech House, Inc., 1986.

[8] J. V. Difranco and C. Kaiteris, " Radar performance review in clear and jamming environments, " IEEE Trans. Aerospace & Electronic Systems, Vol. Aes-17, No. 5, pp. 701-710, Sept. 1981.

[9] Li Nengjing, " Formulas for measuring radar ECCM capability, " IEE Proc. F., Commun., Radar & Signal processing, July 1984, 131, (4), pp. 417-423.

[10] S. L. Johnston, " Correspondence: Formulas for measuring radar ECCM capability, " IEE Proc., June 1985, 132, Pt. F, (3), pp. 198-201.

[11] Skolnik M. I., Introduction to Radar Systems, first edition, McGraw Hill, Inc., 1962.

[12] Z. Chair, and P. K. Varshney, " Optimal data fusion in multiple- sensor detection systems, " IEEE Transactions on Aerospace and Electronic systems, AES-22, No. 1, pp. 98-101, Jan. 1986.

[13] M. H. ElAyadi, "Dependance of processing gain and interferance immunity of adaptive narrowband beamformers on angular locations of interference sources, "IEEE Trans. , Acoust., Speech, Signal Processing, vol. ASSP-38, pp. 174 -175, Jan. 1990.

[14] Robert A. Monzingo and Thomas W. Miller, Introduction to Adaptive Arrays, A Willey-Interscience Publication, John Willey & Sons, 1980.

[15] Y. Bresler, V.U. Reddy and T. Kailath, " Optimum beam forming for coherent signal and interferences, " IEEE Trans. Acoust., Speech, Signal processing, vol. 36. pp. 833-942, June 1988.

Table 1- Qualitative comparison of immunity to repeater deception in absence of pulse-to-pulse carrier frequency agility

negative feature	short pulse	FM pulse compression	phase coded pulse compression
(1) Deception by false targets closer than the actual target,	1	1	1
(2) Delayed saturation of repeater,	0	1	1
(3) Not an LPI radar.	1	1	1
Vulnerability to repeater deception	2	3	3
Immunity to repeater deception	1/2	1/3	1/3

Table 2- Qualitative comparison of immunity to repeater deception in presence of pulse-to-pulse carrier frequency agility

negative feature	short pulse	FM pulse compression	phase coded pulse compression
(1) Deception by false targets closer than the actual target,	0	1	1
(2) Delayed saturation of repeater,	0	1	1
(3) Not an LPI radar.	1	1	0
Vulnerability to repeater deception	1	3	2
Immunity to repeater deception	1	1/3	1/2

Table 3- Relative levels of immunity to repeater deception

negative feature	short pulse	FM pulse compression	phase coded pulse compression
(1) Without pulse-to-pulse carrier frequency agility	3	2	2
(2) With pulse-to-pulse carrier frequency agility.	6	2	3

Table 4- Quality levels associated with global system functions

Entry	Value	Associated quality level
Energy management :		
operator controlled,		$Q_{EM} = 0$ dB
computer controlled.		$Q_{EM} = 3$ dB
Maximum number of tracked targets		
Tracking functions :		
operator,		$Q_{Track} = 0$ [dB]
conical (Sequential lobbing),		$Q_{Track} = 10$ [dB]
amplitude comparison monopulse,		Q_{Track}=10 log 20 [dB]
phase comparison monopulse,		Q_{Track}=10 log 30 [dB]
TWS(1) without POP(2),		Q_{Track}=10 log 10 NTrack [dB]
TWS with POP,		Q_{Track}=10log12.5NTrack [dB]
combined Monopulse and TWS.		Q_{Track}=10log20 NTrack [dB]
Jam Analysis :		
operator,		Q_{JA}= 1
automatic:		
direction of jammer :		
digital Readout,		Q_{JA}= 6
strobe,		Q_{JA}= 4
both.		Q_{JA}= 10
Plot burn through range versus azimuth [yes -No]	if Yes	Q_{JA}= QJA + 5
Adaptive frequency selection(3) [yes -No]	if Yes	Q_{JA}= QJA + 20
Polarization sensing and adaptive selection of orthogonal polarization [yes -No]	if Yes	Q_{JA}= QJA + 400
Prediction of jammer look through interval and changing operating parameters in between [yes-No]	if Yes	Q_{JA}= QJA + 500

(1) TWS denotes track while scan. (2) POP denotes plot over protection.

(3) Adaptive frequency selection means selection of least jammed frequency. Sometimes, it is called clear channel sensing.

Note: Q_{JA} [dB] = 10 log Q_{JA} (Absolute)

Table .5 - Quality factors associated with display system features

Entry	Value	Associated quality factor
Number of monitors N_m		
Zooming capability(1) :		
No,		Z_i =1
Yes		Z_i=2
Persistence(1) :		
fixed,		P_i =1
variable		P_i =2
Number of different possible display types (1) $N_f(i)$		
Data multiplexing (1)		
No,		DM(i)=1
Yes :		
- single coordinate division multiplexing		DM(i)=2
- two coordinate division multiplexing		DM(i)=4

Overall quality of display system: $Q_{display} = 10\log(\sum_{i=1}^{Nm} Z_i P_i N_f(i) DM(i))$

Table 6- Relative weights of three differently structured search radar sets

Compared Radars	Radar A	Radar B	Radar C
elevation coverage in degrees	0-20	0-32	0-20
Maxima of global performance quality curves [dB]			
AP-ECM	76.023	85.34	27.04
AA-ECM	130.11	154.57	105.145
ECCM	143.021	166.86	72.54
Relative weights of the three radars (32°elevation coverage considered)			
AP-ECM	41.61 %	80.74 %	8.69 %
AA-ECM	40.61 %	87.04%	30.59 %
ECCM	41.03 %	87.25 %	18.72 %
Relative weights of the three radars (20°elevation coverage considered)			
AP-ECM	66.53 %	87.26 %	13.90 %
AA-ECM	64.981 %	92.96%	48.94 %
ECCM	65.56 %	93.17 %	29.95 %

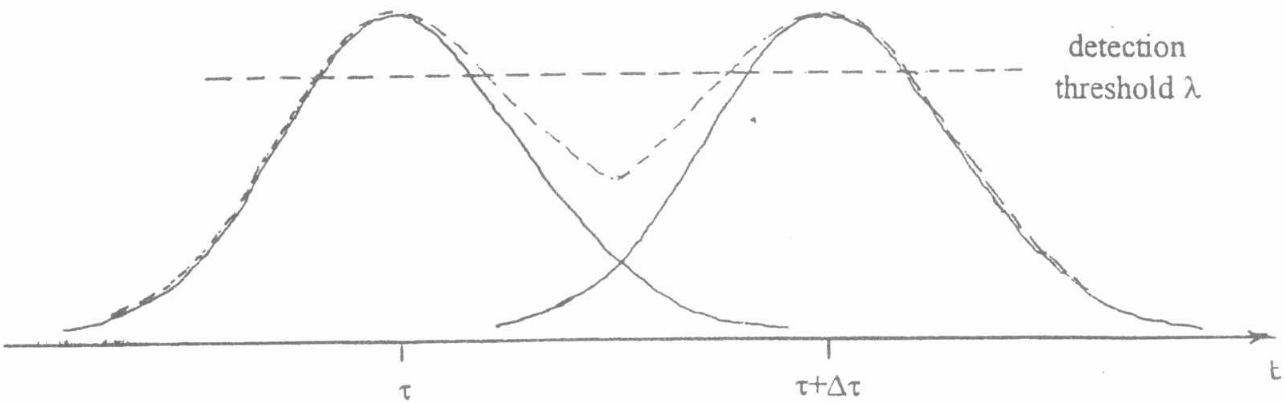

Fig. 1 Superposition of two identical radar echoes closely spaced in range.

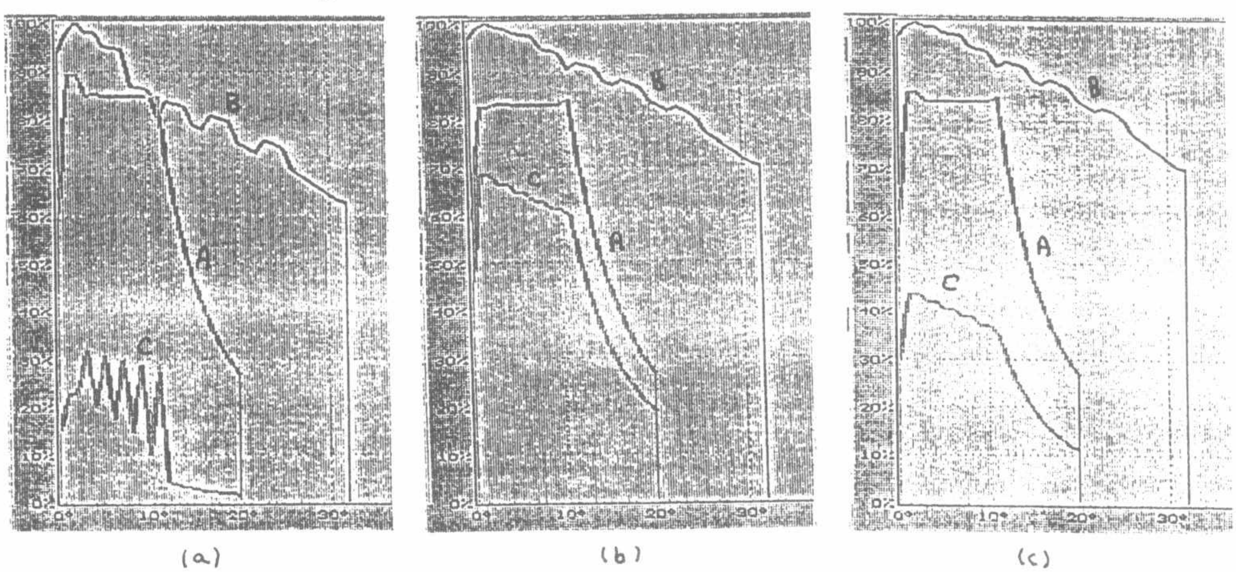

Fig. 2 Normalized global performance quality curves of radars A, B and C.
(a) AP-ECM (b) AA-ECM (c) ECM