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AN EFFICIENCY FUNCTION FOR RATING MECHANICAL SCAN-TRACK RADARS

TECHNICAL DOCUMENTARY REPORT NO. ESD-TR-65-80

March 1965

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J. W. McGinn, Jr.

Prepared for

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496L SYSTEM PROGRAM OFFICE
ELECTRONIC SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
L. G. Hanscom Field, Bedford, Massachusetts

Project 496L

Prepared by

THE MITRE CORPORATION
Bedford, Massachusetts

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FOREWORD

The author wishes to acknowledge the kind assistance of D. M. Jamieson and S. T. Engquist. Both contributed greatly to this report.

AN EFFICIENCY FUNCTION FOR RATING

MECHANICAL SCAN-TRACK RADARS

ABSTRACT

A function, (P_d), introduced in ESD-TDR-63-292, is derived as a measure of effectiveness in rating certain mechanical scan-track radar configurations in the joint performance of two operational requirements. These are:

(1) confirmation, i.e., acquisition and tracking of objects (missiles and/or satellites) detected by collocated surveillance radars, and

(2) scanning, i.e., providing additional surveillance coverage for a missile threat in a sector not searched by the collocated surveillance radars.

We are mainly interested in the application of the P_d function to the problems of selecting a suitable scan-track radar for BMEWS Site II service. It is thought, however, that the function would be of general interest to others with similar problems of selection under joint operating constraints.

REVIEW AND APPROVAL

Publication of this technical documentary report does not constitute Air Force approval of the reports findings or conclusions. It is published only for the exchange and stimulation of ideas.

Thomas O. Wear

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AN EFFICIENCY FUNCTION FOR RATING MECHANICAL SCAN-TRACK RADARS

The P_d function provides a measure of effectiveness for rating various mechanical scan-track radars in their hypothetical performance of two operational requirements: confirmation and scanning. Each scan-track radar is identified in terms of three pedestal parameters:

(1) V_S or azimuth scan velocity,

(2) V_m or maximum azimuth (slew) velocity, and

(3) a, or maximum acceleration.

This report concerns the ability of a radar under test to confirm (i. e., acquire and track) targets detected by surveillance radars operating in an azimuth sector of width A^o while maintaining scan surveillance for a target threat in an adjacent azimuth sector of width B^o. It is assumed that detections in the A^o sector, and, hence, scan-track radar confirming or tracking assignments, occur at periodic intervals. It is further assumed that when the target threat (a missile raid) occurs, it occurs in the B^o azimuth sector and remains within the surveillance volume for a period of W seconds.

The logic for the scanning requirement for each scan-track radar under test is rigid and consists of following each confirmation task in the A^o sector by at least two complete scans of the B^o sector before accepting the next confirmation assignment. The efficiency of the various test radars, is computed based on their ability to fulfill the scanning requirement such that during the scan cycle at least two successive radar scans are obtained on one target during the raid passage time of W seconds.

There are three time intervals necessary for the formulation of P_d:

(1) T_S, or time to complete two scans of the B^o sector. This quantity may be computed in terms of V_S and a as follows:

$$T_S = \frac{2B^o}{V_S} + \frac{2V_S}{a} \quad .$$

(2) T_D, or the average time to obtain two successive radar contacts on a target occurring in the B^o sector. This time interval, as computed in the appendix to this report, is

$$T_D = \frac{3B^o}{2V_S} + \frac{3V_S}{a} \quad .$$

(3) T_A, or the time to confirm, i.e., acquire and track, a detected object in the A^o sector and return to scan in the B^o sector. The time increment necessary for acquiring the target and return to scan, T_{ACQ+R} (exclusive of track time period), is given as[1]:

$$T_{ACQ+R} = \frac{V_S^2}{aV_m} + \frac{2V_m}{a} + \frac{2\Delta\theta}{V_m} - \frac{V_S}{a} \quad .$$

In this equation, $\Delta\theta$ is the azimuthal angular difference between radar beam position in scan (B^o sector) and the position of the target to be confirmed in the A^o sector. The definition of T_A is completed by the addition of a tracking time interval of γ seconds to T_{ACQ+R}.

[1] S. M. Newman et al, "Investigations of Tracking Radar Configurations for the BMEWS Gap," The MITRE Corporation, Report W-5792, February 1963.

Thus

$$T_A = T_{ACQ+R} + \gamma = \frac{V_S^2}{aV_m} + \frac{2V_m}{a} + \frac{2\Delta\theta}{a} - \frac{V_S}{a} + \gamma \ .$$

In addition to the preceding definitions, the following inequalities are useful:

(1) If $W < T_D$, then the scan-track radar will not, on the average, obtain two successive radar scans on a target in the B^o sector. In this case we will say that $P_d \approx 0$; i.e., the measure of effectiveness of the radar with $T_D > W$ should be a minimum value of approximately zero.

(2) If $W > 2T_D + T_A$, then the scan track radar will, on the average, obtain at least two successive radar scans on the target in the B^o sector, even after having performed a confirmation assignment of length T_A. In this case we will say that $P_D \approx 1$; i.e., the measure of efficiency of the radar should be a maximum value of approximately unity.

These two inequalities serve to establish the class of scan-track radars that may be ranked in efficiency of performance by the function P_d. Thus, if a candidate radar has pedestal parameters such that $T_D > W$ or $2T_D + T_A < W$, then it is not an element of the class whose efficiency may be measured by P_d. Conversely, if a candidate has pedestal parameters such that $2T_D + T_A > W > T_D$, then it is an element of the class whose efficiency can be measured by the P_d function. Further, the inequalities are used to establish that the operating range of P_d is in the interval (0, 1). Thus, if $P_d \leq 0$, we arbitrarily assign $P_d = 0$, while if $P_d \geq 1$, we assign $P_d = 1$.

We now proceed to derive P_d. Consider the unit time interval $T = T_A + T_S$ shown in Figure 1. If an event (raid of time duration W) commences in the time interval $(0, T_S - T_D)$, then the scan-track radar will obtain the necessary two scans on the target before being assigned to the confirmation task of length T_A.

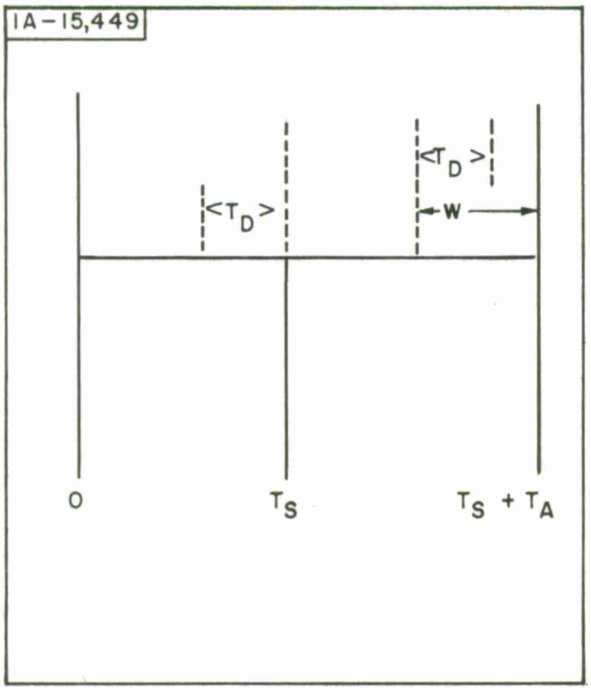

Figure 1. Unit Time Interval $T = T_S + T_A$

During this interval, the radar is operating efficiently. However, if the event commences in the interval $(T_S - T_D, T_S + T_A - W + T_D)$, then no opportunity exists for obtaining the necessary scans on the target. During this interval, the radar is not operating efficiently. Finally, if the event commences during the interval $(T_S + T_A - W + T_D, T_S + T_D)$, then at least a T_D portion of W will carry over to the succeeding portion of T_S in the next

unit period T. In this case, the necessary radar scans on at least one missile in the raid will be obtained, and the radar is operating efficiently in this interval. Summing the efficient intervals and obtaining a ratio with respect to the basic unit T produces a formula for computing P_d:

$$P_d = \frac{W - 2T_D + T_S}{T} = \frac{W - 2T_D + T_S}{T_S + T_A} .$$

Application of the limiting values for P_d noted earlier gives the complete function as

$$P_d = \begin{cases} 0, & \dfrac{W - 2T_D + T_S}{T_S + T_A} < 0 \\[2ex] \dfrac{W - 2T_D + T_S}{T_S + T_A} = \xi, & 0 \le \xi \le 1 \\[2ex] 1, & \dfrac{W - 2T_D + T_S}{T_S + T_A} > 1 \end{cases} .$$

This function can be computed by substituting values for the time intervals T_S, T_D, T_A noted to test the consistency of the result with the inequalities $W < T_D$ and $W > 2T_D + T_A$ and to gain some insight into the ability of the P_d function to operate as the desired measure of effectiveness of a scan-track radar.

The consistency of $W > 2T_D + T_A$ and $P_d \approx 1$ can be shown by letting $W = 2T_D + T_A + \epsilon$, $\epsilon > 0$, substituting in P_d, and solving:

$$P_d = \frac{W - 2T_D + T_S}{T_S + T_A} = \frac{T_A + T_S + \epsilon}{T_A + T_S} > 1 ,$$

or, by our convention, $P_d = 1$. Thus, at least for large values of W, we find that P_d does exhibit the required measure characteristic.

In order to test the consistency of $W < T_D$ and $P_d \approx 0$, let $W = T_D - \epsilon$, $\epsilon > 0$. Then

$$P_d \times (T_S + T_A) \approx 0 \approx T_D - \epsilon - 2T_D + T_S ,$$

$$0 \approx T_S - T_D - \epsilon$$

Substitution of the computed values for T_S and T_D noted earlier yields

$$\frac{B^o}{2V_S} - \frac{V_S}{a} - \epsilon \approx 0 .$$

Letting $\epsilon \rightarrow 0$, i.e., $W \rightarrow T_D$, we obtain the approximate condition under which the inequality $W < T_D$ implies that $P_d \approx 0$:

$$B^o = \frac{2V_S^2}{a} .$$

This implication of this condition is clear. For $V_S > 0$, $a > 0$, there is only a point value, $V_S^1 = \sqrt{B^o_a/2}$, where $P_d \approx 0$. For $V_S > V_S^1$, we compute $P_d < 0$, or, by our convention, $P_d = 0$. However, for $V_S < V_S^1$, we compute

$P_d > 0$, and our assumption that $W < T_D \rightarrow P_d \approx 0$ is inconsistent with this result.

A calculation will help to illustrate the inconsistency.

Let

$$B^o = 50^o, \quad V_S = 10 \text{ deg/sec}, \quad \text{and} \quad a = 36 \text{ deg/sec}^2 .$$

Then

$$V_S = 10^o < V_S^1 = 5(\text{deg})^{1/2} a^{1/2} = 30 \text{ deg/sec} \quad \text{and}$$

$$P_d \times (T_S + T_A) \approx T_S - T_D - \epsilon$$

$$\approx \frac{25 \text{ deg}}{10 \text{ deg/sec}} - \frac{10 \text{ deg/sec}}{36 \text{ deg/sec}} - \epsilon \approx 2.5 \text{ sec} - 0.25 \text{ sec}$$

Thus

$$P_d \approx \frac{2.5 \text{ sec} - 0.25 \text{ sec}}{T_S + T_A} > 0 ,$$

and, in this case, $W < T_D \not\rightarrow P_D \approx 0$. The reason for this inconsistency is found in the definition of T_D as an average quantity, whereas its use in the formulation of P_d was as a deterministic for fixed quantity such as T_S. Thus, the P_d function as defined is probably inadequate for ranking of radars with efficiency ratings of approximately zero. Since this use of the function would not occur in the usual investigation of efficiency of operation, it will not be considered further.

We next consider the versatility of the P_d function. Up to this point, the advantage of P_d in the rating of competitive radars systems which perform a dual operational service has been stressed. This was the use of the function in ESD-TDR-63-292, where three field service units were ranked to indicate the most efficient unit for the dual requirement. During that computation it was found that the most efficient unit actually exceeded the requirements in the sense that the computed value of P_d exceeded unity.

This indicated that an interpolation between the pedestal parameters of the most efficient and nearest competitor unit would provide a description of an optimum solution; i.e., a radar matched to the condition $P_d = 1$. This was computed and presented as the suggested minimum solution for an efficient radar that met the joint operational requirement.

Subsequent to that solution, it was realized that the P_d function offered a much more general vehicle for the examination of the interplay between pedestal parameters and operation requirements. This can be seen by evaluating P_d in terms of these quantities. Let, as was the case in TDR-63-292, $A^o = 120^o$, $B^o = 50^o$, $\gamma = 10$ sec. Then

$$P_d = \frac{W - 2T_D + T_S}{T_S + T_A} = \frac{W - 2\left(\frac{75^o}{V_S} + \frac{3V_s}{a}\right) + \frac{100^o}{V_S} + \frac{2V_S}{a}}{\frac{V_S^2}{aV_m} + \frac{2V_m}{a} + \frac{2\Delta\theta}{V_m} - \frac{V_S}{a} + 10 + \frac{100^o}{V_S} + \frac{2V_S}{a}} .$$

Consolidation of this expression gives

$$P_d = \frac{W - \frac{50^o}{V_S} - \frac{4V_S}{a}}{\frac{V_S^2}{aV_m} + \frac{2V_m}{a} + \frac{2\Delta\theta}{V_m} + \frac{V_S}{a} + \frac{100^o}{V_S} + 10} .$$

With $\Delta\theta = 85^o$ and $W = 40$ sec (as in TDR-63-292) we obtain

$$P_d = \frac{40 - \frac{50^o}{V_S} - 4\frac{V_S}{a}}{\frac{V^2}{aV_m} + \frac{2V_m}{a} + \frac{170^o}{V_m} + \frac{V_S}{a} + \frac{100^o}{V_S} + 10} .$$

Since we are mainly concerned with efficient radar units, we set $P_d = 1$ to obtain the general function relating pedestal parameters to operational requirements:

$$\frac{V_S^2}{aV_m} + \frac{2V_m}{a} + \frac{5V_S}{a} + \frac{170^o}{V_m} + \frac{150^o}{V_S} = 30 .$$

A plot of this function is shown in Figure 2, where a family of solutions is presented for various fixed values of V_S. The optimum solution of ESD-TDR-63-292 is just within the contour of (V_m, a) for $V_S = 10$ deg/sec. Actually, the solution is just within the region (R_1) bounded by the contour, and this implies a slight over-achievement of the operational requirement; i. e., the computed value of $P_d + 1 + \epsilon$, where ϵ is small. Solutions occurring to the left of the contour in region R_2 would indicate that the computed value of $P_d < 1$. For $V_S < 10^o$, generally larger values of the pair (V_m, a) are necessary to obtain equal efficiency (i. e., $P_d = 1$) than those necessary for the case $V_S = 10^o$. Specifically, for any choice of V_m (or a) the coordinate a (or V_m) for the case $V_S = 10^o$ is less than the same coordinate value for $V_S < 10^o$ when $P_d = 1$. Further when $V_S > 10.7$ deg/sec, $V_m < 10.7$ deg/sec. Thus, for high scan rates in the B^o sector, the slew velocity needed to confirm a target in the A^o sector can be eased to a level

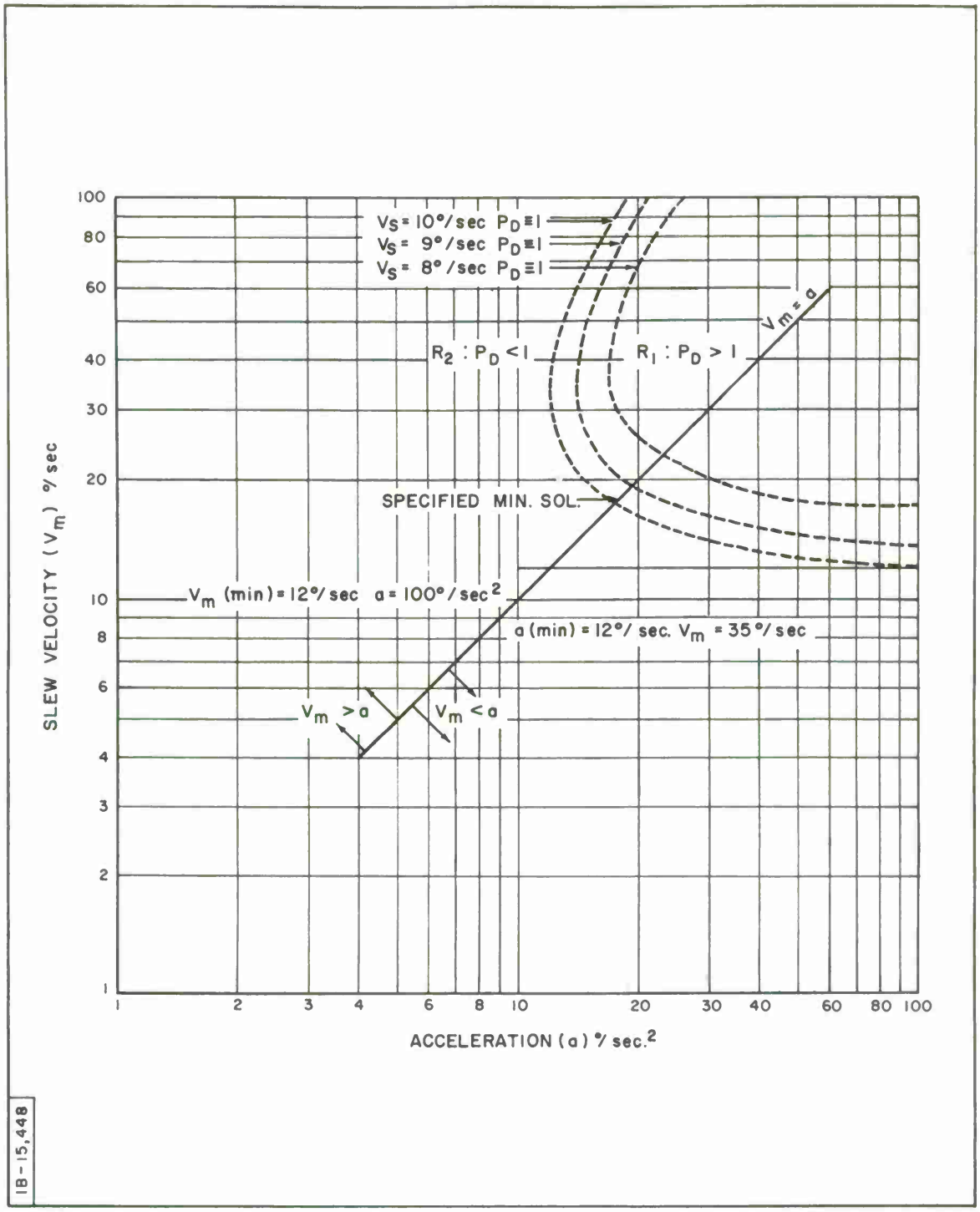

Figure 2. The Relationship of Pedestal Parameters to Operational Requirements for $P_d = 1$

below the scan rate. Since this conclusion disagrees with our physical interpretation of slew velocity as a quantity greater than scan velocity, the case where $V_m < V_S$ has not been investigated.

The investigation of the P_d function is concluded with one further computation. For fixed values of V_S and $P_d = 1$, it is possible to relate V_m and a :

$$W - \frac{B^o}{V_S} - \frac{4V_S}{a} = \frac{V_S^2}{aV_m} + \frac{2V_m}{a} + \frac{2\Delta\theta}{V_m} + \frac{V_S}{a} + \gamma + \frac{2B^o}{V_S} ,$$

$$a = \frac{\frac{V_S^2}{V_m} + 2V_m + 5V_S}{W - \frac{3B^o}{V_S} - \frac{2\Delta\theta}{V_m} - \gamma} .$$

Since both V_m and a are greater than zero, then the denominator

$$W - \frac{3B^o}{V_S} - \frac{2\Delta\theta}{V_m} - \gamma > 0 .$$

If we replace the inequality with an equality by adding a small quantity $\epsilon > 0$ to the right-hand side, we obtain

$$W - \frac{3B^o}{V_S} - \frac{2\Delta\theta}{V_m} - \gamma = \epsilon .$$

Addition of $(2\Delta\theta/V_m)$ to this expression, produces the approximate equality

$$V_m \simeq \frac{2\,\Delta\theta}{W - \dfrac{3B^o}{V_S} - \gamma}$$

Substitution of the values $\Delta\theta = 85^o$, $B^o = 50^o$, $\gamma = 10$ sec, and $W = 40$ sec, and setting $V_S = 10$ deg/sec, we obtain

$$V_m \simeq \frac{170 \text{ deg}}{15 \text{ sec}} = 12 \text{ deg/sec} \quad .$$

This specific solution of V_m is an approximate minimum value solution. As shown in Figure 2, for the specified conditions only values larger than $V_m = 12$ deg/sec are possible. Thus, the P_d function can be used to obtain rough values of the minimum value of slew velocity for given fixed V_S.

James W. McGinn Jr.

James W. McGinn, Jr.

APPENDIX

COMPUTATION OF TIME PERIOD T_D

The time period T_D is defined as the average time to obtain two successive radar contacts or scans on a target occurring in the B^o sector. For the first such scan, let β be the angular difference between target and radar as the radar resumes scan of the sector after a confirmation assignment. Figure 3 then applies.

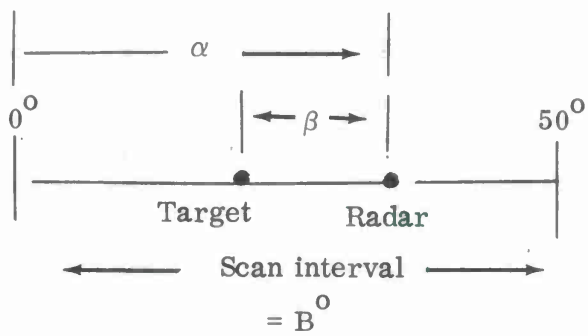

Figure 3. Scan Interval

Case 1. As radar resumes surveillance scan from position α (random variable), let it be in motion toward the target. Then the time for two scans, assuming the target is stationary in azimuth, would be

$$T_{D_1} = \frac{\alpha}{V_S} + \frac{\alpha - \beta}{V_S} + \frac{2V_S}{a} ,$$

where $2V_S/a$ = time period to turn around at end of scan position.

Case 2. As radar resumes surveillance from position α, let it be in motion away from the target. Then the time for two scans would be

$$T_{D_2} = \frac{B^o - \alpha}{V_S} + \frac{2V_S}{a} + \frac{B^o}{V_S} + \frac{2V_S}{a} + \frac{\alpha - \beta}{V_S} .$$

Case 3. In the foregoing, we assumed that β was such that the target was to the left of the tracker at resumption of scan. If we assume that the target is to the right of the radar, again with angular difference β, then with the radar moving toward the target we obtain:

$$T_{D_3} = \frac{2B^o}{V_S} - \frac{2\alpha}{V_S} - \frac{\beta}{V_S} + \frac{2V_S}{a} .$$

Case 4. With the radar moving away from the target we obtain

$$T_{D_4} = \frac{2B^o}{V_S} - \frac{\beta}{V_S} + \frac{3V_S}{a} .$$

If we assign a probability weight of 1/4 to each case (i.e., it is equally probable that, given β to the left or right of the radar, the radar moves toward or away from target as it resumes scan), then

$$\frac{1}{4}\left[T_{D_1} + T_{D_2} + T_{D_3} + T_{D_4}\right] = \frac{3B^o}{2V_S} - \frac{\beta}{V_S} + \frac{3V_S}{a} .$$

It is important to note, at this point, that the starting position of the radar, α, has vanished from the computation. However, the random variable, β, has not vanished, and we replace it by its average value,

$$E(\beta) = 0$$

to produce our final result:

$$T_D = \frac{3B^o}{2V_S} - \frac{E(\beta)}{V_S} + \frac{3V_S}{a}$$

$$= \frac{3B^o}{2V_S} + \frac{3V_S}{a} ,$$

which is used in the text.

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UNITED STATES AIR FORCE

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REPLY TO ATTN OF: ESEP/J.T. O'Brien/5322 23 June 1965

SUBJECT: ESD-TDR-65-80

TO: ESTI (Lt. Rives)

Although ESD-TDR-65-80 does have a 496L connotation, I do not think there should be any objection to permitting this paper--since it is a general theoretical discussion--to be supplied to OTS.

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