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NRL Memorandum Report 2260
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**Operating Guidelines
for
the Airborne Radar Test-System**
[Unclassified Title]

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*Aerospace Radar Branch
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April 1971



NAVAL RESEARCH LABORATORY
Washington, D.C.

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OPERATING GUIDELINES FOR THE AIRBORNE RADAR TEST-SYSTEM

(Unclassified Title)

ABSTRACT

(Secret)

A scaled radar test-system is being flown in an EC-121 aircraft to investigate some of the problems associated with ocean surveillance. This test-system has been scaled so that its performance will simulate that of a satellite-borne ocean-surveillance radar orbiting at an altitude of 200 nautical miles. This report provides some operational guidelines which will aid in obtaining meaningful data from the system. Curves and charts are presented which will: (1) permit the selection of grazing angle; (2) indicate the properly-scaled values for antenna rotation rate and transmitter power; and (3) show the limits of operation as a function of radar altitude and target range.

PROBLEM STATUS

This is an interim report on the problem; work is continuing.

AUTHORIZATION

NRL Problem R02-46
Project A370 5383-6528-1F48111704

DEC 11 1961

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(Unclassified)

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OPERATING GUIDELINES FOR THE AIRBORNE RADAR TEST-SYSTEM

(Unclassified Title)

INTRODUCTION

(S) The Aerospace Radar Branch is currently engaged in a series of tests, the purpose of which is to investigate some of the problems associated with ocean surveillance from a satellite-borne radar system. These tests are being conducted with an airborne test-system which was designed and assembled by the Branch. The design of this airborne radar was based on a satellite reference system whose performance characteristics were scaled so that the resulting model could operate from one of the Laboratory's EC-121 aircraft at an altitude of 15,000 feet. The principles upon which this scaling technique was based are described in a recent NRL report¹.

(S) Because of problems associated with the rather large altitude scaling factor between satellite and aircraft (a ratio of 81:1), the test-system could be designed to match the performance of the reference system for targets lying at only two specific values of grazing angle. It was realized of course that, because of the usual operational difficulties encountered in flight, it would generally not be possible to position the target at the precise values of grazing angle for which the system had been designed. Therefore, the referenced report included an analysis of the effect which range and azimuth errors would have on the accuracy of the scaled data. It was found that if reasonable care were taken in positioning the aircraft in relation to the target, accurate performance data could be obtained with the test-bed radar system.

(U) With the commencement of operational flights, it becomes apparent that an extension of this error analysis is necessary to take into account what the effect will be on the resultant data when the radar is operated at altitudes other than that for which the scaled system had been designed. Although a specified aircraft altitude, once reached, can usually be controlled by the pilot to within 130 feet, situations can arise in which weather conditions or interfering aircraft traffic make it impossible to operate at the design-altitude of 15,000 feet. Therefore, it will be a major purpose of this report to delineate the permissible regions of operation for various altitudes of the radar. At the same time, the opportunity will be taken to update the parameters of the test radar to reflect actual values rather than the design values which were used in the previous error analysis. Furthermore, tables will be presented which show the levels of transmitter r.f. pulse power required to simulate

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the sensitivity of the reference system for various combinations of altitude and range in the test-bed system. Finally, some simple but useful curves will be provided which should be of aid in carrying out the tests.

PARAMETERS OF THE AIRBORNE TEST-SYSTEM

(S) The airborne radar test-system is actually composed of two sub-systems. One sub-system is used for obtaining data on targets at shallow grazing angles; the other, for targets at steep grazing angles. The only difference in hardware between the two sub-systems is that different antennas are used; all other radar components (transmitter, receiver, data processor) are used in common. With respect to parameters other than those of the antennas, the sub-systems use different values of pulse repetition frequency and will require different levels of transmitter power. The parameters for the two subsystems are listed in Table I.

CONSIDERATIONS OF GRAZING ANGLE

(S) In the design of the test-bed radar system, the performance was scaled for two discrete values of grazing angle: 1.5° for the shallow-grazing-angle sub-system, and 28° for the steep-grazing-angle sub-system. However, in judging the validity of test data obtained under various operational conditions, it is not necessary that consideration be restricted to a predetermined value of grazing angle. For example, if a change in radar altitude should degrade the performance of the system at a grazing angle of 1.5 degrees, but result in satisfactorily scaled performance at a grazing angle of 1.1 degrees, then the test results will be quite acceptable. The basic aim of the test program is to investigate surveillance capabilities in regions of shallow (i.e., about 1.5°) and of steep (i.e., about 28°) grazing angle, and as long as the regions of acceptable scaling do not depart too drastically from these nominal values, valid and meaningful data will be obtained. Therefore, the technique which will be used in the computer-aided analysis which follows will be this: Critical performance factors of the airborne test-system will be calculated as a function of grazing angle for a series of aircraft altitudes. These same performance factors will be calculated for the satellite reference system (at a constant altitude of 200 nautical miles) using the same increments of grazing angle. The computer program will also calculate and print out the discrepancies in these performance factors between the two systems. Then, for whatever limits of error we wish to establish, this printout will show the range of grazing angle over which

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TABLE I
SUBSYSTEM PARAMETERS

Parameter	Subsystem for Steep Grazing Angles	Subsystem for Shallow Grazing Angles
Frequency	1230 MHz	1230 MHz
Pulse Length	0.1 μ sec	0.1 μ sec
PRF *	62.5 pps	39.0 pps
Pulse Compression Ratio	200:1	200:1
Antenna Beamwidths *		
Horizontal	44 degrees	10.7 degrees
Vertical	38 degrees	19.5 degrees
Antenna Polarization	Horizontal	Horizontal
Depression Angle of Antenna Beam Center *	26 degrees	1 degree
Antenna Gain *	13.3 dB	22.2 dB
* measured values, which differ slightly from previously used design values.		

operation of the test system will yield valid data. The results will then be plotted in a form which should lead to an appreciation of the scaling limitations of the airborne radar test-system.

PERFORMANCE FACTORS TO BE CONSIDERED

(U) The performance factors which can be expected to change with a change in radar altitude are:

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- (a) the size of the clutter cell
- (b) the signal-to-noise ratio (for a given target size)
- (c) the number of pulses integrated
- (d) sea clutter decorrelation time
- (e) target decorrelation time and the number of independent samples.

Each of these factors will now be considered in detail.

(U) The size of the clutter cell: Fig. 1 illustrates a patch of the surface of the sea illuminated by the radar. This patch is sometimes referred to as the "resolution cell"; its dimensions define the basic resolution limits of the radar. It is also referred to as the "clutter cell" because its size determines the amount of sea clutter which will be backscattered to compete with the signal returned from the target.

(U) In order that the target occupy the same number of resolution cells in both systems, and that the magnitude and distribution of sea clutter be the same, this clutter-cell size should not change appreciably between the test and reference systems. The radial length of the cell on the surface of the sea is

$$r_p = \frac{c \tau}{2} \sec \phi \quad (1)$$

in which c is the velocity of light, τ is the pulse length, and ϕ is the grazing angle. The dimension r_p can be preserved by keeping the same pulse length and by comparing data for identical values of grazing angle, which is what will be done. In the other dimension the width of the clutter cell is $R\theta$, where R is the radar slant-range to the target area and θ is the width of the radar beam. In the current investigation, for a given altitude of the airborne test-system, the clutter-cell width will be calculated for both test and reference systems at each value of grazing angle. Then the difference in cell width will be expressed as a percentage of the reference-system clutter cell; thus

$$\xi = \frac{(R\theta)_{\text{test}} - (R\theta)_{\text{ref}}}{(R\theta)_{\text{ref}}} \times 100\% \quad (2)$$

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The limits for this error function will be chosen to be:

- a. $\xi = \pm 10\%$ - the preferred region of operation
- b. $\xi = \pm 20\%$ - an acceptable region for operation
- c. $\xi > \pm 20\%$ - not acceptable for operation

(U) The value of θ in Eq. (2) depends on the position of the target with respect to the elevation plane of the radar beam. If the target is located at the depression angle at which the beam is pointed, θ will be the principal-plane half-power azimuth beamwidth of the antenna (10.7° for the shallow-grazing-angle subsystem; 44° for the steep-grazing-angle subsystem). At other depression angles the effect of the antenna elevation pattern must be taken into account. The value of θ can be determined by considering the elliptical cross-section of the beam as shown in Fig. 2. The beam is located with its principal azimuth plane (beamwidth = θ_0) along the X-axis, and its principal elevation plane (beamwidth = γ_0) along the Y-axis. The equation for the ellipse is:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \quad (3)$$

in which:

$$a = \frac{1}{2} \text{ the minor axis of the ellipse} = \theta_0/2 \quad (4a)$$

$$b = \frac{1}{2} \text{ the major axis of the ellipse} = \gamma_0/2 \quad (4b)$$

We wish to find the effective azimuth beamwidth, θ , at an angle β from beam center. In Eq. (3):

$$x = \theta/2 \quad (5a)$$

$$y = \beta = (\psi_0 - \psi) \quad (5b)$$

where ψ_0 is the depression angle corresponding to the center of the beam, and ψ is the depression angle corresponding to slant range R (in Eq. (2)). Substituting Eqs. (4) and (5) into (3) and solving for θ :

$$\theta = \theta_0 \sqrt{1 - \frac{4 (\psi_0 - \psi)^2}{\gamma_0^2}} \quad (6)$$

(S) Signal-to-noise ratio: In order that the performance of the airborne test system be meaningfully related to that of the satellite reference system, it is necessary that comparable levels of signal be received and processed, i.e., that the signal-to-noise ratios be the same in both systems for a given-size target. The signal-to-noise ratio (or, more precisely, the signal-to-noise-plus-clutter ratio) is a function of a number of radar parameters, chief of which are: transmitted power, antenna gain, receiver noise figure, receiver bandwidth and frequency. Values for most of these parameters have already been established on the basis of other considerations¹. However, the transmitted r.f. power can be adjusted to achieve the desired level of signal with respect to noise and clutter, provided that the transmitter offers an adequate range of adjustment. If this adjustment is not sufficient, the effect of changing transmitter power can be simulated by inserting attenuation in the receiving line just before the r.f. amplifier. By whichever means this power-level setting is accomplished, the adjustment can be made to accommodate any desired combination of system parameters. Therefore, consideration of this factor will be delayed until all other scaling problems have been settled.

(U) Number of pulses integrated: In order to achieve equal post-detection integration gains in both test and reference systems, the number of pulses integrated should be the same. The number of pulses integrated in the test system is given by

$$n = \left(\frac{\theta}{\omega} \right) (\text{PRF}) \quad (7)$$

in which θ is the effective width of the radar beam (as given by Eq. (6)) and ω is the rotational velocity of the antenna. In the original design of the test-system the desired number of pulses integrated was obtained for each of the two sub-systems by making an appropriate selection of values for both antenna rotation speed and the pulse repetition frequency (PRF). This extra degree of freedom was advantageous because these parameters also produced effects on other performance factors. However, with the present configuration of the radar, PRF values have been established and cannot easily be

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altered. Therefore, any adjustment required in the value of n will have to be made by changing the antenna rotational speed, ω . Operationally, this is a convenient adjustment to make, since the antenna-control system provides for continuous control of antenna speed over a wide range of values.

(U) Sea-clutter decorrelation time: The improvement in detection achieved through integration depends on the fact that the noise component of the received signal is not correlated. In the same manner, the target signals will be enhanced relative to the signals from the surrounding sea, provided that this sea return is decorrelated from pulse to pulse. If the time required for the sea clutter to decorrelate is short in terms of the interpulse period, the clutter has a noiselike character and will have a similar effect in the integration process as does noise. If, on the other hand, the sea clutter remains correlated for a full interpulse period or longer, the character of the clutter will be more like that of the signal itself, and the full improvement from integration will not be realized.

(S) Sea-clutter decorrelation in terms of interpulse periods is given by the "clutter product": $T_d \times (\text{PRF})$, where T_d is the sea-clutter decorrelation time in seconds and the Pulse Repetition Frequency is given in pulses per second. In the satellite reference system this clutter product is equal to 0.211 indicating that sea clutter is completely decorrelated from pulse to pulse (because the product is less than unity). In order to achieve comparable performance in the airborne test-bed system, it is a sufficient condition that:

$$T_d \times (\text{PRF}) < 1 \quad (8)$$

In the design of the test-system, the clutter product was 0.560 for the case of the shallow-grazing-angle sub-system and 0.211 for the case of the steep-grazing-angle sub-system. Therefore, in the current analysis, it is necessary to determine whether changes in the parameters affecting this clutter product can make it increase beyond the limit expressed by Eq. (8). By substituting an approximate expression for sea-clutter decorrelation time, Eq. (8) can be rewritten as:

$$\frac{\lambda}{v\theta} \times (\text{PRF}) < 1 \quad (8a)$$

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where λ is the radar wavelength, V is the linear velocity of the radar platform (i.e., the aircraft), and θ is given by Eq. (6). In Eq. (8a) λ and the PRF remain constant. The effective beamwidth, θ , will vary with grazing angle and will thus cause changes in the clutter product. A change in aircraft ground speed with respect to its nominal value of 311 feet per second will also change the clutter product. Assuming winds of 30 knots, aircraft velocity might be in error by as much as 20%. The effects of these variations in θ and V will have to be considered in the computer program for establishing the operating limits of the airborne test-system.

(U) Target decorrelation time and the number of independent samples: Since a ship target comprises a number of individual scatterers, the cumulative signal returned from the ship will depend on the way in which the returns from these numerous scatterers add in phase and amplitude. The degree to which the target-returns from successive radar pulses will be correlated depends on both the change in the viewing angle (due to motion of the platform) and the motion of the target itself during the interpulse period. These effects can be expressed in terms of a target decorrelation time, a concept which is analogous to the sea-clutter decorrelation time previously discussed. Total target decorrelation time is given by¹:

$$T_t = \frac{T_p \cdot T_s}{T_p + T_s} \quad (9)$$

in which:

$$\begin{aligned} T_s &= \text{target decorrelation due to ship motion} \\ &\quad \text{(assuming sea state 4)} \\ &= 1 \text{ second at steep grazing angles}^* \\ &= 100 \text{ seconds at shallow grazing angles}^* \\ T_p &= \text{target decorrelation due to motion of the} \\ &\quad \text{radar platform} \end{aligned}$$

* These estimates are based on a private communication with Dr. G. Trunk, Radar Analysis Staff, NRL

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$$T_p = \frac{R\lambda}{2 V_s} \quad (10)$$

λ = radar wavelength

R = slant range to target

V = radar platform velocity

s = length of ship target

(U) The value of T_t affects the number of independent samples received by the radar during the viewing (i.e., integration) period. The number of independent samples is

$$N = \frac{I}{T_t} + 1 \quad (11)$$

in which I , the integration period in seconds, is given by

$$I = \frac{\theta}{\omega} \quad (12)$$

(U) Table II illustrates how the value of N is related to system performance². It would be advisable of course, that the value of N be the same in both test and reference systems. This however, was not possible even in the original design of the test-system because of conflicts between various performance requirements. In the current situation, the parameters θ and ω have already been established on the basis of previous considerations and therefore cannot be used to adjust the value of N . Therefore, in the present analysis, the value of N will simply be calculated for each parametric change to determine whether the resultant difference in sensitivity between the test and reference systems is acceptable. The criteria for acceptability will be the same ones used in the previous analysis¹: The sensitivity of the steep-grazing-angle subsystem shall be within ± 0.5 dB of that of the reference system; the sensitivity of the shallow-grazing-angle subsystem shall be within $+0.5$ dB and -2.0 dB of the reference system.

RESULTS OF THE ANALYSIS

(U) From the computer printout of the performance factors and error factors discussed in the previous paragraphs, the limits of

TABLE II

Required Increase In The Signal-to-Noise Ratio
With Respect To Complete Independence

Number Of Independent Samples	Increase in Signal-to-Noise Ratio (in DB)	
	For 90% Probability of Detection	For 99% Probability of Detection
1	7.5	11.75
2	4.5	7.25
4	3.0	4.75
10	1.25	2.0
100	0	0

system operation can be delineated. The results have been plotted in Fig. 3 for the shallow-grazing-angle subsystem and in Fig. 4 for the steep-grazing-angle subsystem. In both cases, the chief parameter which determined these operating regions was the factor ξ , the percentage error in clutter-cell width as given by Eq. (2). The other performance factors were checked and found to be within acceptable limits in these regions.

(U) These curves provide other useful guides for the operation of the test radar. Thus, in Fig. 3 the contours of constant grazing angle are shown for the shallow-grazing-angle subsystem. By selecting an appropriate altitude and controlling the flight path so that the range to the target is within the acceptable region, radar data can be gathered for any desired value of grazing angle from 0° to 2.0° . Contours of constant rotation rate, ω , are also shown in Fig. 3. It can be appreciated from the values of ω shown on these curves, that this is not a particularly critical parameter for this subsystem. Over the entire operating region the value of ω does not vary more than 13% from a nominal value of 1.9 degrees per second.

(U) For the case of the steep-grazing angle subsystem, the operating regions delineated in Fig. 4 show that there is a minimum altitude for gathering meaningfully-scaled data. Thus, to take

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advantage of the preferred region of operation, the aircraft must fly at altitudes above 14,000 feet. Contours of constant ω are also shown in Fig. 4. Because of the geometrical relationship between radar and target in this subsystem, the contours of constant grazing angle coincide with contours of constant ω . In order to avoid confusion in the diagram, only the contours of integer values of ω have been drawn, but these have also been labeled with the resultant (noninteger) values of grazing angle. Although the plot here shows a preferred region extending out as far as 12.5 nautical miles (for an altitude of 16,000 feet), in general, it will be the area close to the left edge of the preferred region which will be utilized. This will be consistent with one of the basic aims of the tests, which is to examine surveillance capabilities at steep grazing angles where system sensitivity is clutter limited.

(U) As an example of how these curves would be used during a data-gathering flight, refer to Fig. 4. Suppose that for operational reasons the airplane must fly at an altitude of 14,000 feet. The shaded bands of Fig. 4 show that the range to the target must lie between 4.1 and 10.2 nautical miles, if meaningfully scaled data are to be obtained. At this altitude, the performance of the test system will most closely simulate that of the reference system if the target is at a range of about 6.2 nautical miles (when it is broadside to the flight vector), since this point lies within the "preferred" region of operation. However, a more important consideration would probably be to gather data in regions where the sea-clutter return is high. Therefore, we might choose to take data where the grazing angle is steeper, say at a grazing angle of 27.5 degrees. The 27.5 degree line in Fig. 4 shows that if we wish to operate at this point we must set the antenna speed at 36 degrees/second and adjust the aircraft flight path so that the target will be at a range of 4.5 nautical miles as the plane passes by it.

R.F. POWER REQUIREMENTS

(S) As mentioned earlier, the signal-to-noise ratio of the satellite reference radar will be simulated in the airborne test system by an appropriate adjustment of transmitter power output. The level of r.f. power required for this simulation can be calculated from the basic radar equation. A computer program was set up to perform these calculations using the equations which are detailed in Appendices A and B. A flow chart of the computer program is presented in Appendix C.

(U) The results of these power calculations are shown in Fig. 5 for the shallow-grazing-angle subsystem and in Fig. 6 for the

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steep-grazing-angle subsystem. Values of r.f. pulse power are shown for increments of altitude and range in the areas of interest. The charts also reflect the regions of operation which were delineated in Figs. 3 and 4, the various shaded regions having the same meaning as before. The fact that transmitter pulse power, rather than average power, was selected as the parameter for display is simply a matter of operational convenience.

(U) The power levels shown in Figs. 5 and 6 are for measurements made at the directional coupler. These levels are therefore 0.8 dB lower than the actual transmitter output because of the intervening line loss. If the adjustment available at the transmitter proves to be inadequate for lowering the signal to the desired level, known values of attenuation can be inserted in the receiver line (before the r.f. amplifier) to further decrease system sensitivity.

TRACK-AID CONTOURS

(U) In order to make proper use of the foregoing guides, the aircraft flight-path should be oriented so that the target will be at the selected radar range when its bearing is 90 degrees from the aircraft flight vector. This situation will be referred to as the "broadside aspect". This broadside situation is the "design center" in regard to various scaling considerations. For target angles other than the broadside aspect, scaling is less perfect, although, as has been shown previously¹, the scaled performance will be quite adequate over a considerable range of aspect angles. However, in order to minimize scaling errors, the aim during a data-pass should be to achieve the intended radar-to-target range for the broadside aspect.

(U) For this purpose the Track-Aid contours of Figs. 7 and 8 have been drawn. Based on the simple geometric relationship between radar-to-target aspect-angle and range, the plots trace the apparent path of a target as the radar passes by. For example, suppose one were to sight a target at a range of 60 nautical miles at 90° (broadside) aspect. Then, assuming a constant aircraft flight vector, the track of this target in range and bearing would follow the curve labeled "60". However, it is actually the converse situation in which these curves find their utility. That is, in order to achieve a specified range at broadside, one must adjust the aircraft flight path until the target lies on the desired contour; thereafter, if the flight vector is held constant, the target-track will follow the selected contour. The way in which these curves can be utilized during an operational flight is illustrated with reference to Fig. 7. Suppose that on the approach the target is located at a bearing of 54° (from the nose of the aircraft) and a range of 8. nautical miles.

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This position of the target is plotted in Fig. 7 at the intersection of the 54-degree abscissa with the 84-nautical-mile ordinate. This point, marked "A" in Fig. 7, lies on the 68-nautical-mile contour. However, suppose it had been desired on this data run that the target be at a range of 60 nautical miles at broadside aspect. One must then (by a suitable maneuver of the aircraft) shift the target from the 68-nautical-mile contour to a position on the 60-nautical-mile contour, or from point A to some point such as B in Fig. 7. It is not possible nor is it necessary, to describe here the precise aircraft maneuver which is required to accomplish this change between contours. This task may best be left to the pilot, who should be able to make the desired adjustment of the flight vector upon being given an instruction to "execute an S-turn to increase range by eight nautical miles".

SUMMARY

(U) Calculations have been made and a number of aids have been presented which will prove useful in the operation of the airborne test-bed radar system. The curves and charts will:

- (1) permit the selection of grazing angle
- (2) indicate the proper value of antenna rotation speed
- (3) show the limited regions of operation
- (4) indicate the proper setting of transmitter power
- (5) provide assistance in orienting the aircraft flight vector.

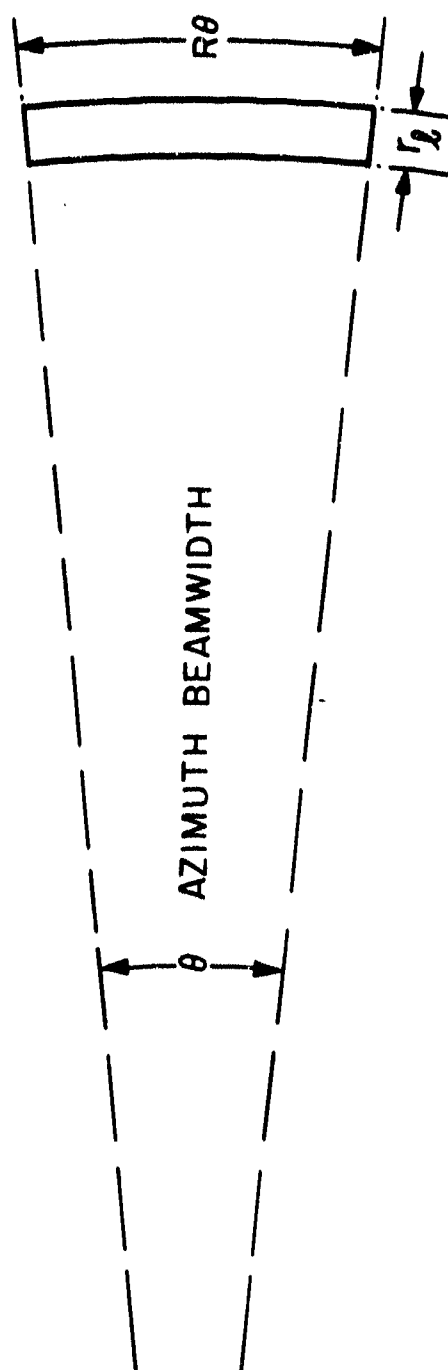


Fig. 1 - The radar clutter cell on the surface of the sea. The length of the cell in the radial direction is r_l , and the width of the cell at range R is $R\theta$.

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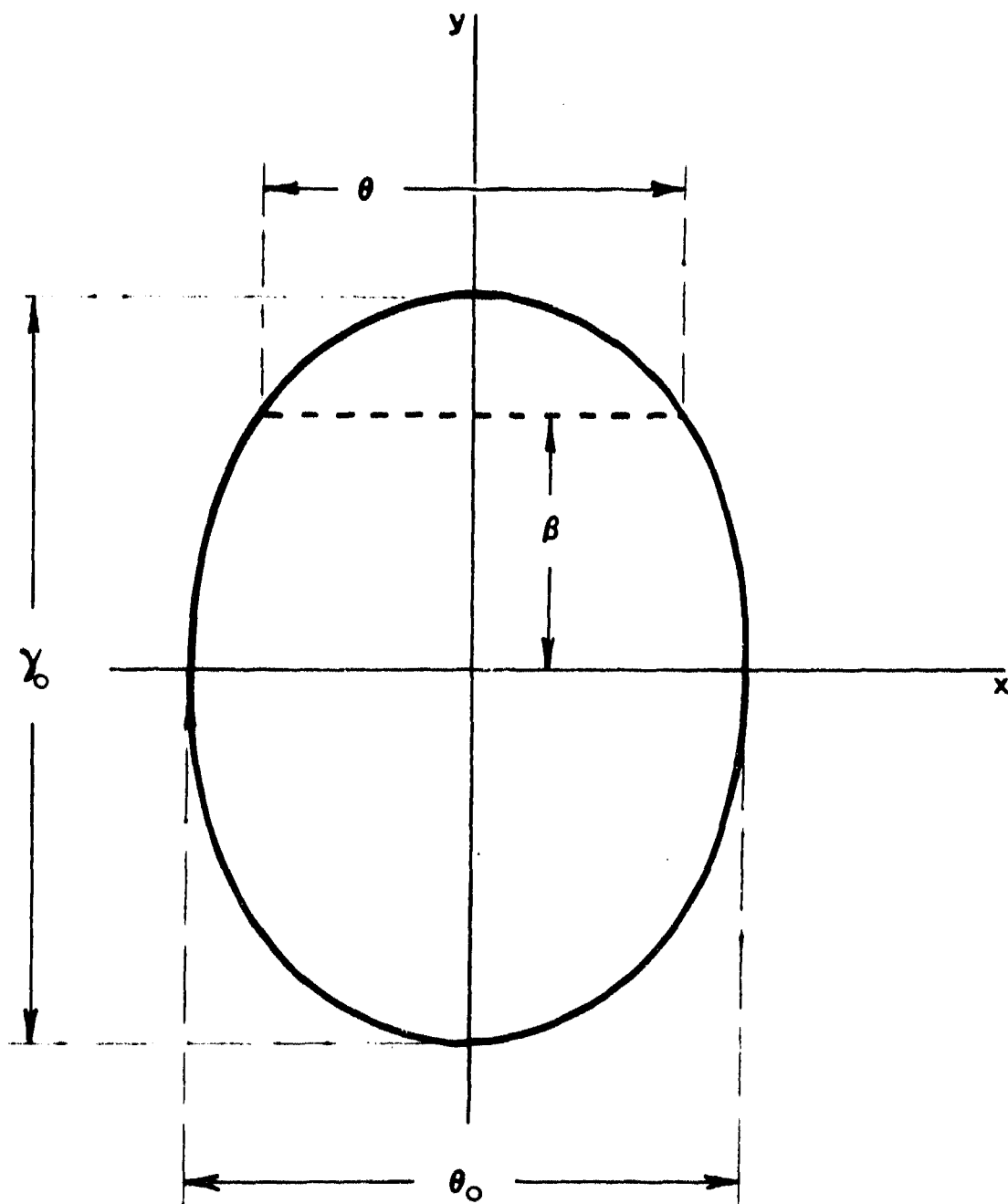


Fig. 2 - Elliptical cross-section of the radar beam. The principal-plane beamwidths are θ_0 (in azimuth) and γ_0 (in elevation). θ is the (azimuth) width of the beam at angle β from the elevation axis.

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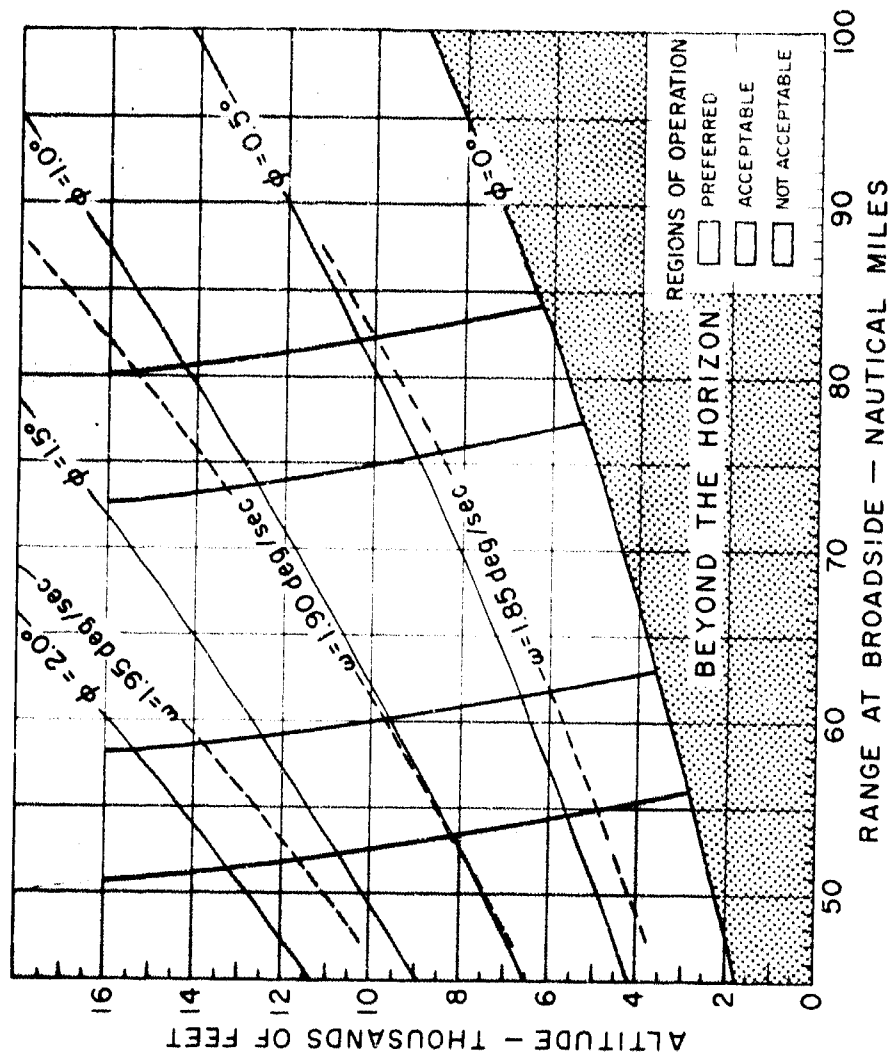


Fig. 3 - Operating regions and parameters for the shallow-grazing-angle subsystem. ϕ is the grazing angle; ω is the antenna rotation speed.

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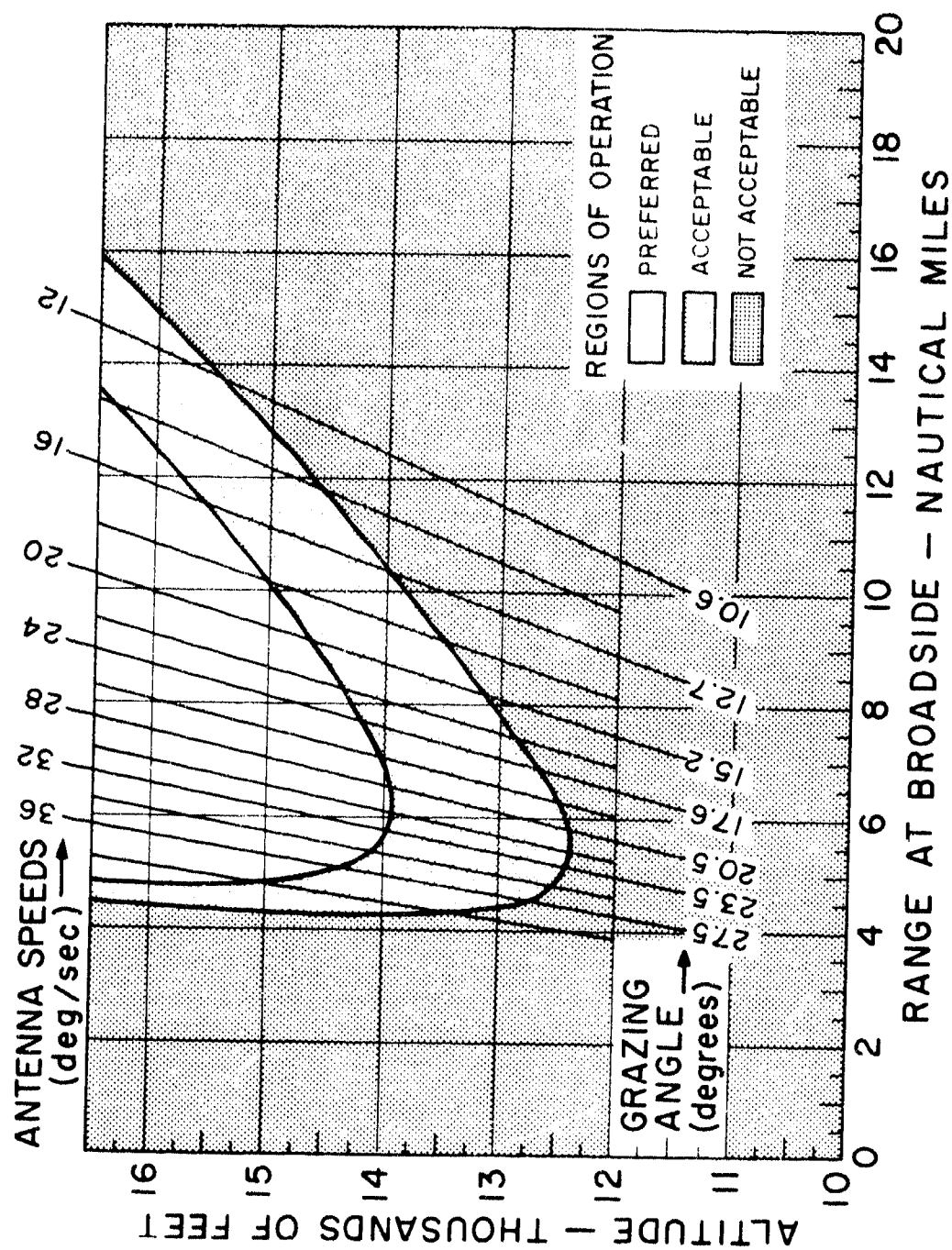


Fig. 4 - Operating regions and parameters for the steep-grazing-angle subsystem. Contours of Antenna Speed are coincident with contours of Grazing Angle.

POWER IN KW		TARGET SIZE = 200 SQUARE METERS															22 MARCH 1971 (DATE)	
ALTITUDE (feet)		RADAR RANGE TO TARGET (nautical miles)																
		52	54	56	58	60	62	64	66	68	70	72	74	76	78	80	82	
16,000		2.80	3.25	3.84	4.41	5.05	5.76	6.54	7.58	8.55	9.62	10.78	12.05	13.81	15.37	17.06		
15,000		2.77	3.21	3.81	4.38	5.02	5.72	6.49	7.54	8.51	9.58	10.74	12.01	13.78	15.34	17.04		
14,000		2.74	3.18	3.78	4.35	4.98	5.68	6.45	7.51	8.48	9.54	10.70	11.97	13.76	15.32	17.01		
13,000		2.71	3.15	3.75	4.32	4.95	5.65	6.42	7.48	8.45	9.51	10.67	11.93	13.75	15.31	17.00		
12,000		2.69	3.12	3.72	4.29	4.92	5.62	6.39	7.46	8.42	9.48	10.64	11.90	13.74	15.30	16.99		
11,000			3.10	3.70	4.27	4.89	5.59	6.36	7.44	8.40	9.46	10.62	11.88	13.74	15.30	16.99		
10,000			3.08	3.68	4.25	4.87	5.57	6.33	7.42	8.38	9.44	10.60	11.86	13.74	15.30	17.00	18.83	
9,000			3.06	3.67	4.23	4.86	5.55	6.31	7.41	8.37	9.43	10.58	11.85	13.75	15.31	17.01	18.84	
8,000			3.05	3.66	4.22	4.84	5.53	6.30	7.40	8.36	9.42	10.58	11.84	13.76	15.33	17.02	18.86	
7,000			3.03	3.65	4.21	4.83	5.52	6.28	7.40	8.36	9.42	10.57	11.83	13.78	15.35	17.05	18.89	
6,000				3.64	4.20	4.82	5.51	6.27	7.40	8.36	9.42	10.57	11.84	13.81	15.38	17.08	18.92	
5,000				3.64	4.19	4.82	5.50	6.27	7.40	8.37	9.42	10.58	11.84	13.83	15.38	17.04	18.85	

Fig. 5 - Transmitter pulse power (in kilowatts) for the shallow-grazing-angle subsystem.

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TARGET SIZE = 200 SQUARE METERS

POWER IN WATTS

ALTITUDE (feet)	RADAR RANGE TO TARGET (nautical miles)															
	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	10.0	11.0	12.0	13.0	14.0	15.0
16,000	88	73	80	98	125	162	210	266	336	426	675	1044	1570	2234	3267	4544
15,500	68	63	74	93	120	158	206	261	334	426	683	1061	1600	2343		
15,000	55	55	68	89	117	155	201	259	334	429	692	1081	1635			
14,500	45	51	64	85	114	153	198	258	335	433	704	1104				
14,000	38	47	61	83	112	149	196	259	338	439	718					
13,500	34	44	59	81	111	147	196	261	343	447						
13,000	31	41	57	79	108	146	198									
12,500		39	55	78												
12,000																
11,500																

Fig. 6 - Transmitter pulse power (in watts) for the steep-grazing-angle subsystem

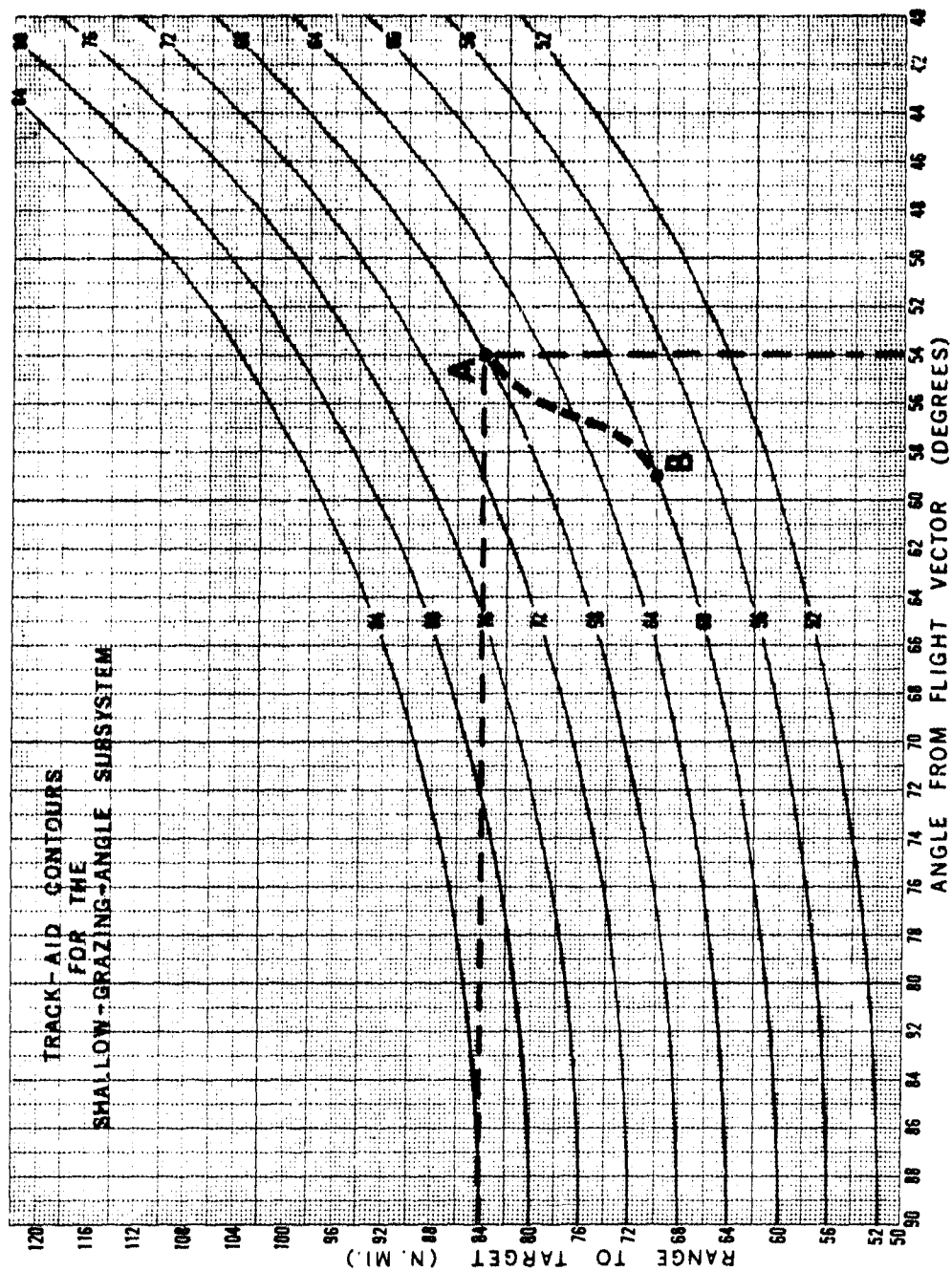


Fig. 7 - Track-aid contours for the shallow-grazing-angle subsystem. If the target is at point A on the 68-nautical-mile contour, and it is desired that it be at a range of 60 nautical miles when it is broadside to the flight vector, the aircraft must be maneuvered to shift the position of the target to some point on the 60-nautical-mile contour such as B.

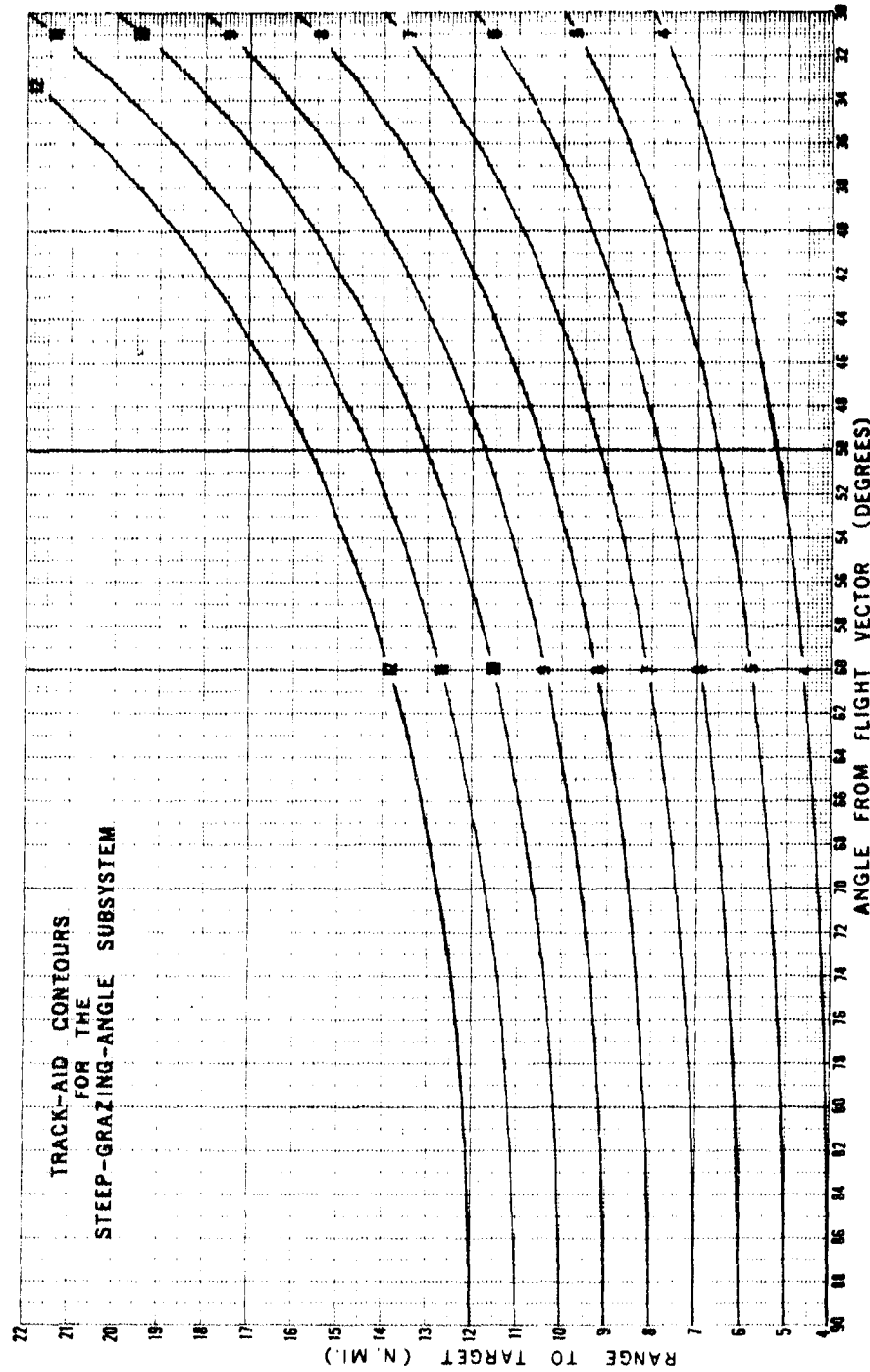


Fig. 8 - Track-aid contours for the steep-grazing-angle subsystem

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APPENDIX A

CALCULATION OF R.F.-POWER LEVELS

INTRODUCTION

The levels of R.F.-power shown in Figs. 5 and 6 in the text were calculated in a computer program using a version of the basic radar equation. A flow chart of this computer program is shown in Appendix C. However, before presenting the form of the equation used in these calculations, certain parameters which appear as factors in the equation should be discussed in detail. These are:

- (a) Antenna gain, G
- (b) System transmitting losses, L
- (c) Receiving system noise power, N_o

ANTENNA GAIN, G

The values of antenna gain at beam center for the two subsystems were listed in Table I: 13.3 dB for the steep-grazing-angle system and 22.2 dB for the shallow-grazing-angle system. Since, in general, the target will not be located at the depression angle which corresponds to beam center, it is necessary to take into account the effect of the vertical pattern on antenna gain. For this purpose, the following function will be used to approximate the real antenna power pattern:

$$G = \frac{\pi^4}{16} \left[\frac{\cos^2 x}{\left[\frac{\pi^2}{4} - x^2 \right]^2} \right] G_o \quad (A-1)$$

where

- $x = F \sin (\psi_o - \psi)$
- $F =$ a factor relating to antenna size
- $\psi_o =$ depression angle to beam center
- $\psi =$ depression angle to target
- $G_o =$ antenna gain at beam center

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Equation (A-1) describes the pattern of a rectangular aperture with a cosine-tapered illumination and sidelobes of approximately 25 dB. In order to relate this gain function to the actual vertical power pattern, the factor F will be evaluated so that the theoretical relative gain matches the actual relative gain at the half-power points of the pattern. That is, the following equation is solved for F:

$$\frac{G}{G_0} = \frac{\pi^4}{16} \left[\frac{\cos \left(F \sin \frac{\gamma_0}{2} \right)}{\frac{\pi^2}{4} - \left(F \sin \frac{\gamma_0}{2} \right)^2} \right]^2 = 0.5 \quad (A-2)$$

in which γ_0 is the measured vertical half-power beamwidth of the antenna.

Equation (A-2) yielded $F=11.03$ for the shallow-grazing-angle subsystem, and $F = 5.74$ for the steep-grazing-angle subsystem. Using these factors, Equation (A-1) is then solved for antenna gain for the appropriate value of depression angle.

SYSTEM TRANSMITTING LOSSES, L

The losses on transmission enter into the loss factor, L, in the denominator of the radar equation. Table A-1 lists these losses for both subsystems and notes (under "Justification") how the loss values were obtained. As indicated by the table, the tropospheric absorption is a constant for the steep-grazing-angle subsystem. However, at shallow grazing angles this loss factor does vary, both with grazing angle and with range. Table A-2 shows values for the tropospheric loss factor in the region of interest. These values were obtained from curves presented in Ref. 3. For determining the tropospheric loss in the computer program, equations were used which gave straight-line approximations to these values with grazing angle as the dependent variable.

RECEIVING SYSTEM NOISE POWER, N_0

The losses in the receiving system are accounted for in terms of the receiving system noise power, N_0 . Blake³ discusses the concept of system noise temperature, which is related to system noise power by the equation:

TABLE A-1
List of System Transmission Losses

Loss	Symbol	Magnitude Of Loss		Justification
		Shallow-Grazing Angle Subsystem	Steep-Grazing Angle Subsystem	
Transmission Line*	L_t	1.75 dB	1.75 dB	By Measurement
Antenna Pattern	L_p	1.60 dB	1.60 dB	See Ref. 3
Radome (Two-Way)**	L_d	1.00 dB	1.00 dB	Calculated (See Ref. 4)
Tropospheric Absorption	L_α	See Table A-2	0.10 dB	From Fig. 22 in Ref. 3

* This is the transmission-line loss from the antenna terminals to the directional coupler where the transmitter power is monitored.

** To be rigorous, only one-half the total radome loss should be applied here and the other half should be accounted for in the receiving-system noise temperature calculation. For the sake of simplicity, however, the entire loss will be applied here.

TABLE A-2
Two-Way Tropospheric Absorption (in DB) at 1230 MHz

RANGE n. mi.	Grazing Angle			
	0°	0.5°	1.0°	2.0°
50	1.05	0.95	0.90	0.80
60	1.20	1.15	1.05	0.90
70	1.40	1.30	1.20	1.00
80	1.60	1.45	1.30	1.10

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$$T_s = \frac{P_n}{k B_n} = \frac{N_o}{k} \quad (A-3)$$

in which:

T_s = the overall receiving system noise temperature

P_n = available noise power of the receiving system

B_n = noise bandwidth of the receiver

k = Boltzmann's constant = 1.3805 watt-sec/K°

N_o = Noise power per unit bandwidth, the form of the parameter as it will be used in the radar equation.

As Blake shows, each of the components of the receiving system contributes its own effective noise temperature, so that the overall system noise temperature is

$$T_s = T_a + T_r + L_r T_e \quad (A-4)$$

in which:

T_a = antenna noise temperature

T_r = transmission-line noise temperature

L_r = transmission-line loss factor

T_e = noise temperature of the receiver

We will now discuss each of these factors in detail.

Antenna Noise Temperature: If the sea is assumed to be a perfect (although not necessarily specular) reflector at 1230 MHz, then the effective noise-temperature contribution from the antenna is:

$$T_a = \frac{T_a' + 290 (L_a - 1)}{L_a} \quad (A-5)$$

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in which:

- T_a' = temperature of extra-terrestrial noise sources as given by Fig. 11 in Ref. 3.
- = 65° K for shallow grazing angles (i.e., approximately 1°)
- = 22° K for steep grazing angles (i.e., approximately 25°)
- L_a = losses in the antenna, estimated to be 0.6 dB (or a loss factor of 1.15) for both subsystems

Substituting the appropriate values into Eq. (A-5) the resultant antenna noise temperature is found to be 94° K for the shallow-grazing-angle subsystem and 57° K for the steep-grazing-angle subsystem.

Transmission-Line Noise Temperature: For a transmission line with a loss factor of L_r , the noise temperature is:

$$T_r = 290 (L_r - 1) \quad (A-6)$$

The measured line loss between the antenna and the receiver in the test-bed system is 5.9 dB, corresponding to a loss factor of 3.89 (the antilog of 5.9/10). Using this value in Eq. (A-6), the transmission-line noise temperature is found to be 838° K (for both subsystems).

Noise Temperature of the Receiver: The effective noise temperature of a receiver with a noise factor of NF is:

$$T_e = 290 (\overline{NF} - 1) \quad (A-7)$$

The receiver currently being used in the airborne test-bed system has a noise figure of 4 dB, which corresponds to a factor of 2.51. Thus, from Eq. (A-7) the receiver has a noise temperature of 438°.

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Overall System Noise Power: Substituting these component noise temperatures into Eq. (A-4), values for system noise temperature are found for each of the subsystems. The product of system noise temperature and Boltzmann's constant gives the overall system noise power per unit bandwidth, N_o . The results are listed in Table A-3.

TABLE A-3

System Noise Power

Subsystem	System Noise Temperature in deg. K	Noise Power Per Unit Bandwidth in watt-sec
Shallow-grazing-angle	2636	3.639×10^{-20}
Steep-grazing-angle	2599	3.588×10^{-20}

THE CALCULATION OF R.F. POWER

We are now ready to present the equations used to calculate the r.f. power required in the test system for simulating the detection performance of the reference system. The following form of the radar equation was employed:

$$P_a = \frac{K (4\pi)^3 \tau_c B_n N_o (PRF) R_s^4 \left(\frac{S}{C+N}\right)_n L}{G^2 \lambda^2 S_i(n) \left[\sigma_T - \frac{\sigma_c \left(\frac{S}{C+N}\right)_n}{S_i(n_c)} \right]} \quad (A-8)$$

In order to convert to pulse power, which is the parameter we wish to monitor in the test-bed system, the following supplemental equation is used:

$$P_p = \frac{P_a}{\tau_c (PRF) (PCR)} \quad (A-9)$$

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The symbols in these equations have the following definitions and values:

- P_a = average transmitter power, watts
- P_p = pulse power in Kw which corresponds to the calculated average power
- K = (1852 meters/nautical mile)⁴
= 11.76424×10^{12}
- $(4\pi)^3$ = 1.98440166×10^3
- B_n = receiver noise bandwidth, Hz
- τ_c = compressed pulselength, seconds
- $\tau_c B_n$ = 1
- (PRF) = the pulse repetition frequency, pulses/sec
= 39.0 pps for the shallow-grazing-angle subsystem
= 62.5 pps for the steep-grazing-angle subsystem
- N_o = receiving system noise power per unit bandwidth, watts per Hz. See previous discussion of this parameter.
- R_s = radar slant range, n.mi. This parameter is an incremented variable.
- $(\frac{S}{C+N})_n$ = integrated signal-to-clutter plus-noise ratio required for a probability of detection (P_d) of 0.90 for fluctuating targets, and a probability of false alarm (P_{fa}) of 10^{-10} . This ratio is a function of integration time. In the computer program the required value of signal-to-clutter-plus noise ratio is calculated from equations based on Fig. 10 of Ref. 2.
- L = system transmitting losses. See Table A-1.

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G = antenna gain. Refer to previous discussion of this parameter.

λ = wavelength, meters

= 0.24373 (1230 MHz)

$S_i(n)$ = integration improvement factor. The following equations are approximations to a curve in Introduction to Radar Systems by M. I. Skolnik. These equations give values for the integration improvement factor when n pulses are integrated.

$$\begin{aligned} S_i(n) &= 1.01 n^{0.944} & 1 \leq n < 4 \\ &= 1.282 n^{0.775} & 4 \leq n < 20 \\ &= 1.675 n^{0.688} & 20 \leq n < 100 \\ &= 2.59 n^{0.593} & n \geq 100 \end{aligned} \quad (A-10)$$

in which

$$n = (\theta/\omega) (\text{PRF}) \quad (A-11)$$

where

θ = effective azimuth beamwidth in radians as given by Eq. (6) in the text.

ω = rotational velocity of the antenna, rad/sec

σ_T = the average cross section of a fluctuating target in square meters

= 200 square meters in this analysis

σ_c = effective radar cross-section of sea clutter within a resolution cell

$$= \sigma^0 K_1 R_s \theta \frac{c \tau_c}{2} \sec \phi \quad (A-12)$$

in which:

σ^0 = backscattering coefficient of the sea, which is dependent on frequency and grazing angle.

K_1 = $3.429904 \times 10^3 \text{ m}^2/(\text{nmi})^2$

R_s = slant range, nmi

c = speed of light

= $1.61875 \times 10^8 \text{ nmi/sec}$

ϕ = grazing angle at the earth's surface

= $\arccos \left(\frac{\cos \psi (r_e + h)^*}{r_e} \right)$ (A-13)

where:

r_e = earth radius

= 3440.0 nmi

h = aircraft altitude, nmi

ψ = depression angle measured at the radar platform.

$S_1(n_c)$ = modified integration improvement factor to account for partial correlation of sea clutter. When the product of the decorrelation time (T_d) and pulse repetition frequency (PRF) is less than unity (i.e., no correlation between pulses), $S_1(n_c) = S_1(n)$ as given in Eq. (A-10). When $T_d \times (\text{PRF}) \geq 1$ (i.e., partial correlation between pulses), determine $S_1(n_c)$ from Eq. (A-10) with:

* The derivation of Eq. (A-13) is shown in Appendix B.

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$$n_c = n/(Td(PRF)) \quad (A-14)$$

where:

$$\begin{aligned} Td &= \text{decorrelation time} \\ &= \lambda/(\theta V_t) \quad (A-15) \\ V_t &= \text{velocity of aircraft} \\ &= 311 \text{ feet/sec} \end{aligned}$$

$$\begin{aligned} PCR &= \text{pulse compression ratio} \\ &= 200 \end{aligned}$$

APPENDIX B

DERIVATION OF EQUATIONS FOR DEPRESSION ANGLE AND GRAZING ANGLE

To obtain the desired tabulation of r.f. power levels using the radar equation, it is necessary to calculate grazing angle for any given value of radar altitude and slant range. Fig. B-1 shows the geometry for a radar at altitude h illuminating a target at radar range R_s . The target lies at a grazing angle ϕ with respect to the ray from the radar. This same ray makes an angle ψ with the local horizontal plane at the radar. ψ is called the depression angle. α is the angle subtended by the radar and target at the center of the earth.

By the law of cosines:

$$\cos \psi_x = \frac{(r_e + h)^2 + R_s^2 - r_e^2}{2 (r_e + h) R_s} \quad (\text{B-1})$$

$$\psi_x = \arccos \left(\frac{(r_e + h)^2 + R_s^2 - r_e^2}{2 (r_e + h) R_s} \right) \quad (\text{B-2})$$

However,

$$\psi = 90 - \psi_x$$

Therefore,

$$\psi = \arcsin \left(\frac{(r_e + h)^2 + R_s^2 - r_e^2}{2 (r_e + h) R_s} \right) \quad (\text{B-3})$$

Next, applying law of sines to Fig. B-1, we obtain the following:

$$\frac{R_s}{\sin \alpha} = \frac{r_e}{\sin \psi_x} = \frac{r_e + h}{\sin (90 + \phi)} \quad (\text{B-4})$$

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Since $\psi_x = 90 - \psi$, Eq. (B-4) can be written as

$$\frac{r_e}{\sin (90 - \psi)} = \frac{r_e + h}{\sin (90 + \phi)}$$

in which the first term of Eq. (B-4) has been dropped.

Then, by the trigonometric identity $\sin (90 \pm x) = \cos x$:

$$\frac{r_e}{\cos \psi} = \frac{r_e + h}{\cos \phi} \quad (B-5)$$

Solving this equation for the grazing angle, we obtain:

$$\begin{aligned} \cos \phi &= (1 + h/r_e) \cos \psi \\ \phi &= \arccos \left((1 + h/r_e) \cos \psi \right) \end{aligned} \quad (B-6)$$

In the computer program for calculating r.f. power, Eq. (B-6) is used in conjunction with Eq. (B-3) to determine the grazing angle for selected increments of altitude and range. Using these values of grazing angle, the radar equation is solved as outlined in Appendix A to obtain values of radar pulse power.

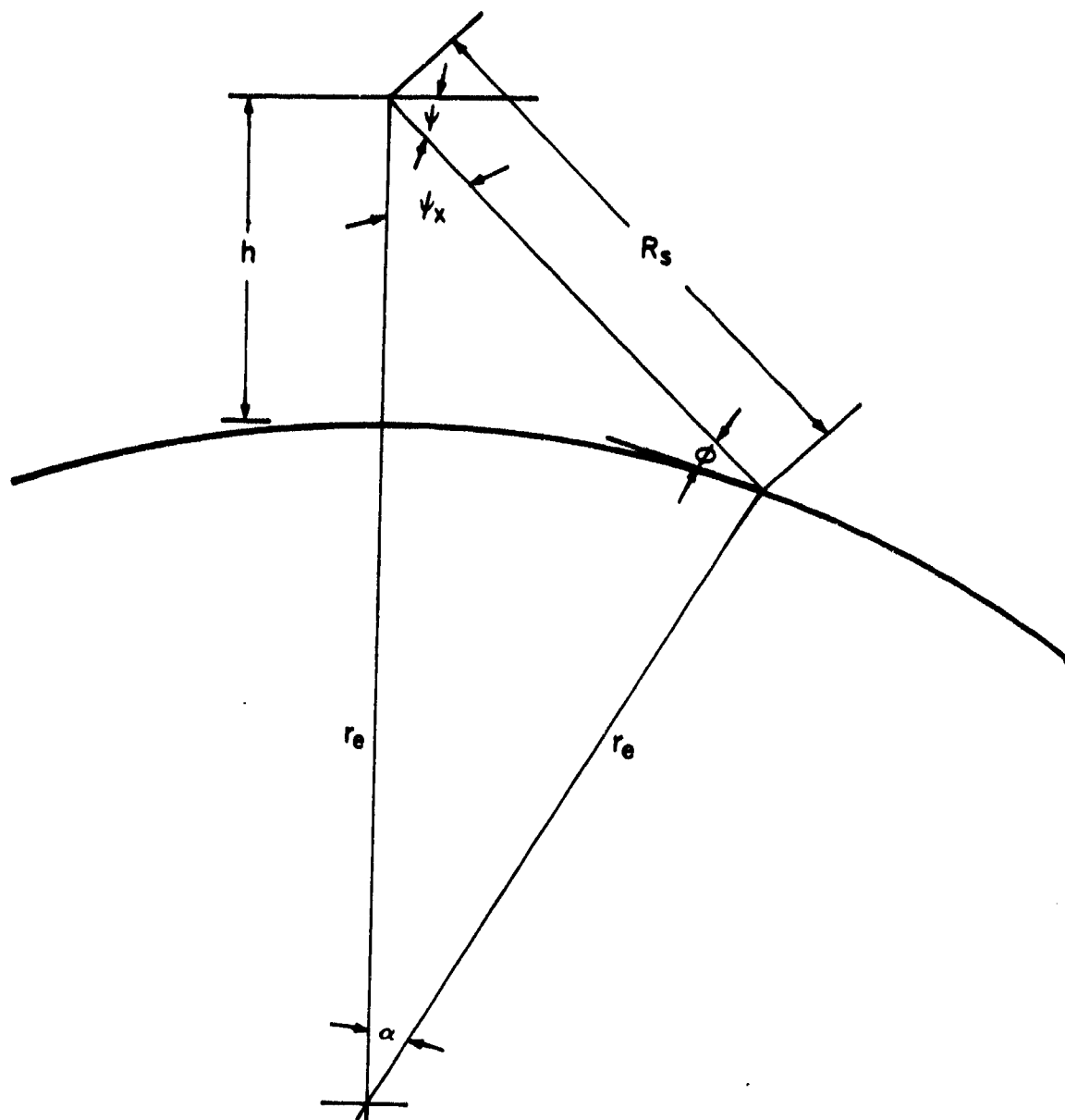


Fig. B-1 - Geometrical relationships between grazing angle, (ϕ), depression angle (ψ), radar altitude (h), and slant range (R_s).

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APPENDIX C

FLOW CHART OF THE COMPUTER PROGRAM
FOR CALCULATION OF R.F POWER

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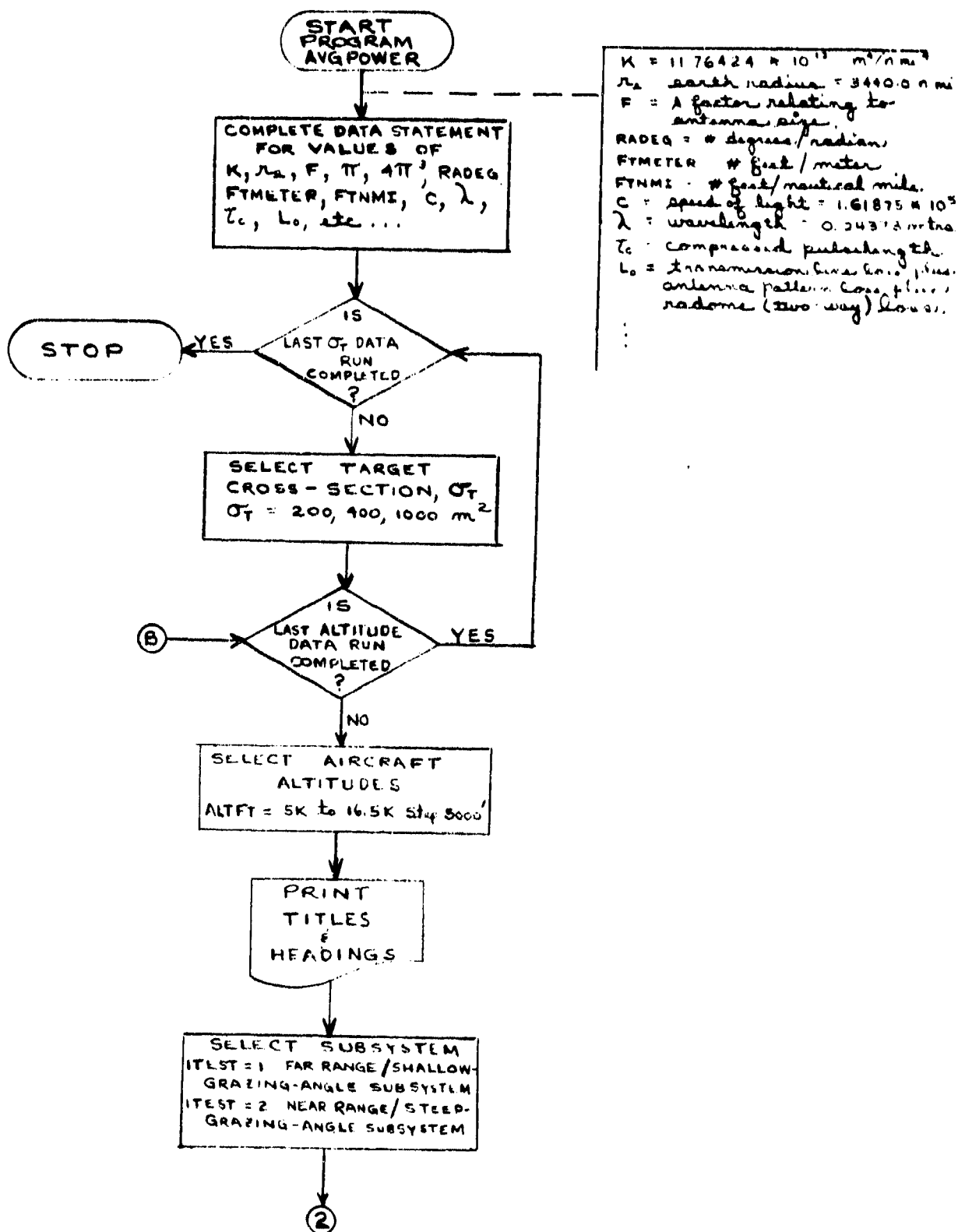


Fig. C-1 - Computer program flow chart

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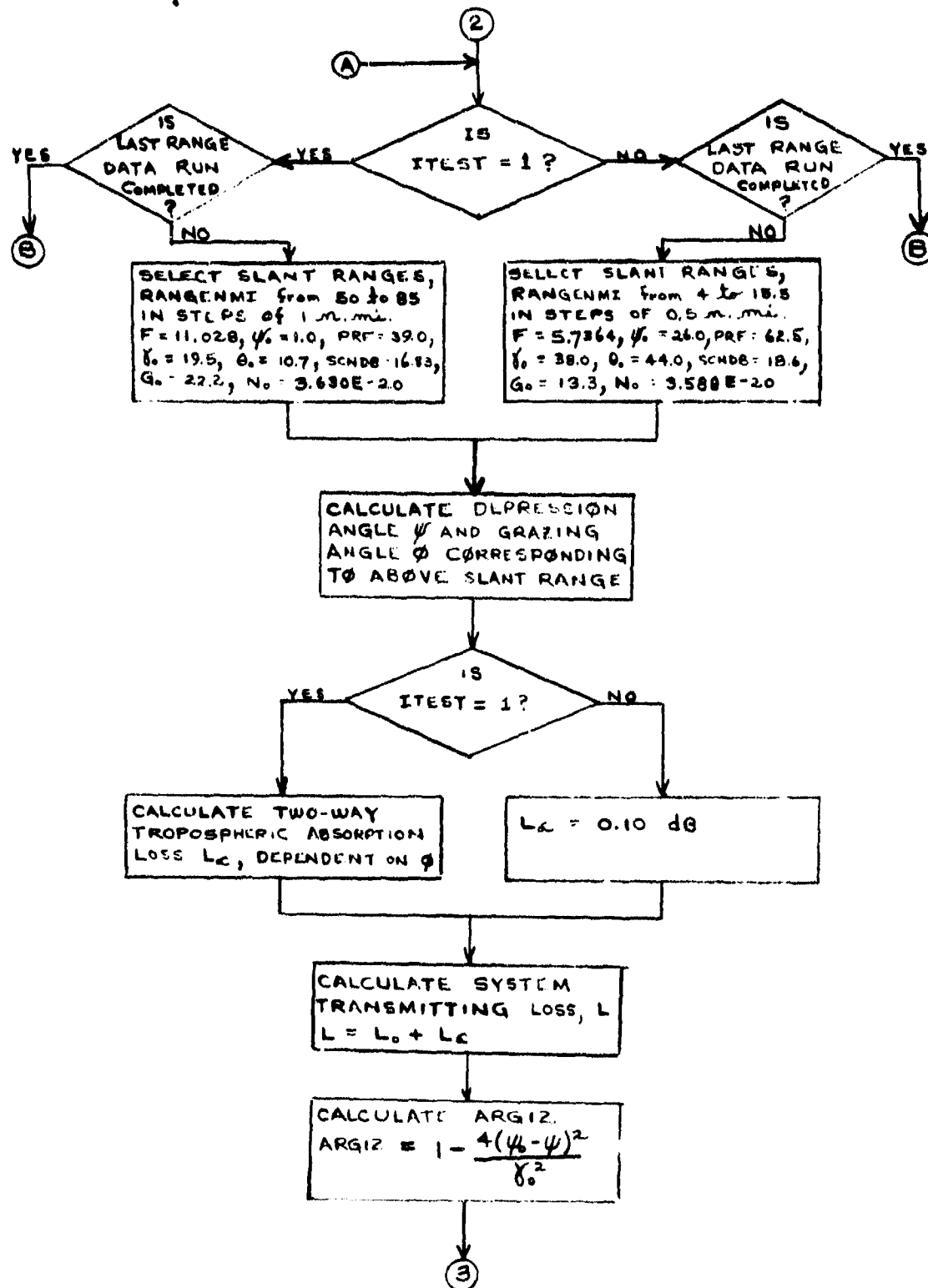


Fig. C-2 - Computer program flow chart (continued)

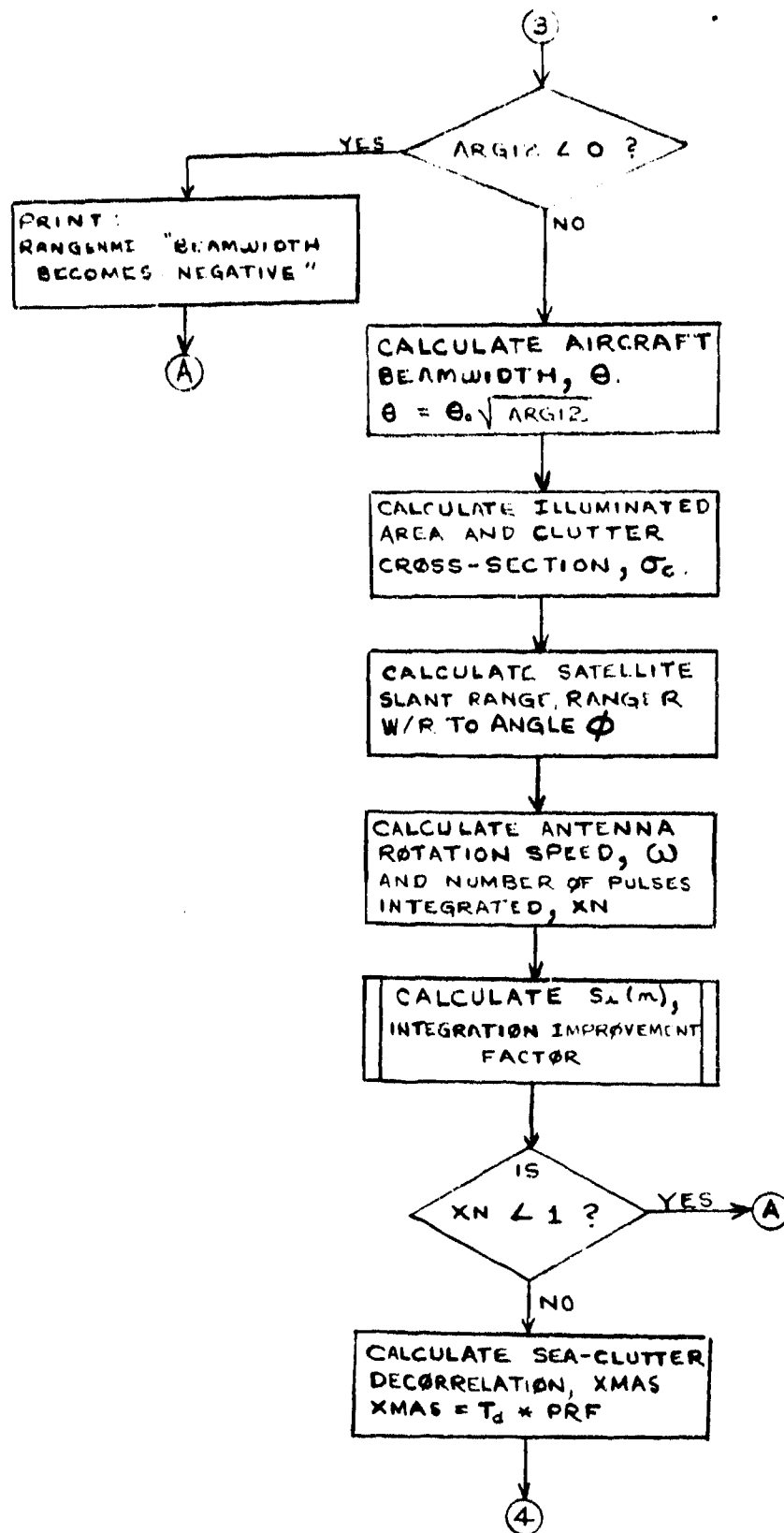


Fig. C-3 - Computer program flow chart (continued)

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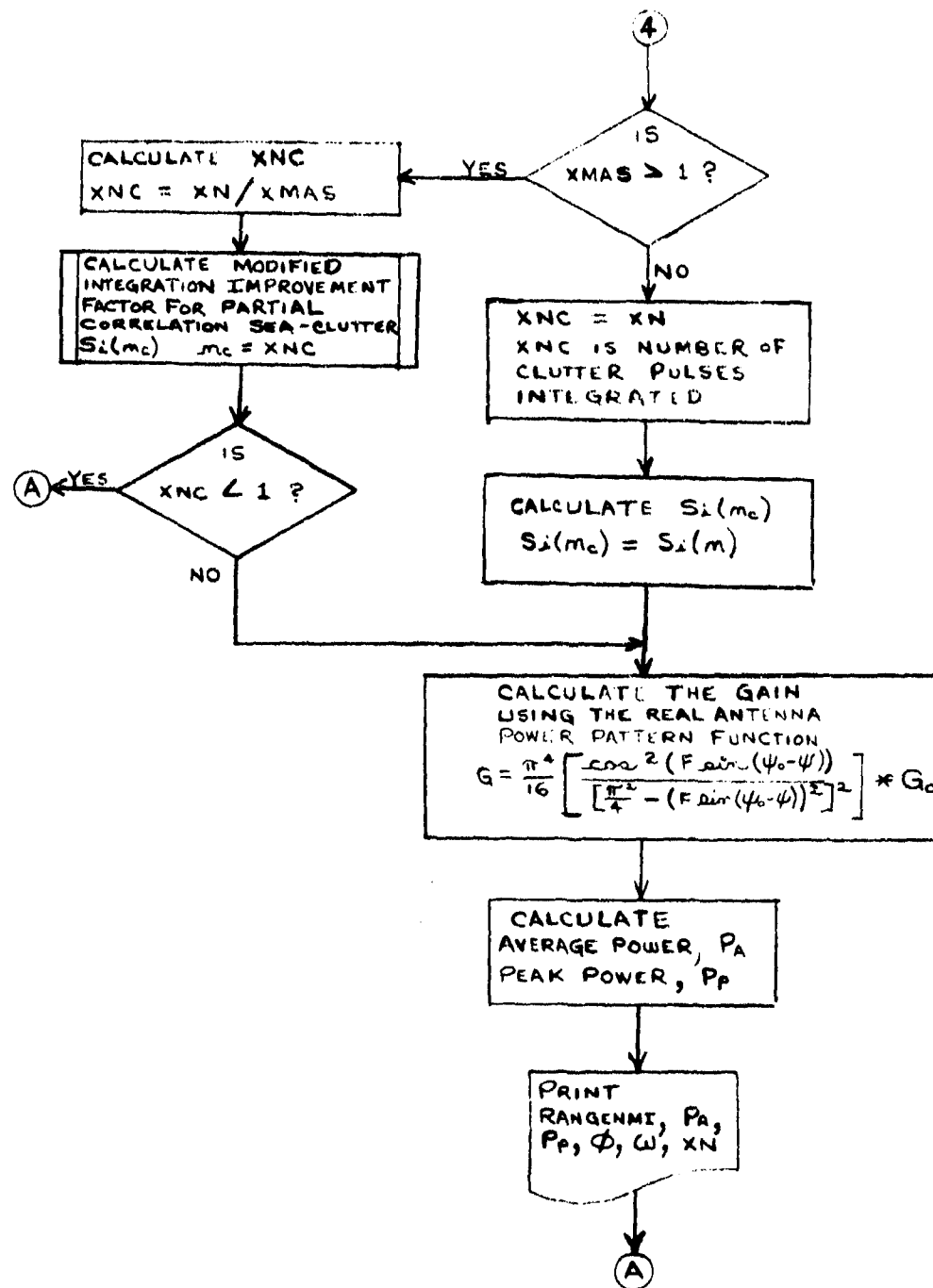


Fig. C-4 - Computer program flow chart (continued)

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Security Classification

DOCUMENT CONTROL DATA - R & D		
Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified		
1. ORIGINATING ACTIVITY (Corporate author)		2a. REPORT SECURITY CLASSIFICATION
Naval Research Laboratory Washington, D. C. 20390		SECRET
		2b. GROUP
		3
3. REPORT TITLE		
OPERATING GUIDELINES FOR THE AIRBORNE RADAR TEST-SYSTEM (Unclassified Title)		
4. DESCRIPTIVE NOTES (Type of report and inclusive dates)		
This is an interim report on the Problem; work is continuing		
5. AUTHOR(S) (First name, middle initial, last name)		
Richard L. Eilbert Steve A. Zuro		
6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
April 1971	46	4
8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)	
NRL Problem 53R02-46	NRL Memorandum Report 2260	
b. PROJECT NO.		
c. A3705383-652B-1F48111704		
d.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	
10. DISTRIBUTION STATEMENT		
Distribution limited to U.S. Government Agencies only; test and evaluation; April 1971. Other requests for this document must be referred to the Director, Naval Research Laboratory, Washington, D.C. 20390.		
11. SUPPLEMENTARY NOTES		12. SPONSORING MILITARY ACTIVITY
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13. ABSTRACT		
(S) A scaled radar test-system is being flown in an EC-121 aircraft to investigate some of the problems associated with ocean surveillance. This test-system has been scaled so that its performance will simulate that of a satellite-borne ocean-surveillance radar orbiting at an altitude of 200 nautical miles. This report provides some operational guidelines which will aid in obtaining meaningful data from the system. Curves and charts are presented which will: (1) permit the selection of grazing angle; (2) indicate the properly-scaled values for antenna rotation rate and transmitter power; and (3) show the limits of operation as a function of radar altitude and target range.		

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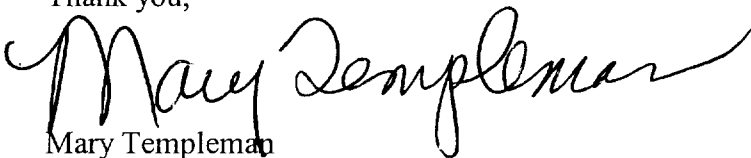
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- 1 - AD NUMBER: 516110
- 2 - FIELDS AND GROUPS: 15/4, 17/9
- 3 - ENTRY CLASSIFICATION: UNCLASSIFIED
- 5 - CORPORATE AUTHOR: NAVAL RESEARCH LAB WASHINGTON D C
- 6 - UNCLASSIFIED TITLE: OPERATING GUIDELINES FOR THE AIRBORNE RADAR TEST-SYSTEM.
- 8 - TITLE CLASSIFICATION: UNCLASSIFIED
- 9 - DESCRIPTIVE NOTE: INTERIM REPT.,
- 10 - PERSONAL AUTHORS: EILBERT,RICHARD L. ;ZURO,STEVE A. ;
- 11 - REPORT DATE: APR 1971
- 12 - PAGINATION: 46P MEDIA COST: \$ 7.00 PRICE CODE: AA
- 14 - REPORT NUMBER: NRL-MR-2260
- 16 - PROJECT NUMBER: NRL-53R02-46, A370-5383/652-B/1F48-111-704
- 20 - REPORT CLASSIFICATION: ~~CONFIDENTIAL~~
- 22 - LIMITATIONS (ALPHA): DISTRIBUTION LIMITED TO U.S. GOV'T.
-- AGENCIES ONLY; TEST AND EVALUATION; APR 71. OTHER REQUESTS FOR
-- THIS DOCUMENT MUST BE REFERRED TO DIRECTOR, NAVAL RESEARCH LAB.,
-- WASHINGTON, D. C. 20390.
- 23 - DESCRIPTORS: (*RADAR, AIRBORNE), TEST EQUIPMENT, TEST
-- FACILITIES, MODEL TESTS, SCALE, SIMULATORS, TEST METHODS, ALTITUDE,
-- RANGE(DISTANCE), RADAR TRACKING, EFFECTIVENESS
- 24 - DESCRIPTOR CLASSIFICATION: UNCLASSIFIED
-
- 29 - INITIAL INVENTORY: 2
- 32 - REGRADE CATEGORY: C
- 33 - LIMITATION CODES: 3
- 35 - SOURCE CODE: 251950
- 36 - ITEM LOCATION: DTIC
- 38 - DECLASSIFICATION DATE: OADR
- 40 - GEOPOLITICAL CODE: 1100
- 41 - TYPE CODE: N
- 43 - IAC DOCUMENT TYPE:
- 49 - AUTHORITY FOR CHANGE: S TO C GP-3

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