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Ocean Surveillance Radar Parametric Analysis

[Unclassified Title]

Final Report

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Aerospace Radar Branch
Radar Division

March 1969

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OCEAN SURVEILLANCE RADAR PARAMETRIC ANALYSIS - FINAL REPORT

(Unclassified Title)

ABSTRACT

(S) The engineering analysis part of a program to determine the best type and the optimum parameters for a satellite radar system for ocean surveillance has been completed. Three basic radar system types were considered in the analysis, which were: a forward scan system, a non-coherent sidelooking system, and a coherent sidelooking or synthetic aperture system.

(S) Each of the basic systems was determined to have a capability of meeting the required probability of detection requirements. The parameters of the best of each of the basic system types were arrived at through a combination of computer aided studies to develop trends and optimize parameters, and the use of modeling data and constraints which were made uniform for all systems. The selection of the best single system was based on the application of a consistent set of factors to determine the relative development risks, reliability, complexity, and costs.

(S) The coherent sidelooking system was judged to be the least acceptable system type because of significantly higher development risks, complexity, and costs together with lower reliability.

(S) The real aperture sidelooking and the electronic forward scan system were determined to be nearly identical in projected costs. The real aperture system, though having only an insignificant cost advantage over the forward scan system, was judged as being less of a development risk, less complex, and more reliable.

(S) The selected system, which was required to provide contiguous equatorial coverage, was based on a constellation of three real aperture sidelooking radars equally spaced in the same orbital plane at an altitude of 150 n.m. The major parameters of this system which would provide a 0.90 probability of detection on a 200 square meter fluctuating radar target with a 10^{-10} probability of false alarm are: 1300 MHz frequency, 500 watts average radiated power, 200 kW peak power, 83 pps, 0.1 microsecond effective pulse length, 1-degree azimuth resolution, 48 x 21 ft. antenna, and a range swath of 520 n.m. per radar.

PROBLEM STATUS

(S) Work on the parametric analysis phase of this program has been completed. Work on other phases of this program will continue.

AUTHORIZATION

NRL Problem R02-46 Project A37538/652/69/F48111704 SECRET

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CONTENTS

OCEAN SURVEILLANCE RADAR PARAMETRIC ANALYSIS - FINAL REPORT

(Unclassified Title)

INTRODUCTION

(S) The Aerospace Radar Branch of the Radar Division of the Naval Research Laboratory has completed an extensive parametric analysis of radar systems for ocean surveillance from an orbiting satellite. The primary objective of this analysis was to determine what is the best radar system for the Navy to develop for this application. Three basic types of radar systems were considered in this work, namely; the forward scan, the real aperture side-looking, and the synthetic aperture side-looking.

(U) Four interim reports [1,2,3,4] have been published on this project. The first of these reports covered the background and justification of the various parametric models used in the analysis. The other three reports discuss the parametric trends that had emerged for each system type at about the mid-point in the study. This report is concerned with the final phases of the parametric analysis which involved the selection of the best system for each of the three basic types and finally the selection of the radar system recommended by NRL as the one which should be developed.

(S) A prime consideration during the entire analysis has been that the system must be reliable to the very highest degree. Since any satellite radar system will be quite costly, it must have a long life to be operationally feasible. System simplicity is considered to be the basis for high reliability. As a consequence, this study has emphasized the simple systems; and if the job could be done with a simple system, a complex system was not considered.

(U) In order to make this report self-contained or complete for the casual reader, background material such as the parametric models used in the analysis will be included with minimal discussion and no justification. For the more inquisitive reader, the four reports referenced previously should also be reviewed. In fact, these four reports plus this report must be considered as a five-volume report in order to obtain a complete reporting of the parametric analysis.

PARAMETRIC MODELS

(S) In all three of the system types investigated in this analysis, as much commonality as possible between systems was maintained in order to provide a reasonably uniform base for system comparison. The same sea clutter model, troposphere loss model, Faraday rotation loss model and launch vehicle capabilities, both weight and size, were used for all systems. Some parameters and constraints were of necessity peculiar to certain system types, for example, the sea clutter decorrelation time for a forward scan radar is considerably different than that for a side-looking radar.

Frequency

(U) In this analysis eight frequencies, 140, 220, 440, 900, 1300, 2900, 5250 and 8500 MHz/sec were used for all systems. These values were not considered to be the actual operating frequencies for a proposed radar system but are representative of and located in the existing radar frequency bands.

Sea Clutter Model

(U) The sea clutter model used is shown in Fig. 1. Curves A and C are plots generated from measured data. Curve B is an interpolation between Curves A and C as an inverse function of wavelength.

System Losses

(U) A tabulation of the radar system losses[3] used in this analysis is shown in Table 1. These losses include antenna pattern, transmission line, tropospheric and system degradation. Many of these losses can only be estimates until the final system configuration is determined at which time they can be fairly accurately calculated.

Noise Figure and Effective System Input Noise Temperature

(U) The receiver noise figures[3] and effective system input noise temperature as a function of frequency that were used are shown in Table 2.

Faraday Rotation Losses

(U) The losses resulting from the Faraday rotation[5] of radio signals passing through the ionosphere are shown in Tables 3 and 4. The rotation has an effect on both the signal return and the sea clutter return as shown in the two tables.

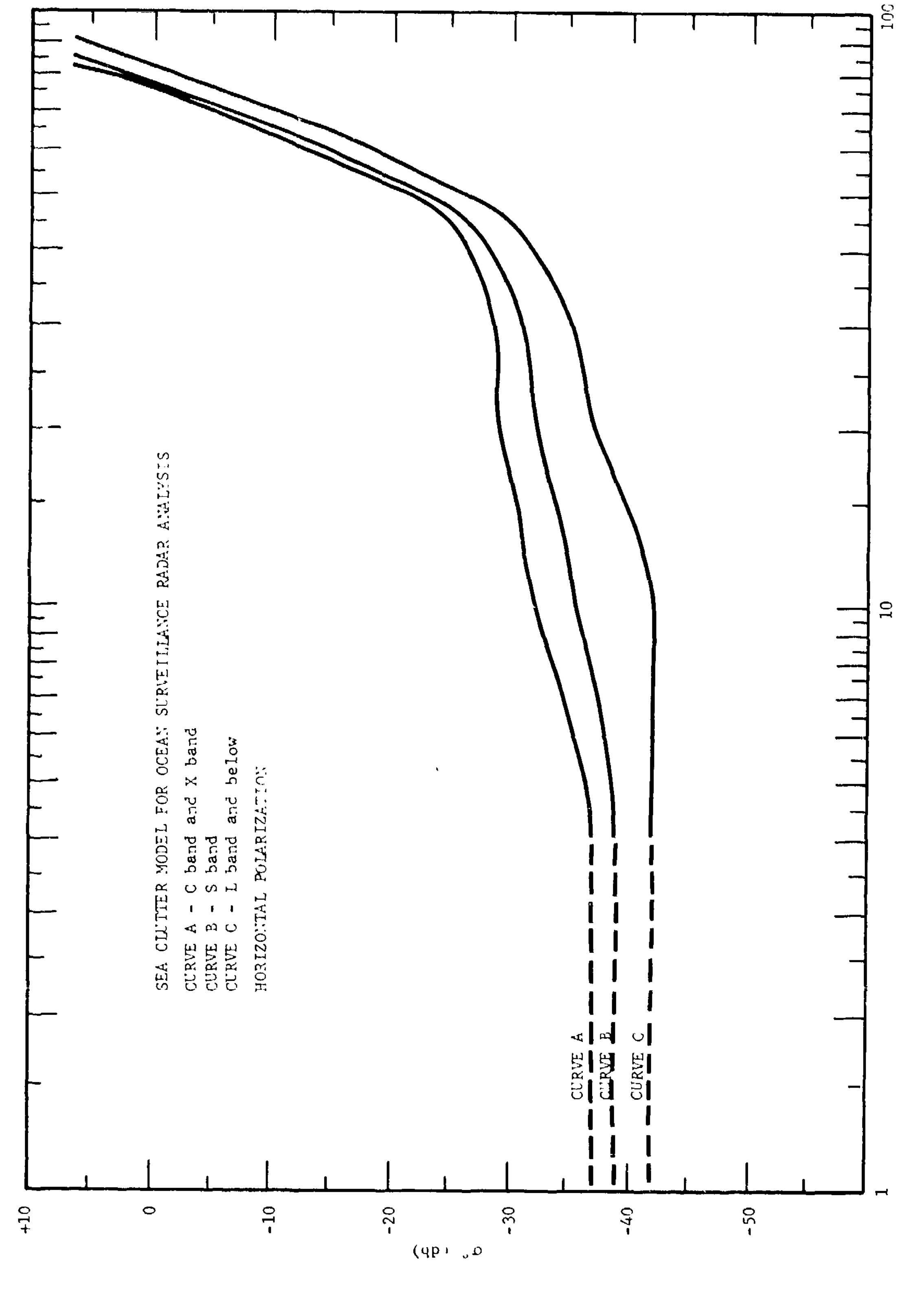


Fig. 1 - Sea clutter model

TABLE 1

Total System Losses vs. Frequency and Grazing Angle

Frequency MHz

Grazing Angle, Degrees	140 Loss dB	220 Loss dB	440 Loss dB	900 Loss dB	1300 Loss dB	2900 Loss dB	5250 Loss dB	8500 Loss dB
0	6.16	6.59	7.74	9.11	9.28	10.27	10.80	11.70
2	6.01	6.26	6.85	7.51	7.68	8.07	8.30	8.70
4	5.94	6.14	6.53	6.96	7.13	7.43	7.61	8.00
6	5.90	6.08	6.41	6.79	6.93	7.17	7.34	7.55
8	5.85	6.03	6.31	6.66	6.78	7.03	7.20	7.33
10	5.80	6.01	6.26	6.54	6.64	6.87	7.03	7.18
12	5.80	5.99	6.24	6.52	6.62	6.84	7.00	7.13
15	5.80	5.89	6.21	6.46	6.56	6.80	6.96	7.10
20	5.80	5.89	6.17	6.41	6.51	6.72	6.89	7.03
40	5.80	5.89	6.04	6.32	6.40	6.61	6.75	6.86

TABLE 2

Receiver Noise Figure and Effective System Input Noise

Temperature vs Frequency

Frequency MHz	Receiver Noise Figure dB	Effective System Input Noise Temperature* °k, @ 10° Grazing Angle
140	3.0	1773
220	3.1	1098
440	3.4	790
900	3.9	829
1300	4.3	936
2900	5.7	1430
5250	6.9	2009
8500	8.0	2727

* For an ocean surveillance satellite-borne radar.

TABLE 3

Signal-to-Noise Power Degradation Factor

Alt. n.m.	140 MHz	220 MHz	440 MHz	900 MHz	1300 MHz	2950 MHz	5250 MHz	8500 MHz
150	0.0001	0.0001	0.0001	0.743	0.974	1.0	1.0	1.0
200	0.0001	0.0001	0.0001	0.340	0.810	0.992	0.998	1.0
250	0.0001	0.0001	0.0001	0.094	0.670	0.986	0.998	1.0
300	0.0001	0.0001	0.0001	0.0120	0.566	0.980	0.998	1.0
400	0.0001	0.0001	0.0001	0.0001	0.460	0.973	0.997	1.0
600	0.0001	0.0001	0.0001	0.0001	0.408	0.967	0.997	1.0

TABLE 4

Signal-to-Clutter Power Degradation Factor

Alt. n.m.	140 MHz	220 MHz	440 MHz	900 MHz	1300 MHz	2950 MHz	5250 MHz	8500 MHz
150	0.0001	0.0001	0.0001	1.0	1.0	1.0	1.0	1.0
200	0.0001	0.0001	0.0001	1.0	1.0	1.0	1.0	1.0
250	0.0001	0.0001	0.0001	0.1632	1.0	1.0	1.0	1.0
300	0.0001	0.0001	0.0001	0.0077	1.0	1.0	1.0	1.0
400	0.0001	0.0001	0.0001	0.0001	1.0	1.0	1.0	1.0
600	0.0001	0.0001	0.0001	0.0001	1.0	1.0	1.0	1.0

Sea Clutter Decorrelation Time

(U) The decorrelation times[5] for the sea clutter is smaller for the side-looking radar than for the forward scan radar. The decorrelation times used in this analysis for the side-looking cases are shown in Table 5 and for the forward scan cases in Table 6.

PARAMETRIC CONSTRAINTS

(S) At the beginning of the parametric analysis, very loose constraints were placed on the values of parameters used in the calculations. This was done deliberately to insure that no significant parametric trends were overlooked. As the analysis progressed and parametric trends began to emerge, logical limits on certain parameters became apparent. In addition, the practical considerations of the problems of construction of a satellite radar system placed definite limitations on other parameters. For example, an original antenna size of 500 ft. by 500 ft. was obviously not practical. These factors and their resultant parametric constraints will be briefly discussed in the following paragraphs.

Launch Vehicle

(S) The type of satellite booster or launch vehicle employed will place upper constraints on a number of radar system parameters. The capabilities of the launch vehicle will have a direct effect on the satellite orbital altitude, weight and size. Satellite weight and orbital altitude are directly related in that the greater the weight, the lower the maximum orbital altitude that the launch vehicle can achieve. Satellite size is somewhat related to weight but probably is more directly constrained by the shroud size limitations of the launch vehicle.

(U) For this analysis, a number of launch vehicles were considered but the Titan III-C was selected as the most likely candidate. This decision was based upon two factors, namely, the Titan III-C is the largest vehicle that could be used and be reasonably cost effective; and secondly, the Titan III-C is likely to be, in the near future, the one booster class that the ranges will be instrumented to handle. A shroud size of 12 ft. in diameter by 48 ft. long was selected as the largest size that would allow a reasonably high percentage of launch days as a function of wind velocity.

(S) Fig. 2 shows a series of curves representing the allowable weights of the one, two and three radar sensor as a function of orbital altitude and system input power for a Titan III-C launch vehicle. These curves represent the weights of the radar sensor alone, since all other system weights such as command and telemetry,

TABLE 5

Decorrelation Time for A Sidelooking Radar

Beamwidths - 2θ

Mc	.5°	1°	1.5°	2°
140	.0322	.0161	.0107	.0081
220	.0205	.0102	.0068	.0051
440	.0102	.0051	.0034	.0026
900	.0050	.0025	.0017	.0013
1300	.0035	.0017	.0012	.0009
2900	.0016	.0008	.0005	.00[illegible]4
5250	.0009	.0004	.0003	.0002
8500	.0005	.0003	.0002	.0001

T_d is in seconds

TABLE 6

Decorrelation Time for A Forward-Looking Radar

Beamwidths - 2θ

Mc	.5°	1°	1.5°	2°
140	13.869	3.467	1.541	.866
220	8.826	2.206	.980	.551
440	4.413	1.103	.490	.275
900	2.157	.539	.239	.134
1300	1.493	.373	.166	.093
2900	.669	.167	.074	.041
5250	.369	.092	.041	.023
8500	.228	.057	.025	.014

T_d is in seconds

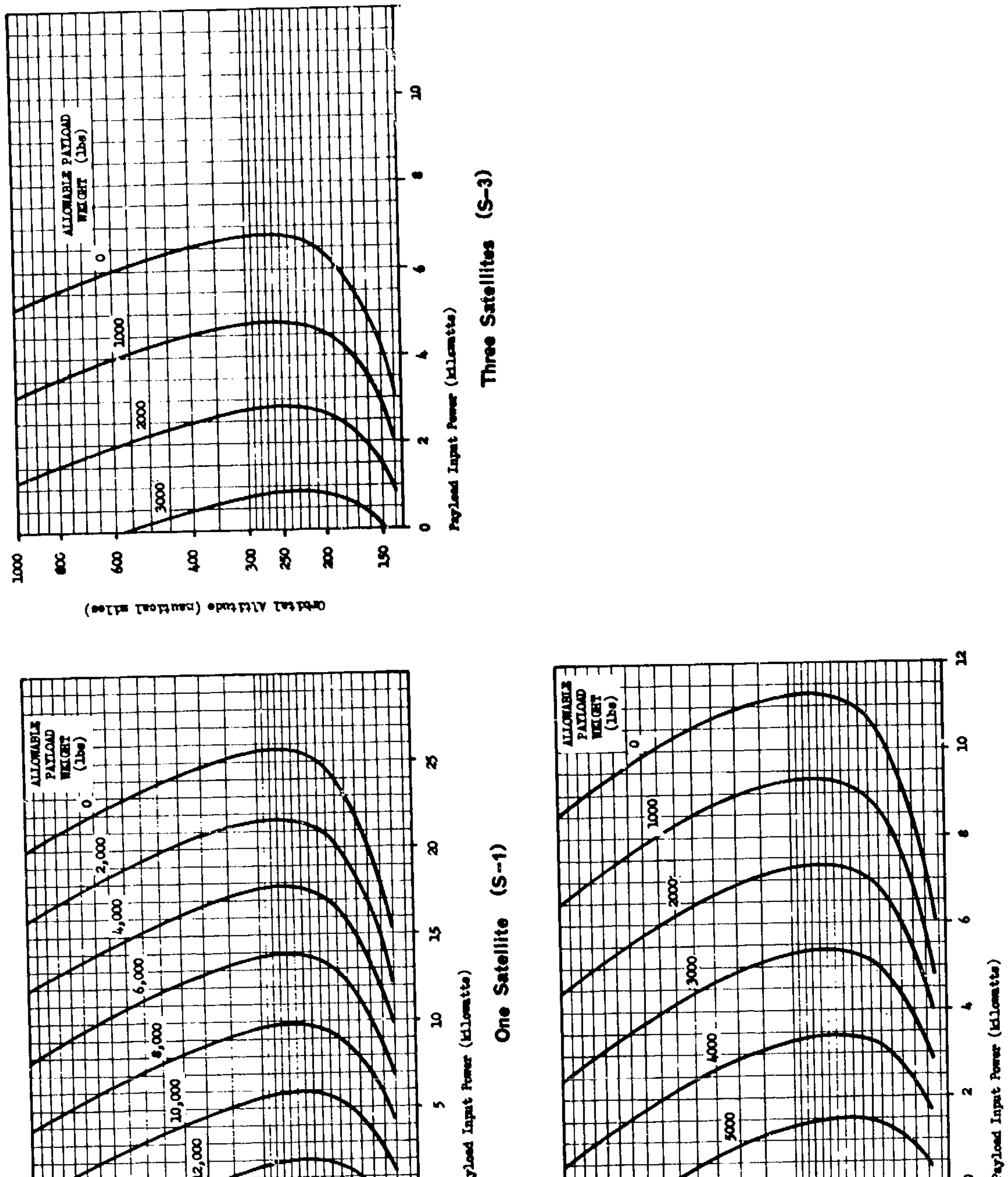


Fig. 2 - Pov /weight limitations per satellite for one, two, and three atellites launched by a single Titan III-C

altitude stabilization fuel, prime power supply and all housekeeping functions have been included in the construction of the curves. Fig. 2 is representative of a series of figures of satellite weights that will vary for different conditions and orbital altitudes.

Satellite Prime Power

(S) The total prime power that can be generated in a satellite may place constraints upon the radar system. For example, the prime power might place a limit on the radar system maximum transmitter average power. In some system employing a very complex data processor, the size and capacity of this unit could also be limited by the prime power capabilities.

(S) In this analysis, a number of prime power supplies were considered but the list rapidly narrowed to two types, namely, the solar cell array and the nuclear supply, either isotope or reactor types. Although the nuclear supply has a number of attractive advantages, it also has some disadvantages that outweigh the advantages. The problem of shielding the electronic equipment from the nuclear supply becomes increasingly difficult as the size of the supply increases, plus the fact that there is a considerable amount of development work yet to be done before such supplies become practical. In addition, the political problems of obtaining approval for the use of a nuclear supply of the size required appear to be rather formidable. As a result, the only prime power supply considered in the final phases of this analysis was the solar cell array.

(S) The solar cell technology is such that solar cell arrays in the 1 to 20 kilowatt range should be feasible in the next few years. Since this analysis is concerned only with the radar sensor, no detailed discussion of solar cell arrays will be included. In general, it was concluded that because of the cost, size and weight of solar cell arrays, about a 5 kilowatt upper limit would seem to be a good compromise.

Transmitter Power

(S) In the final phase of the analysis, the average transmitter power was limited to between 500 and 1000 watts. The 500 watt or lower figure was, in general, used. This limitation was influenced by several factors, such as the resultant peak transmitter powers required, and the decreasing probability of good reliability with higher powers. These factors will be discussed more fully in later sections.

Swath Width

(S) In order to provide as much commonality as possible between the system types, a constraining model of the ground coverage was used. A polar orbit was assumed, although this is not necessarily the optimum orbital plane[6]; and each system was required to have sufficient swath width to provide contiguous ground coverage at the equator. No consideration was given to coverage at the poles, either overlaps or voids. Furthermore, it was stipulated that if more than one satellite could be mounted in the 12-foot diameter by 48-ft long shroud, multiple satellites could be used, providing the contiguous ground coverage was maintained at the equator. It was also assumed that multiple satellites would be equally spaced in the same orbital plane. Thus, if two satellites were employed instead of one satellite, each radar sensor could have one half the swath coverage of a single satellite.

(S) For a single satellite at an orbital altitude of 150 n. mi., the minimum swath width required for contiguous coverage would be about 1350 n. mi. If two satellites were employed, each would be required to have a swath width of about 675 n. mi. and for three satellites, each would require about a 450 n. mi. swath. In this analysis, a swath in excess of the minimum values stated above was required of the radar systems.

(U) In the following text, one, two and three satellites per launch vehicle are considered. The single satellite case is referred to as S-1, the double satellite case as S-2, and the three satellite case as S-3.

Target

(U) Based upon the work of Daley[7], the radar cross section of the minimum ship targets was selected as 200 sq. meters or about the effective cross section of the beam aspect of a surfaced submarine. Also, it was assumed in the early stages of the analysis, that the target was non-fluctuating simply as a matter of convenience, since details of a target model were rather vague.

(U) However, most ship targets will be composed of many individual point scatterers; and each target will be viewed from different or changing aspect angles. As a result, the target will not be steady but will fluctuate because of the interference between reflections from the point scatterers. Thus, it can be readily established that a non-fluctuating model is not correct. This poses a good question as to what is a reasonable target model to use and how many independent pulse samples can be obtained with a given model during the radar viewing time.

(U) A fluctuating target model was developed by Trunk[5] using a Monte Carlo method to determine the number of independent pulse signal samples, for both the side-looking and forward scan radar systems, as a function of the orientation of the target. A physical ship size of 150 ft. long by 20 ft. wide by 15 ft. high was used in the model development. Figure 3 shows the number of independent samples obtained for the target model for the side-looking radar at frequencies of approximately 1000 and 300 MHz for a particular geometry. The number of independent samples for the forward scan radar is shown in Fig. 4.

(U) Since the number of independent samples will change with target aspect angle, the required signal to noise plus clutter to maintain a fixed probability of detection must also change. A more useful approach is to determine the required signal-to-noise plus clutter ratio required for an overall probability of detection, assuming that the ship targets will be uniformly distributed in viewing aspect. Trunk[5] shows that for an overall probability of detection of 0.90, and a probability of false alarm of 10^{-10}, the following signal-to-noise ratios S/(N+C) are required:

(a) For a side-looking system using 3.2 sec integration time

S/(N+C) = 17.8 dB at 1300 MHz

S/(N+C) = 16.2 dB at 2900 MHz

(b) For a forward scan system using 1.5 sec. integration time

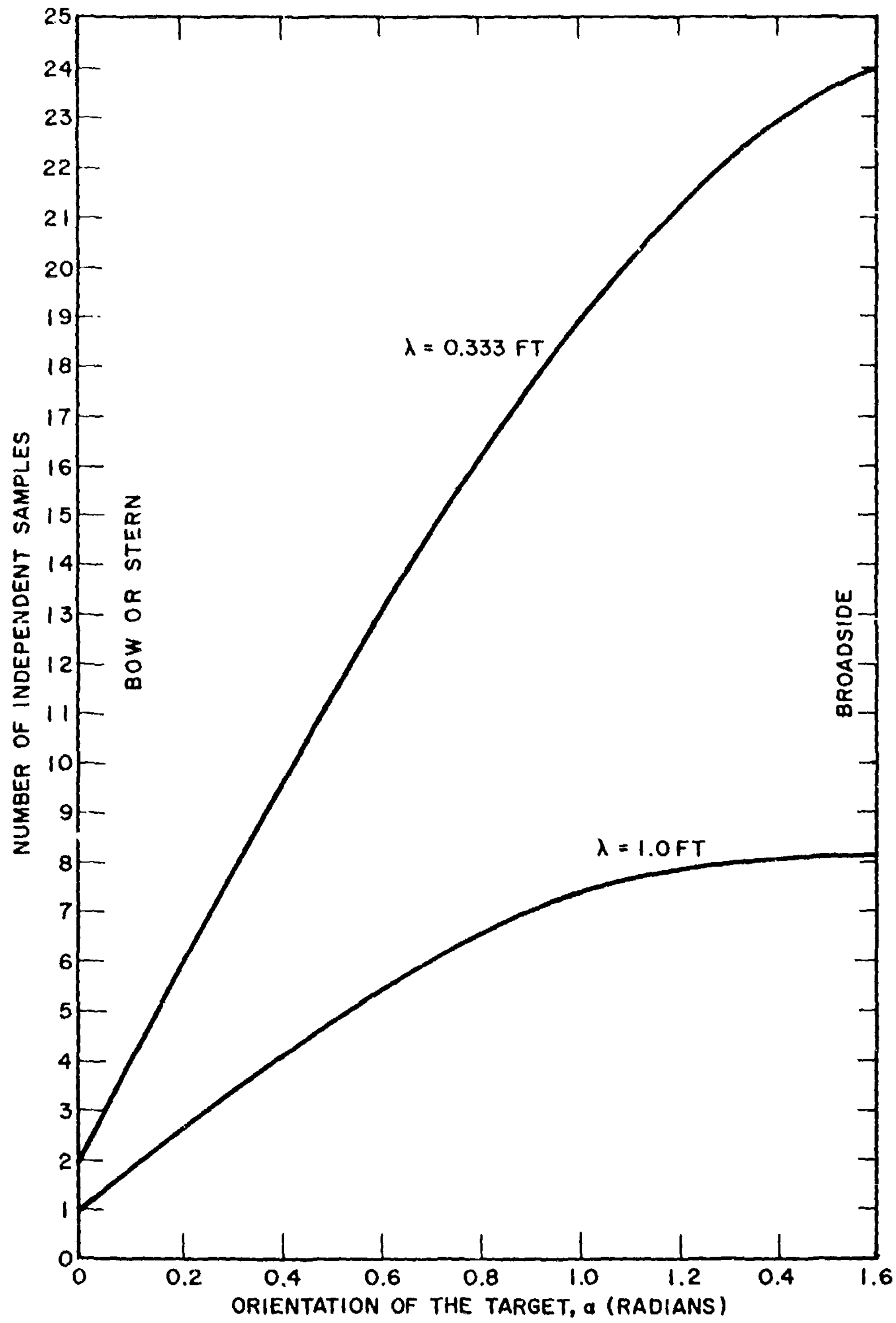
S/(N+C) = 19.2 dB at 1300 MHz

S/(N+C) = 18.3 dB at 2900 MHz

(U) Using this target model, S/(N+C) ratios were calculated for both systems at various integration times[5]. These ratios were used in the final phases of this analysis.

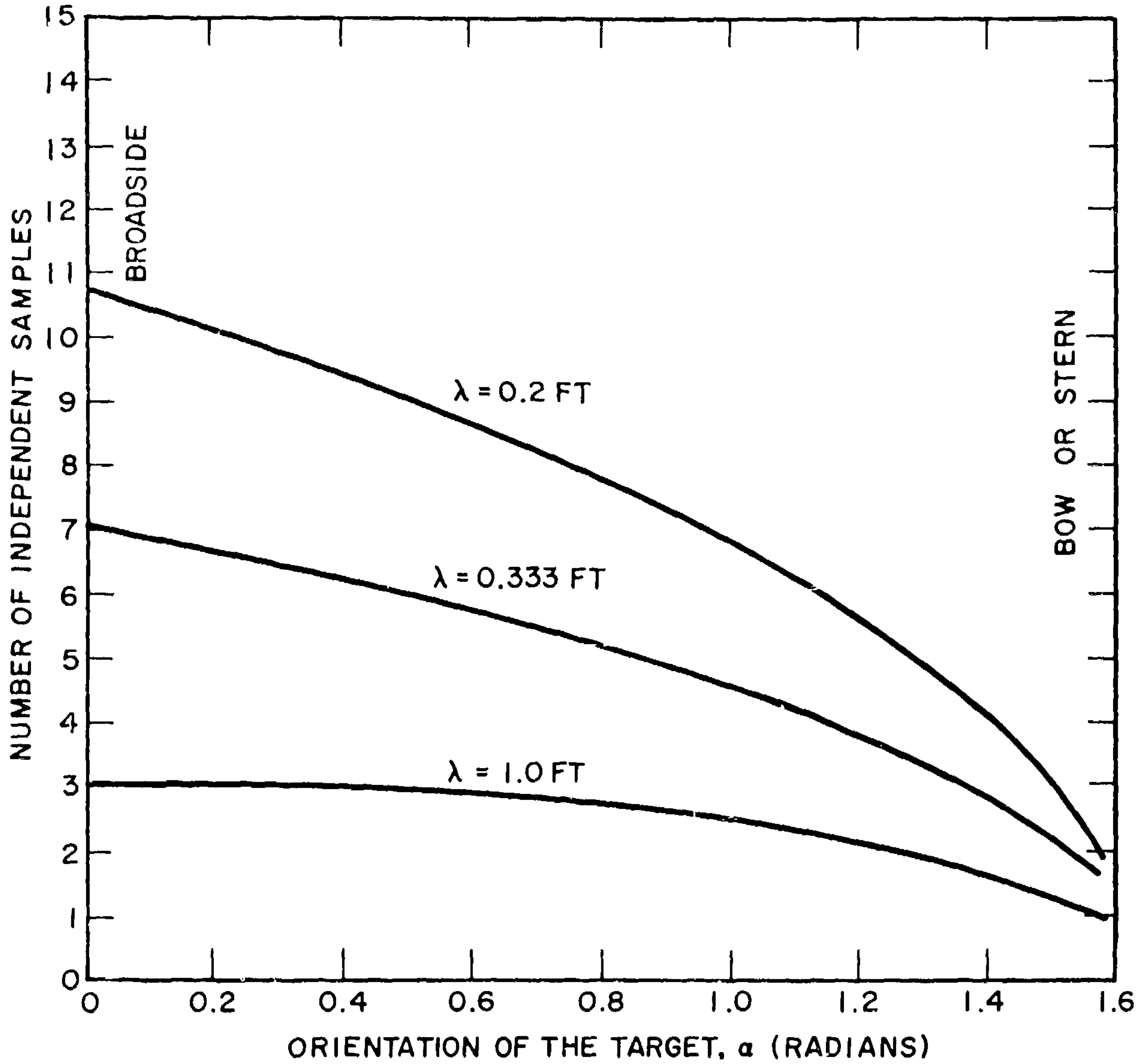
Antennas

(S) The antenna constitutes one of the major problem areas in the design of a spaceborne radar surveillance system. Because of the extended ranges which must be covered (of the order of 1000 nautical miles), one senses that rather large apertures will be required. However, the antenna must be designed within the physical constraints imposed by the launching vehicle; and these constraints may severely limit the choice of antenna type and size. In addition, once in orbit, the antenna will face the rigors of the space environment (temperature extremes, radiation, etc.). Although other components of the radar system can be shielded and protected to some degree, this is difficult to do for the antenna since it must of necessity, be exposed directly to this harsh space environment. While realizing the importance of these environmental effects, these problems were not treated directly in this analysis.



Grazing Angle = 3.60
Integration Time = 3.2 Sec.

Fig. 3 - The number of independent samples for a sidelooking radar



Grazing Angle = 3.60
Integration Time = 1.5 Sec.

Fig. 4 - The number of independent samples for a forward scan radar

The purpose of this study was to investigate the best combinations of system parameters by which the goals of a surveillance radar could be achieved. For this purpose, all that was necessary was to establish an upper bound on size to assure that any antenna proposed could be built, and maintained in space, within acceptable limits of dimensional tolerance, reliability and cost. For this, reliance was placed on data for various antennas which had been designed by industry for surface and space applications. A survey was made of these designs to determine a "practical" upper bound for antenna size as a function of frequency. These data are plotted in Fig. 5, where the specified "frequency" for a particular size antenna is based on an rms surface tolerance of $\lambda/16$. In this figure, the crosses represent ground-based antennas (all actually built and in operation); the circles represent spaceborne antennas (mostly proposed; few, except for the smaller sizes, actually flown in space). Solid lines are drawn on the graph to define several values of the ratio of linear dimension to tolerance, D/ϵ, a common way of expressing the practical difficulty of building a given-size antenna. As should be expected, the ground-based antennas as a group plot at higher D/ϵ values than the spaceborne antennas, an indication of the greater difficulties attendant with spaceborne antenna design. Based on the distribution of the plotted data, a value for D/ϵ of 3×10^3, shown dotted in Figure 5, was accepted as a reasonable upper limit for antenna size. Actually, as the analysis progressed and other problems were investigated, antenna size was eventually restricted somewhat below this limit. One of the chief restrictions which further limited antenna size was that due to packaging considerations.

(S) In the analysis, aperture sizes were considered which require folding in order to be packaged within the spacecraft shroud. A number of such antenna folding techniques have been devised by industry. One design which has been worked out in considerable detail for large antennas is an expandable-truss type structure proposed by the Convair Division of General Dynamics. Because of the detailed packaging data[8] available for this design, it was used as a basis for determining the extent of folding which is possible in order to reduce the antenna to packageable proportions. This choice does not imply that a selection in favor of the Convair design has been made. Depending on the dimensions of the resulting antenna, some other folding technique may work equally well or better. However, the Convair design provided the only available detailed data.

(S) The limiting weight for the radar equipment is established by the lifting capabilities of the Titan III-C launch vehicle. Therefore, estimates had to be made of the weights of the various system components. In order to estimate the weight of the antenna, data for a number of existing and proposed space antennas were plotted to establish a relationship between size and weight. Two such plots are shown in Fig. 6 (for non-scanning antennas) and Fig. 7 (for electronically-scanned arrays). A curve has been drawn in each plot to represent the average weight of the specific type of antenna as a function of aperture area. The resulting relationship is admittedly crude; however, it provided some means in the initial investigations for

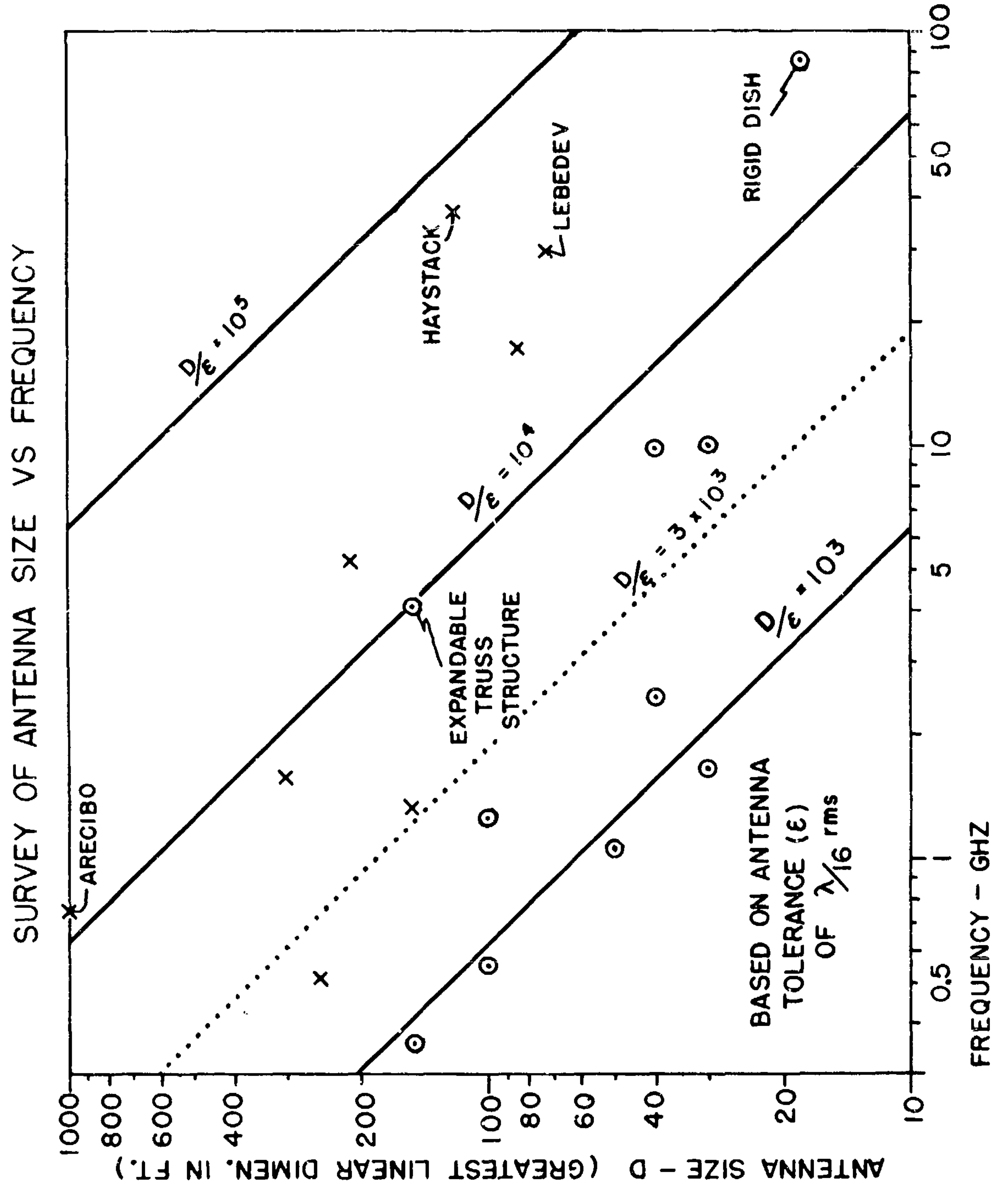


Fig. 5 – Antenna size limitation as a function of frequency

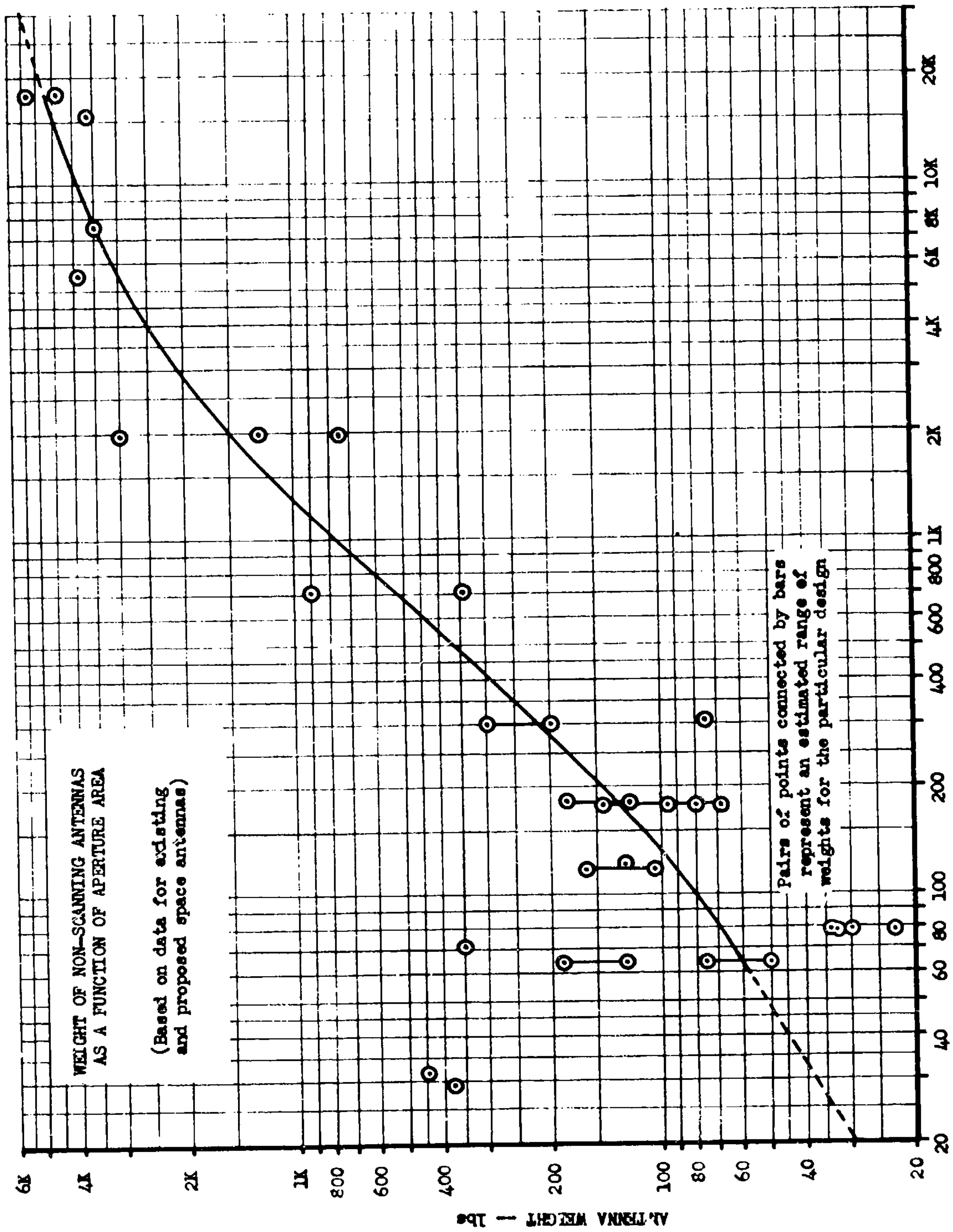


Fig. 6 - Weight of non-scanning antennas

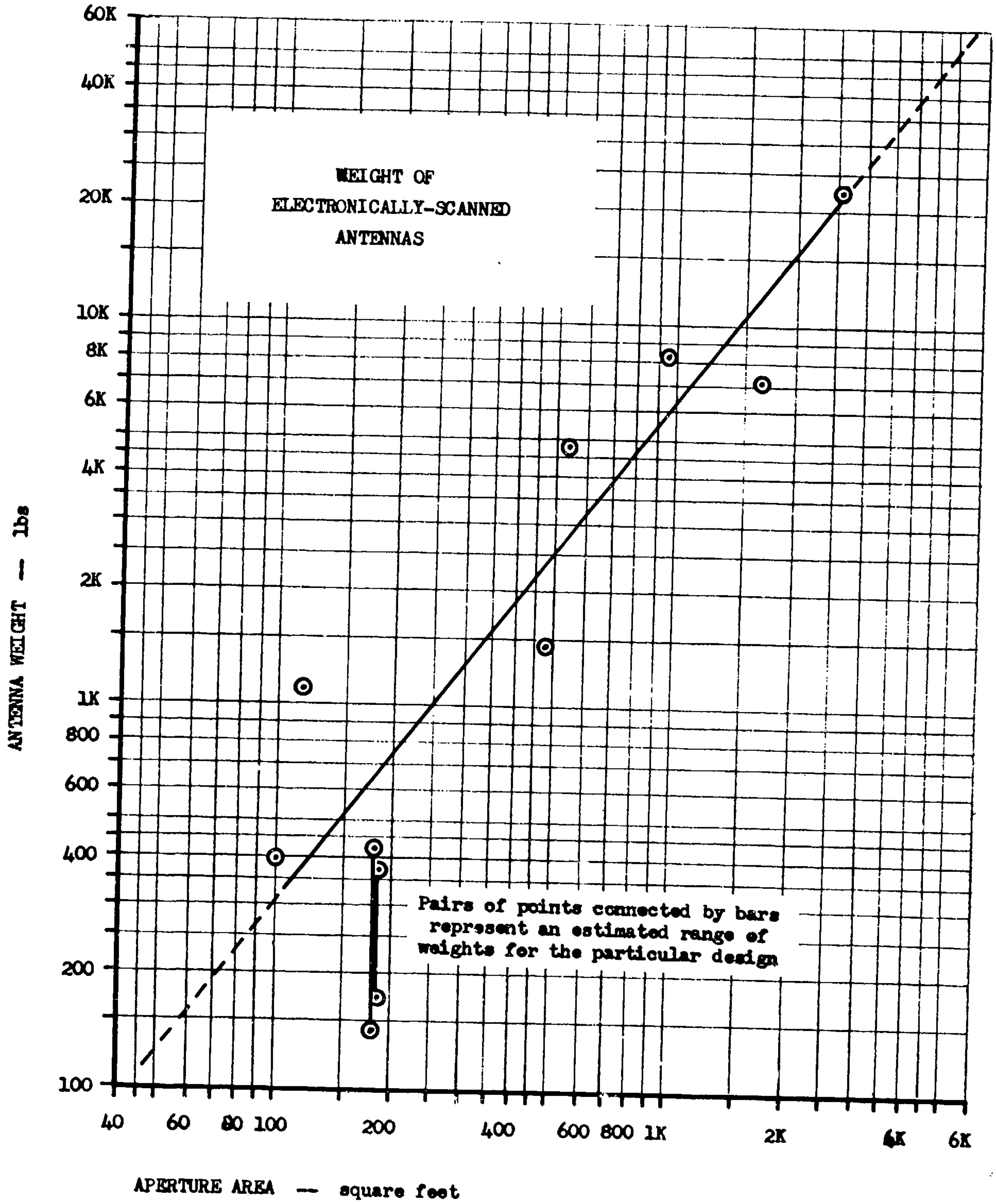


Fig. 7 - Weight of electronically-scanned antennas

restricting considerations of antenna size to values which had a reasonable expectation of being launched. Later, when the choice of a preferred system had been made, and the antenna-type could be specified, a more accurate weight was calculated from a detailed consideration of the antenna components.

(S) One factor which should be considered in comparing various radar systems is cost. No pretense will be made that engineers in a research organization can determine actual dollar costs for a complex radar system to be manufactured by someone else. A confident cost estimate can only be made by a company intimately acquainted with the required manufacturing techniques and processes. However, "relative" cost estimates can be made for the purpose of determining how much more expensive one type of system should be in comparison with another. Figures for antenna costs used in the early stages of the analysis were based on data gleaned from industrial cost estimates for proposed spaceborne antenna systems of similar type and size. After the parameters for the three (Case I, Case II and Case III) candidate systems had been selected, a more detailed estimate was made of antenna costs. Even though more detailed, these later estimates have no real meaning in terms of actual dollar amounts. They will still be significant only for determining relative costs for antennas of different types and sizes.

(U) In designing the antenna for the sidelooking radar cases, some degree of beam shaping is advisable in order to effectively illuminate a wide swath. That is, the pencil beam in elevation should be "spoiled" to illuminate targets at the steeper depression angles (i.e., closer ranges). Investigations have been carried out to determine the best shaping of the beam and the effects of various radar parameters on swath width. The results of these investigations[9] are reported elsewhere; suffice it to say here that for any specified beam shaping there is an optimum antenna size which will yield the widest possible swath; aperture larger or smaller will cause swath coverage to be reduced.

Grazing Angle

(S) In the early stages of this analysis, radar beam grazing angles oˆ 0 degrees were used. Such a low grazing angle is not a feasible parameter because of the stability tolerance of the spacecraft attitude plus the greater uncertainty of the possibility of beam ducting.

(U) Ducting can occur during periods of abnormal refraction whenever the refractive index gradient exceeds a certain critical value. Ducts may be formed either at, or above the surface of the earth, and can have two effects. The first effect is to cause radio rays that are trapped in the duct to be guided in such a way that detection is possible at much greater distances around the curve of the earth than would otherwise be possible. The second effect is to create "radio holes" in the regions where the ducts cause a deficit of field strength of the radio rays that would ordinarily illuminate these volumes. The second effect is the more detrimental and is the one of greatest concern for the satellite radar. The question arises as to how frequently do ducts occur and at what grazing angles will coupling into ducts occur.

(U) Studies have been made in various locations of the prevalence of ducting conditions. As examples, Bean[10] cites the results of studies at three locations, one in the Arctic, one in a temperate zone, and one in a tropical maritime climate. The greatest percentage of occurrence of ducts in the Arctic (Fairbanks, Alaska) was 9.2% occurring in the winter monthsdeclining to less than 1% in the summertime. In a temperate zone location, (Washington, D. C.) the maximum percentage was about 4.6% occurring in the summertime, declining to less than 1% in the winter. At Swan Island, West Indies, a tropical maritime location, the percentage was 13.8 in the fall of the year, and less than 3% in the winter.

(U) When a duct exists, radio waves enter or are trapped only if their grazing angle at the duct is less than a fraction of a degree. Rays that impinge on a duct surface at angles greater than about one half a degree are rarely trapped, and rays that impinge at angles greater than a degree are almost never trapped. The critical angle in a specific case depends on the refractive index gradient. In addition, the lowest frequency trapped is a function of the thickness of the duct. Microwave frequencies, for example, are trapped more often than UHF.

(U) Bean states that the frequency 1000 MHz . will be trapped by 50% of the ducts that occurred in the reference study. Also for this study, the maximum initial elevation angle of a ray, grazing angle, that would be trapped by a duct was .33 degree.

(U) In addition to purely stratified horizontal ducts, there also occur refractive irregularities in the atmosphere which have some effect on wave propagation. These irregularities are sometimes semi-stratified, and cause some effects similar to those of complete ducts, but of a less drastic nature[11]. Also, elevated ducts can sometimes be tilted or inclined to the horizontal, so that they can trap rays at slightly greater grazing angles than previously mentioned. The Tradewind IV study[12] shows that the tilted duct was rather common, and that measured over several hundred miles, the tilt was about 0.1°, with one extreme case of about 0.9° over a 200 n. mi. path.

(S) In general, it is concluded that abnormal refraction conditions should not produce any "radio hole" phenomena for grazing angles greater than about one degree. In other words, a one degree grazing angle, neglecting spacecraft altitude stabilization, would be a reasonable constraint to place on minimum grazing angle. As a result of the sparseness of data relative to "radio holes" and shallow angle grazing propagation, a conservative approach was used and the minimum grazing angle of 5° was specified.

CASE I - FORWARD LOOKING RADAR SYSTEMS

(S) NRL Memo Report 1882[2] published in June 1968 was an interim report on the parametric analysis for the Forward Scan Ocean Surveillance Radar. In that report, the computer program used in the parametric analysis and the constraints imposed on the system were described; and the trends that existed at that time were presented. To maintain continuity, the Summary of Trends and Future Work sections of that report will be repeated in this section.

TABLE 7

Summary of Trends - Forward Scan

Frequency	-	S Band
Antenna Size	-	Maximum Allowable Within Constraints
Pulse Width	-	0.05 μsec to 0.1 μsec
Swath Width	-	800 n.mi. to 1600 n.mi.
Altitude	-	Lowest possible subject to antenna degradation
Grazing Angle	-	Small - depends on antenna height and ducting phenomena

(U) In discussing the optimum values of the various parameters it will be seen that they generally followed the trends summarized in Table 7. Items 1 through 7 in Table 8 will be discussed in this section. Item 8 will be treated in a later section of this report.

(S) The sea clutter decorrelation time for the forward scan radar was inserted into the program, and as expected, shifted the worst case target location from the edge of the swath to the center of the swath. For a given geometry, it required a lowering of the grazing angle and an increase in average power to achieve the same $(\frac{S}{C + N})$.

(S) The target model was then changed from a 200 m^2 non-fluctuating target to a 200 m^2 fluctuating target as previously described. The resulting increase in required $(\frac{S}{C + N})$ forced the consideration of altitudes where sustainers would be necessary for orbit sustenance. Altitudes as low as 150 n.mi. were considered with the appropriate weight and drag penalties as described in the discussion of Fig. 2 curves. A consideration which made the reduction in operating altitude more attractive was the capability of launching more than one ocean surveillance radar satellite per launch vehicle. The configurations previously described and designated S-1, S-2 and S-3 reduce the required swath coverage in proportion to the number of satellites carried. This permits the operation of electronic scan systems at the low altitudes, i.e., the required scan angles do not exceed the maximum achievable scan angle.

TABLE 8

Future Work

1. Rerun programs with new decorrelation time
2. Include weather effects
3. Finalize antenna size constraints
4. Determine effectiveness of operating at lower altitudes with sustainer
5. Determine data processor requirements
6. Consideration of mechanical scan
7. Case I cost-effectiveness analysis for optimum system
8. Case I, II, and III cost-effectiveness analysis for optimum system

Significant Problem Areas

(U) In an ocean surveillance radar, there are two problems which are present for all radar types but are considerably more severe for the forward scan radar. These problems are the decorrelation of sea clutter and the detection of the fluctuating target.

Sea Clutter Decorrelation

(U) Decorrelation of sea clutter can be achieved by separation in space, time and frequency. Based on the models used in the NRL analysis, the following criteria have been established for decorrelation:

a. Frequency - Separation in frequency equivalent to the compressed pulse bandwidth.

b. Space - Separation by one beamwidth

c. Time - The sea is assumed to be decorrelated by its own motion after 0.04 sec at 2900 MHz and 0.09 sec at 1300 MHz. This was calculated for a sea under 20 knot wind conditions. It is also assumed that for calmer seas where the decorrelation time is longer, the loss in the number of independent samples to be integrated for S/C is offset by the reduction in the backscatter coefficient due to the calmer sea condition.

Fluctuating Target Detection

(U) Consideration of a fluctuating target causes the S/(C+N) required for detection to be increased over that required for the non-fluctuating target. The amount of the increase is dependent on the target model and the radar parameters. NRL Report 6804[5] describes the model and the calculation of the required S/(C+N). Figure 8, taken from the above referenced report, demonstrates the sensitivity of the required S/(C+N) to integration time.

(U) It has been proposed that sufficient frequency separation to produce target decorrelation will also reduce the required S/(C+N). It was assumed in the parametric analysis that frequency diversity could not compare with long integration time in reducing the required S/(C+N), assuming the target fluctuation periods could be in the order of seconds. Additional analysis is necessary to determine the extent to which frequency diversity can accomplish the desired reduction.

Mechanical Scan Considerations

(S) The forward scan analysis as described in Memo Report 1882 used the electronic scan antenna for the basic system. After the analysis was completed on the electronic scan, the mechanical scan radar was considered using the common parameters which were developed in the analysis of the electronic scan.

(S) In the mechanical scan configuration, the sea clutter decorrelation problem can be attacked in frequency by frequency diversity and in time by scan to scan integration. The problems associated with the fluctuating target can be eased by lengthening the integration time using scan to scan integration.

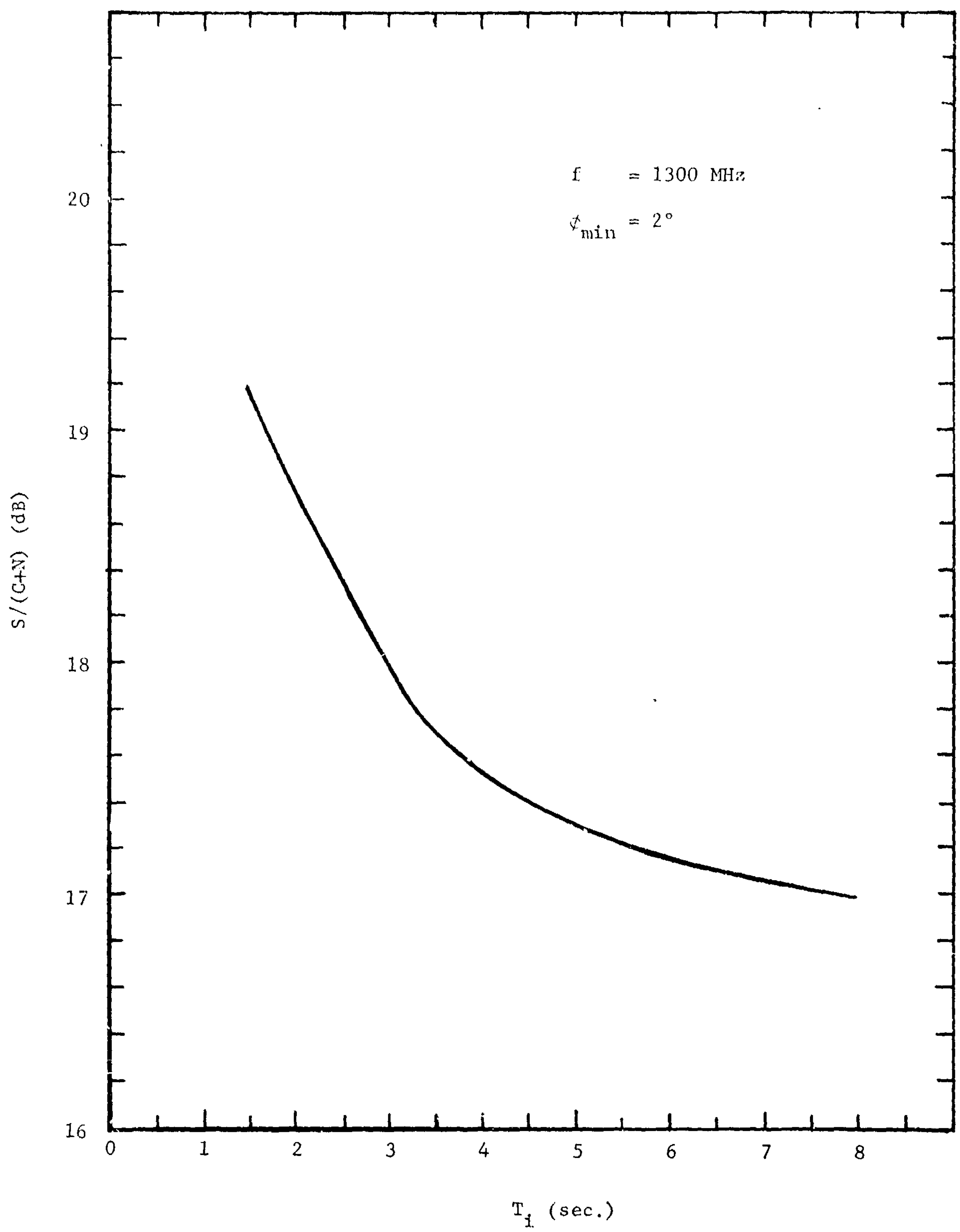


Fig. 8 - Required S/(C+N) for a 200 m^2 fluctuating target

(S) The following mechanical scan configurations were considered: Sector Scan and 360° rotation. Each of these types were considered using single scan integration and scan to scan integration, and frequency diversity employing up to 10 frequencies. The antenna size used in the mechanical scan case was: Antenna area ≤ 1250 ft^2.

(S) Mechanical scan solutions were not competitive with the electronic scan solutions. The difference between them was almost an order of magnitude in average power; therefore, the mechanical scan was dropped from consideration. This is not to say that the mechanical scan radar can not perform the ocean surveillance task, but rather that the degree of complexity required for it to do so represents a significantly greater risk than the electronic scan.

Electronic Scan Considerations

(S) To attack the problem of sea clutter decorrelation, the electronic scan radar can make use of frequency agility, scan to scan integration and the basic scan agility that is inherent in the electronic scan. The method selected makes use of the scan agility to achieve separation in space, and the decorrelation time of the sea itself. Fig. 9 is a diagram of the scan pattern of the electronic scan radar. For this particular case, R_s max = 1076 n.mi. having a corresponding unambiguous range PRF of 75. For L band, therefore, with a decorrelation time of 0.09 sec every eighth pulse is independent on the basis of time separation.

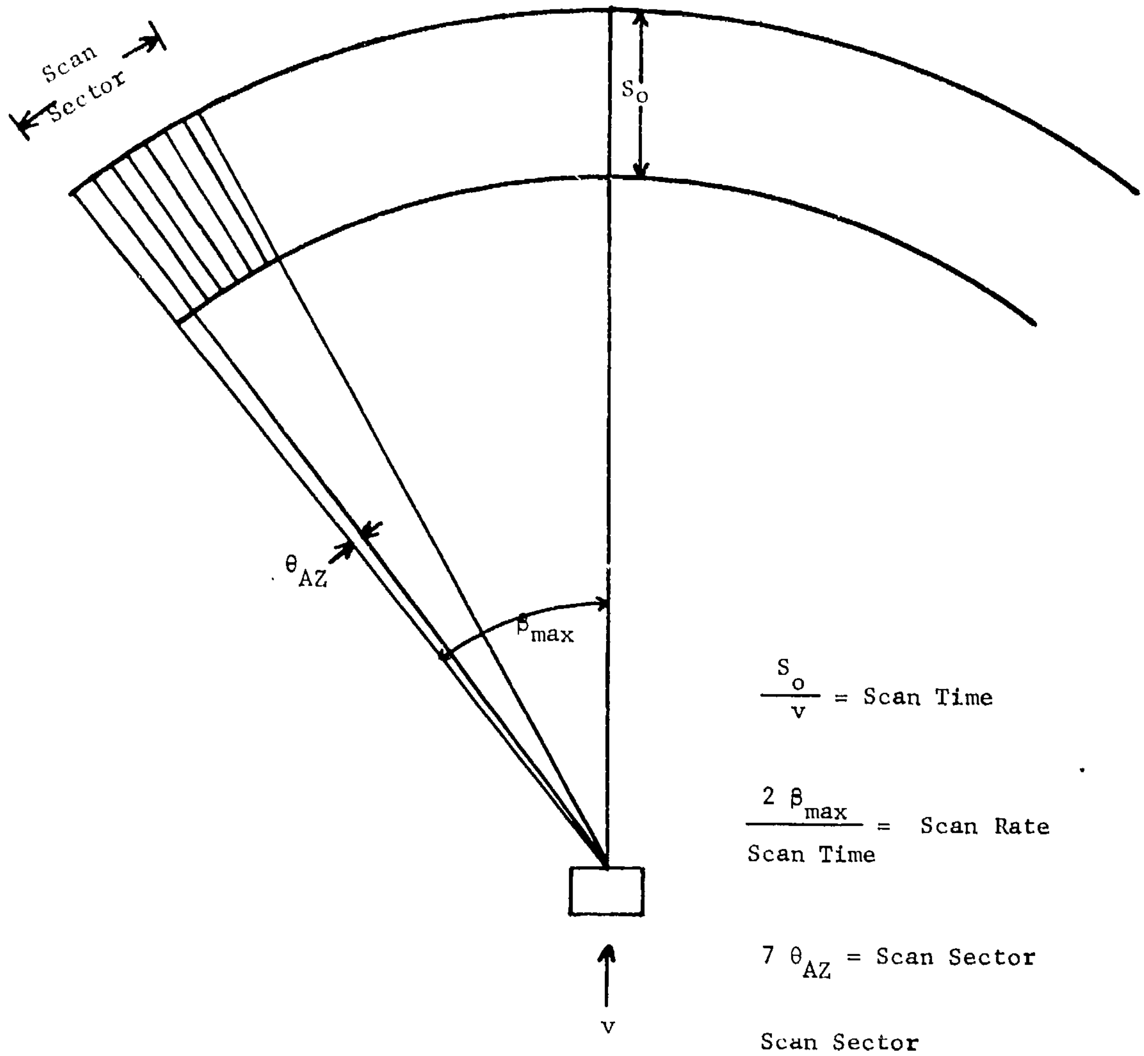
(S) As shown in Fig. 9, the satellite radar is pictured travelling as indicated at velocity V. β_{max} is the maximum azimuth scan angle on either side of the ground track. Also pictured is the azimuth beamwidth θ_{AZ}, a scan sector, and S_o (the distance along the ground track illuminated by the radar antenna).

$$\text{Scan Time} = \frac{S_o}{V} \quad \text{and Scan Rate} = \frac{2\,\beta_{max}}{\text{Scan Time}}$$

A scan sector is set equal to seven azimuth beam positions, i.e., Scan Sector = 7 θ_{AZ} and the time for the antenna to scan a sector is

$$\frac{7\,\theta_{AZ}}{\text{Scan rate}}.$$

(S) The scan agility is used to shift the beam within a scan sector one beamwidth at a time on a pulse to pulse basis. After scanning through the seven



$$\frac{S_o}{v} = \text{Scan Time}$$

$$\frac{2\,\beta_{max}}{\text{Scan Time}} = \text{Scan Rate}$$

$$7\,\theta_{AZ} = \text{Scan Sector}$$

$$\frac{\text{Scan Sector}}{\text{Scan Rate}} = \text{Integration Time}$$

Fig. 9 - Forward scan radar scan pattern using scan agility

beam positions, the antenna repeats the scan over and over until the time for the antenna to scan a sector is used up. The antenna then shifts to the next sector and repeats the process. This continues until the entire swath width has been scanned and then the antenna repeats the process on the next scan.

This scan pattern accomplishes the following things:

1. Every pulse is an independent sample with respect to clutter, i.e., the seven beam positions in a scan sector are independent spatially being a beam width apart and there is more than 0.09 sec between looks at the same beam position giving independence on a time basis.

2. The number of pulses integrated in any beam position is the same as in a uniform scan pattern but the time over which the integration occurs is increased by a factor of seven. This permits a significant reduction in the required S/(C+N) for the fluctuating target, for example, for a 1 sec integration time per beam position with a uniform scan, a S/(C+N) of 19.2 dB is required, while for the 7 position sector with the same number of pulses integrated, a S/(C+N) of 17 dB is required.

(S) The above scan method, while achieving excellent results with regard to sea clutter decorrelation and fluctuating target detection, passes some complexity along to the system data processor. Seven beam positions must be integrated simultaneously, over a time period seven times as long as would be required on a uniform scan. The effect of this is to increase the complexity and cost of the data processor.

Consideration of Frequency Diversity for Clutter Decorrelation and Fluctuating Target Detection

(S) If, as described previously, frequency diversity can achieve comparable performance to the scan agility method for detecting the fluctuating target, then the complexity required in the data processor for scan agility can be eliminated.

Finalization of Trends

Frequency

(S) Within the constraints imposed in the analysis, the optimum frequency is in L or S band with the decision as to which of these is optimum, depending on the desired minimum grazing angle. However, as mentioned previously, weather effects were not included in the programs. The effect of weather on L band is negligible and although it is small at S band, it is significantly greater than L band. Considering this effect, the optimum frequency is in L band.

Grazing Angle

(S) The optimum grazing angle at 1300 MHz for the antenna height being considered is 6 degrees. At 2900 MHz, the optimum grazing angle for the same antenna size is 2 degrees. These grazing angles are related to the sea clutter curves shown in Fig. 1. The optimum minimum grazing angle is dependent on the illumination of the region in the flat portion of the curves, i.e., less than 10° at L band and below, and less than 4° at S band.

Altitude

(S) The optimum altitude for the forward looker is 200 n.mi. This is due to the large frontal area presented by the antenna of the forward looker. Lower altitudes are better for radar operation but the drag becomes more severe, whereas higher altitudes reduce the drag effects but require increased radar capability. 200 n.mi. appears to be the best compromise between the two effects.

Antenna Size

(S) The best antenna size for the electronic scan is one that fits within the satellite contour, filling the area already contributing to drag, and having a minimum of additional drag surface. In addition to this constraint, the weight of the antenna is directly related to size (Fig. 6) and also the cost of the antenna depends significantly on size. Considering all these factors, the best antenna is 400 ft^2 in area; and the dimensions are 36 ft long by 11 ft high. This permits packaging two of these radar satellites in a launch vehicle as described previously for configuration S-2. The satellites are flown sideways with the antenna normal to the flight path.

Pulse Width

(S) The optimum pulse width is 0.1 μsec. This pulse width is narrow enough to keep the clutter down to a reasonable level but wide enough to ease the peak power requirements and simplify the bandwidth requirements of the radar circuitry.

Pulse Repetition Frequency

(S) Maximum PRF for unambiguous range has been the PRF criteria throughout the study. In the case of the mechanical scan when frequency diversity was used, the PRF was increased in direct relation to the number of frequencies.

Swath Width

(S) The minimum swath width required for a two satellite per launch vehicle system is approximately 685 n.mi., for 200 n.mi. altitude without allowing for any overlap of coverage. An 800 n.mi. swath width provides more than enough overlap to insure full coverage with the expected satellite stabilization inaccuracies. Increasing the swath width beyond 800 n.mi. at this altitude causes the required average power to be increased, due to the decrease in gain for electronic scan antennas as the azimuth scan angle increases. 800 n.mi. appears to be the optimum swath width at this altitude.

Azimuth Scan

(S) In an electronic scan system, it is necessary to keep the maximum scan angle less than 45° due to the antenna pattern degradation at large scan angles. The antenna gain is a maximum along the antenna boresight and decreases as the scan angle increases.

Average Power

(S) Throughout the parametric analysis, average transmitted power was used as a criterion for determining the acceptability of solutions. The development of a highly reliable radar transmitter is considered to be one of the greatest challenges in the ocean surveillance radar problem, and the degree of difficulty in this development is greatly dependent on the average power requirement of the transmitter. An average power in the vicinity of 500 watts was established as a goal for all of the radar systems. Other areas sensitive to the transmitter power requirements are the size of the solar arrays necessary for supplying prime power to the radar, and the problems associated with the removal of the heat dissipated in the system.

Pulse Compression Ratio

(S) In keeping with the desirability to avoid system complexity wherever possible pulse compression ratios have been held to the levels attainable by chirp techniques rather than going to the higher values attainable by phase coding techniques which would increase system complexity. A value of 300/1 is a compression ratio readily attainable at this time and is therefore used in the program.

Antenna Considerations

(S) Having settled on an aperture size of 36 ft by 11 ft, it is now possible to consider the type of antenna which will be used, in order to obtain a reasonably accurate weight and cost estimate. Although the forward-scanning technique requires that the beam be positioned in both azimuth and elevation, there is a requirement for beam steering only in azimuth. In elevation, the required depression angle can be achieved by squinting the beam electronically a fixed amount. Although this could also be accomplished by tilting the aperture down (thus permitting the use of a simpler antenna such as a parabolic cylinder with an electronically-scanned line feed), this approach was discarded because of the non-constant-range swath which results.

(S) A planar array is the best choice for satisfying these beam-positioning requirements. The choice can be made from among several types, such as arrays of: (1) slotted waveguides, (2) solid state modules, and (3) dipoles or horns. These types were investigated from the standpoint of weight, packageability, cost and reliability. On the basis of these considerations, the array of slotted waveguides was preferred. The proposed antenna therefore consists of waveguide sections stacked in the azimuth dimension. Each waveguide has a series of longitudinal shunt slots (for horizontal polarization) and is phased so as to cause the beam to squint down the required amount (about 20°). The waveguide elements are fed by a corporate network through diode phase shifters to permit azimuth scanning of the beam. Although this design for the antenna is somewhat tentative, it does provide a concept upon which detailed weight and cost estimates can be determined.

Peak Power

(S) It is desirable to have peak power as low as possible, but given an average power, pulse width, pulse compression ratio and PRF, the peak power is specified. A maximum value of 300 kw has been the goal to avoid X-radiation and voltage breakdown problems.

Reliability

(S) Reliability has been a governing factor throughout the analysis. The constraints which were imposed on some of the parameters, such as average power and peak power, were dictated primarily by a concern for reliability or probability of success. It was partly a concern for reliability that caused the elimination of the mechanical scan system from consideration, i.e., the system complexity required for a competitive system appeared to negate the reliability goals.

Number of Satellites

(S) As described previously, the possibility exists of putting up from 1 to 3 radar satellites per launch vehicle depending on size, weight and power requirements.

The corresponding swath width requirements are inversely proportional to the number of satellites per vehicle for a given altitude, e.g., at 200 n.mi. altitude, S-1 swath requirement = 1370 n.mi., S-2 = 685 n.mi., S-3 = 510 n.mi. For the electronic scan radar, the restriction on azimuth scan angle due to the antenna pattern degradation at large scan angles eliminates the S-1 configuration from consideration. The relative insensitivity of the radar to swath width for moderate scan angles causes the three satellite system to require practically the same radar as the two satellite system. The weight and size requirements are too great for the S-3 configuration. This leaves the two satellite or S-2 configuration as the only acceptable one for the electronic scan.

(S) In the mechanical scan case, the restriction on scan angle does not apply and the optimum configuration is the single satellite configuration or S-1.

System Weight

(S) For purposes of considering system weight, the system is broken down into three categories; antenna, transmitter and data processor (including receiver). As discussed previously, preliminary designs were done on the data processor and antenna to determine weight and cost estimates. The resulting weight estimate for the antenna is 1600 lbs. and for the data processor is 100 lbs. Transmitter weight is based on a general estimate of one pound per watt of average transmitter power, i.e., a transmitter with an average radiated power of 500 watts is considered to have a weight of 500 lbs as shown in Fig. 10.

System Power Requirements

(S) The prime power requirements for the radar are based on the requirements of the transmitter and data processor. From the previously described preliminary design, the data processor power requirement is 400 watts. The transmitter power requirement is based on a 25% efficiency and is four times the average transmitter power, i.e., for the 500 watt average power transmitter mentioned above, the transmitter prime power required is 2000 watts and the system prime power would be 2,400 watts.

System Costs

(S) The antenna cost estimates are based on the preliminary design. This cost includes research, development, test and evaluation (RDT&E) of the antenna with an engineering model, a prototype model, and two space qualified flight models. 2.5 million dollars is the cost, with additional flight models costing $300,000 each. The cost of the data processor based on the preliminary design is estimated at 2.5 million

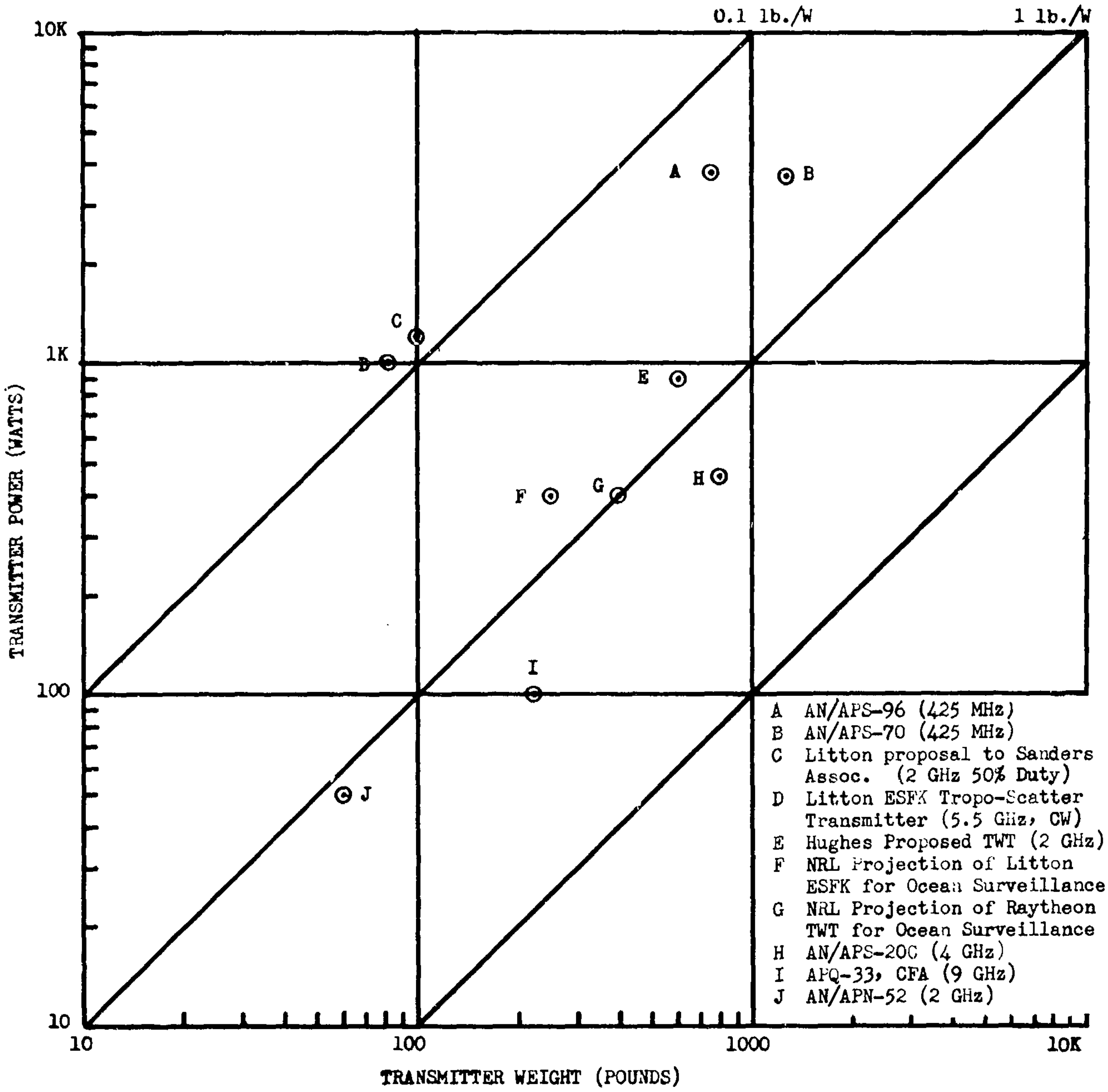


Fig. 10 - Transmitter weight as a function of power

for RDT&E plus 0.75 million unit cost. No space qualified models are included in the RDT&E cost. The cost of the prime power source, which is a solar array, is based on the general estimate of one million dollars per kilowatt of prime power for a solar array using one axis for solar orientation.

(S) Transmitter costs are based on costs of current AEW systems plus an estimate of the effect of high reliability and space qualification. Figure 11 shows the curves used for transmitter RDT&E and unit costs.

(S) It must be emphasized that these costs are merely estimates, but their accuracy is not expected to affect the optimum system selection because they are applied uniformly to all systems and types of systems. They are valuable as an indication of the relative complexity of the various systems.

Selection of the Preferred Forward Scan System

(S) Having determined the optimum values for most of the parameters affecting the radar design, the selection of the optimum radar system follows without much difficulty. Two electronic scan systems have been presented in Table 9. Both of these systems have the optimum values for altitude, swath width, pulse compression, pulse width, antenna length and height, and PRF and both use substantially the same data processor. In addition, System #1 is at the optimum frequency and optimum grazing angle for that frequency whereas System #2 is at 2900 MHz and the minimum grazing angle (which is optimum for 2900 MHz). Comparing the systems, it can be seen that there is little or no difference between them in transmitted power, system weight, prime power or cost. The reason for selecting System #1 as the system over System #2 is as stated previously due to the effect of weather which will be more detrimental to System #2 than System #1.

(S) It will be noted that the values for effective beamwidth in Table 9 are not the usual 3 dB beamwidth values. The effective azimuth is 0.92 times the 3 dB azimuth beamwidth. This is to account for the reduction in antenna gain in azimuth at $+ \frac{\theta_{AZ}}{2}$ at the near and far edge of the illuminated swath. The effective elevation beamwidth (θ_{EL} eff.) is 0.55 times the 3 dB elevation beamwidth (θ_{EL}). The justification for this factor is contained in the following discussion.

(S) It was determined in the analytical program that the swath width in the forward direction (S_o in Fig. 9) corresponding to the 11 ft antenna height was not the optimum size. The maximum antenna height was determined by physical constraints, i.e., the size of the shroud and the desirability for a non-folding antenna. It was desired to reduce the value of S_o without increasing antenna height or increasing frequency which had already been optimized. A computer program was written to consider the effect of using something other than the 3 dB elevation beamwidth of the antenna. Values from 0.1 θ_{EL} to θ_{EL} were considered and the best radar performance for the selected systems occurred at 0.55 θ_{EL}.

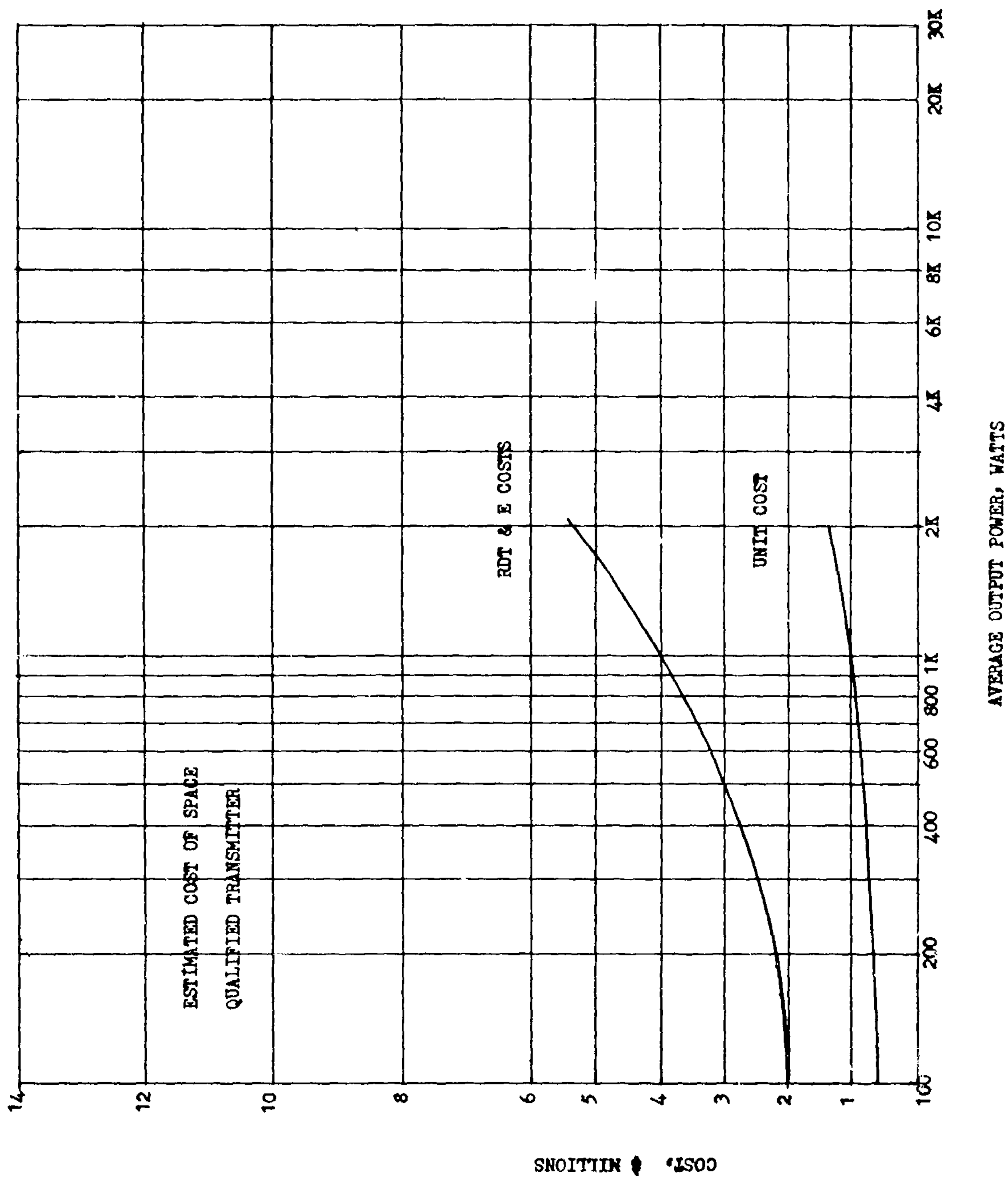


Fig. 11 - Estimated cost of space qualified transmitter

TABLE 9

PREFERRED SYSTEMS

PARAMETER	SYSTEM #1	SYSTEM #2
Frequency (MHz)	1300	2900
Min. Grazing Angle (deg.)	6	2
Altitude (n. mi.)	200	200
Swath Width (n. mi.)	800	800
Average Power (watts)	530	530
Peak Power (kw)	190	235
Pulse Compression Ratio	300/1	300/1
Pulse Width (μsec)	0.1	0.1
Antenna Area (ft^2)	400	400
Antenna Length (ft)	36	36
Antenna Height (ft)	11	11
Azimuth Beamwidth (deg.)	1.4	0.7
El. Beamwidth (effective) (deg.)	2.7	1.2
Azimuth Scan (± deg.)	37.25	28.8
PRF (pps)	92	75
Max. Slant Range (n. mi.)	838	1076
No. Pulses Integrated	95	49
System Weight (lb x 10^3)	2.4	2.4
System Prime Power (kw)	2.6	2.6
System Cost ($ x 10^6)	16.1	16.1

(S) Additionally, an antenna pointing optimization was programmed. This program determined the optimum depression angle by requiring the same S/(C+N) for the target at the far edge of the swath as that obtained from the target at the near edge of the swath.

Preferred System

(S) System #1 is the preferred forward scan system. The system is capable of detecting the 200 m^2 fluctuating target with a 90% probability of detection as previously specified. The 800 n.mi. swath width contains sufficient overlap to insure complete coverage of the earth twice a day, using the S-2 configuration. The 800 n.mi. swath is centered about the ground track providing the capability for future systems of pointing another type sensor at the target for identification purposes. There is an unused weight capacity of approximately 200 lbs available for some system redundancy.

(S) The antenna is enclosed within the confines of the satellite, i.e., the satellites resemble a cylinder split in half along its longitudinal axis with the antennas mounted on the flat surfaces. Each satellite flies sideways with the antenna surface normal to the direction of motion. The antenna (36' x 11') fills the flat surface of the satellite, thus the antenna is almost the maximum which can be included in the launch vehicle shroud without folding. The absence of a folding requirement is particularly important for the electronic scan type antenna for reliability considerations as well as development costs.

CASE II - REAL APERTURE SIDELOOKING RADAR SYSTEMS

(S) The analysis of real aperture sidelooking radar sensors and the selection of a preferred system was predicated on the requirements for a simple and highly reliable system. The results of the parametric analysis program indicate that there are many potential systems which are theoretically capable of detecting the specified 200 square meter fluctuating ship target from a satellite platform. Of the many potential systems, they do not all represent the same degree of risk, the same confidence or reliability, or projected costs; and it is these factors on which the final selection of the preferred system is based.

Major Parameters and Tradeoffs

Altitude

(S) As was indicated earlier[1], the altitudes considered in the analysis ranged from 100 to 1000 n.mi. The relationship between satellite orbital altitudes, the available sensor system prime power, and the maximum allowable weight for t'e sensor system based on a Titan III-C launch vehicle are shown in Fig. 2. In this particular family of curves, the prime power available for the sensor system is maximized at an orbital altitude of approximately 250 n.mi. However, as a result of the iterative design process, neither maximum power or weight is required. For reasons that include the ease of development, higher reliability and lower costs, an altitude of 150 n.mi. was selected.

Number of Satellites

(S) Within the limits imposed on the parametric analysis, satisfactory solutions could not be achieved with a single sidelooking real aperture radar. The S-1 sidelooker did not have the capability of covering the required swath. For S-2 and S-3 satellites, there were numerous potential solutions. The required minimum swaths in each case are specified to provide contiguous equatorial coverage. Except for polar zones, this is equivalent to two detections per target per 24-hour period.

Packaging

(S) In each case, the weight and the stowed size of the sensor package is limited to values that are appropriate for nesting the required 2 or 3 satellites within a 48 ft long, 12 ft diameter shroud. In the majority of real aperture sidelookers considered, weight was not the limiting factor. The stowed bulk of the antenna was usually the major limiting factor. As a result, though the antenna cannot be readily increased in size, the weight of the systems may be increased to gain reliability through the use of other redundant system elements.

Prime, Average and Peak Power

(S) Long term reliability decreases and development costs increase rapidly as the peak and average operating power levels of a power amplifier are raised. Starting with an initial upper limit of 1000 watts average radiated power, the required power has been reduced to the present level of 500 watts. Further, to avoid X-radiation and voltage breakdown problems, pulse compression is specified and the peak powers are limited to a maximum of 300 kw. Based on tentative and general information, an overall transmitter chain efficiency of 25% has been postulated. Assessed in this efficiency value are: power amplifiers, drivers, modulators, power supplies, power conditioners, and thermal cooling power requirements. Power requirements for the receiver and the data processor and auxiliary equipment have been assessed separately.

Single Vs. Double Sidelooking Configurations

(S) Both single and double sidelooking configurations have been considered for the real aperture sidelooking sensor. As a basis for selecting the more effective configuration, two systems are compared in Table 10. Common to the two systems in the table are: the total average power, the total antenna cross section, and the operating frequency.

TABLE 10

Factor	Single Sidelooker	Double Sidelooker
No. of Antennas	1	2
Antenna Size, ft.	48 x 21	48 x $10\frac{1}{2}$
Average Radiated Power, W	500	500
Transmitter	Single, 500 W unit	Two, 250 W units
Min. Grazing Angle, deg.	1	11
Total Swath, n.m.	615	610
Swath Interlace	Less Complex	More Complex
Reliability	Higher	Lower

(S) In the above table, the antenna sizes are such that the 48 x 21 ft unit requires two folds in the vertical dimension and the 48 x $10\frac{1}{2}$ ft antenna requires one such fold per antenna.

(S) Figure 12 is a swath coverage diagram and helps to illustrate the difference in complexity of the swath interlace. The shaded areas represent coverage on a twice a day basis. Except for the polar regions, the remainder of the unshaded areas represent greater than twice a day coverage.

(S) The double sidelooker in Table 10 covers 305 n.mi. of swath, either side of the sub-satellite track, for a total of 610 n.mi. The single sidelooker is computed to cover 615 n.mi. of swath. Thus, with regard to swath, the total performance is nearly identical.

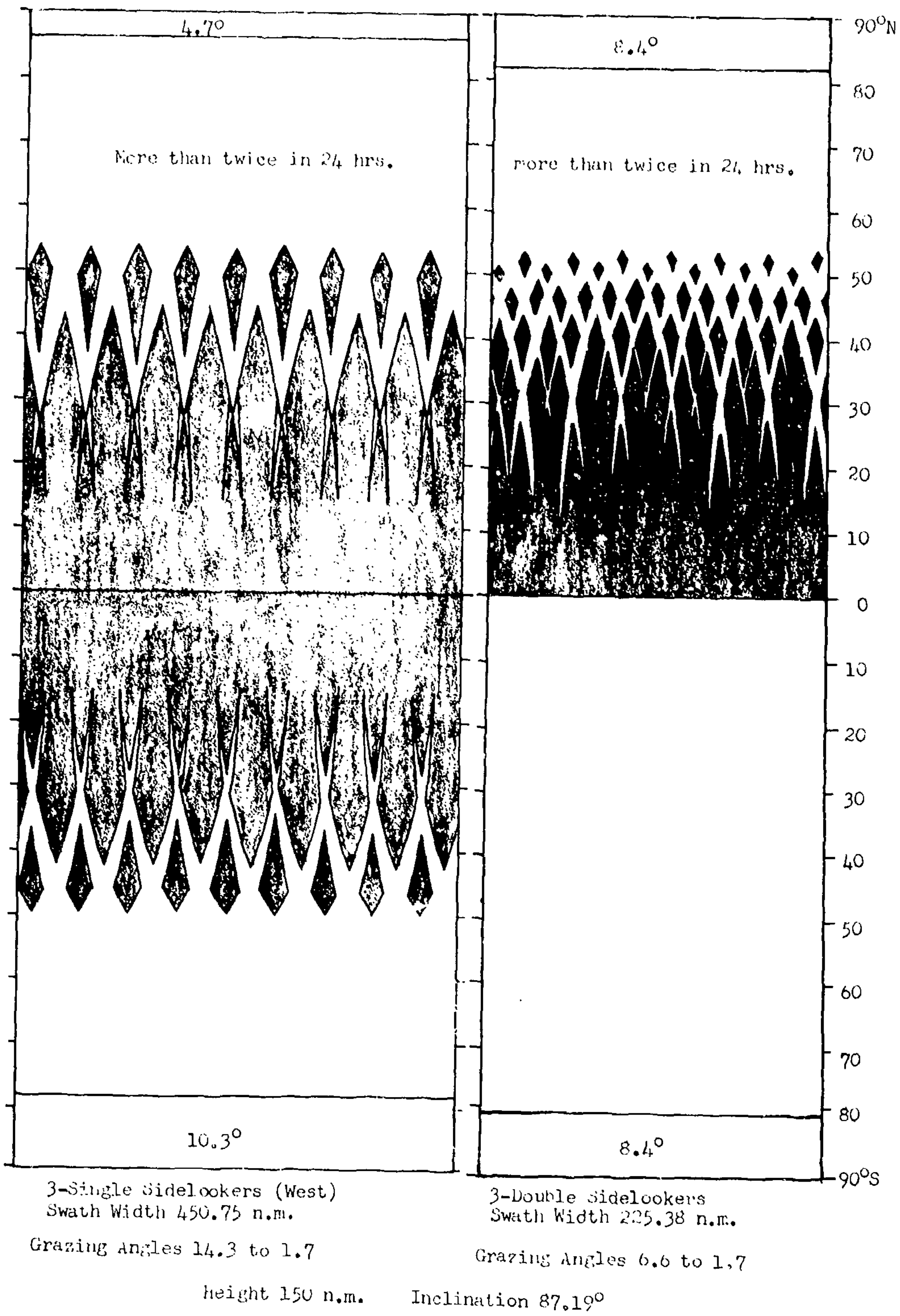


Fig. 12 - Ground swath coverage

(S) The overall estimate on reliability is that the single sidelooker would be superior. The single sidelooker requires the erection of a single distributed line antenna feed and a single antenna with two folds. The double system requires the erection of two distributed line feeds and the unfolding of two separate antennas, each with one fold. The double sidelooker would use power amplifiers of half the power of the single system which would make for greater single unit reliability. The two units of the double sidelooker are not redundant, and for reliability purposes are part of a series chain, and the net effect is an anticipated lower reliability. On the basis of less complexity in both hardware and swath coverage and higher reliability, the single sidelooker is selected as being the preferred configuration.

Frequency

(S) As a result of the various limits and constraints which were imposed as the parametric analysis developed, satisfactory solutions were obtained at 900 and 1300 MHz. Solutions at frequencies of less than 900 MHz were not achieved primarily because of the effects of Faraday rotation and secondarily because of the limits on antenna packaging size. Satisfactory solutions at frequencies above 1300 MHz were not obtained in the final sets of computations because of the combined effects of: high clutter levels, decreased receiver sensitivity, increasing atmospheric losses and the requirement for more severe vertical beamshaping. Specifically, solutions were achieved for 2900 MHz, but at average power levels of almost double the 500 watt level finally elected as a design limit. Alternative approaches, such as a consideration of stacked beams as well as higher power could have provided satisfactory swath coverage at higher frequencies, but would have violated the objective of specifying the simplest possible detection radar system.

Minimum Grazing Angle

(U) A somewhat conservative limit has been placed on the grazing angle, limiting the outer bound angle at 5 degrees to avoid possible signal loss problems associated with tropospheric anomalies. This is an arbitrary approach, and in fact the systems may well be expected to be capable of operating very reliably to grazing angles of 1 degree, with a consequent increase in the useful swath.

Swath

(S) As was noted earlier, only constellations of 2 or 3 equally spaced satellites are capable of providing the required coverage for a sidelooking system. At the selected 150 n.mi. altitude, the required minimum swath for contiguous equatorial coverage is 675 n.mi. for the two satellite constellation and 451 n.mi. for the 3 satellite constellation. As a safety factor, the swath specified is to be at least 10% greater than the minimum required for contiguous equatorial coverage. The combination of several factors: the excess swath specification, an allowance for ±½ degree of satellite roll and pitch, and the probability that target detection can be accomplished to the 1 degree grazing angles will result in a higher correlation of target track for many targets in all except the most extreme environmental conditions.

Antenna

(U) Tradeoffs on antenna size and various dimensional ratios are considered in Ref. 9. The effect of changing antenna size and dimensional ratios on azimuth resolution and swath coverage for a few cases may be seen in the data presented in Table 11. Each of the systems presented in Table 11 uses shaping of the vertical beam to optimize swath coverage and the details on beam shaping are also covered in Ref. 9.

Pulse Repetition Frequency

(U) Specification of the maximum PRF for unambiguous range has been a criteria throughout the analysis. In setting the maximum PRF, in some cases advantage has been taken of the radar platform altitude by transmitting just before the return from the near edge of the swath, such that sidelobe returns from below the radar platform occur at some time after the return from the far edge of the swath[3].

Pulse Compression

(U) Pulse compression is specified for the systems being considered in order to maintain adequate range resolution while keeping peak powers and voltages at lower levels in order to improve reliability. The pulse compression ratios specified have been based on values which can be attained with chirp techniques. Very high values could be achieved through phase coding techniques, but at a cost of increased complexity. A value of 300/1 is regarded as attainable and is the value used in this program.

Pulse Length

(U) At shallow grazing angles with a noise limited system, pulse length has comparatively little effect on the required average power. At steeper grazing angles, a clutter limited situation exists and the power required increased markedly with increasing pulse length. In this analysis, the optimum pulse width has been found to be 0.1 μsec. This pulse width is narrow enough to keep the clutter at

TABLE 11

REAL APERTURE SIDELOOKING RADAR SYSTEMS

PARAMETER					
System	A	B	C	D	E*
Number of Satellites	2	3	3	3	3
Frequency, MHz	1300	1300	1300	1300	2900
Average Power, W.	1000	500	500	500	500
Peak Power, kw	400	200	200	200	200
Pulse Compression	300/1	300/1	300/0	300/1	300/1
Effective Pulse Length, μ sec	.1	.1	.1	.1	.1
Altitude, n.mi.	150	150	150	150	150
Horizontal Beamwidth, deg.	1.0	1.0	1.0	0.5	0.5
Antenna Length, ft.	48	48	48	96	48
Antenna Height, ft.	9.8	22	22	9.8	8
Reference Target, m^2 (fluctuating)	200	200	200	200	200
Minimum Grazing Angle, deg.	1.0	2.4	5.0	5.0	2.3
Pulse Repetition Frequency, pps	83	83	83	83	83
Pulses in Beamwidth, max. range	359	329	282	141	145
Pulses in Beamwidth, min range	96	106	96	46	43
Max. Slant Range, n.mi.	970	890	770	770	900
Max. Ground Range, n.mi.	940	860	740	740	870
Swath, n.mi.	720	615	520	530	520
Cost, $M	18.9	15.5	15.5	16.0	15.0
Reliability	Worst	Best	Best	Intermed.	Worst

* System E is based on different ground rules than Systems A-D, and is regarded as being unrealistic because of the assumed extreme efficiencies and minimal losses.

manageable levels yet wide enough to ease the peak power levels and simplify the bandwidth requirements on the radar circuitry.

Azimuth Resolution

(S) The achievable azimuth resolution is a function of the physical length of the antenna and the operating frequency. Packaging limits and dimensional tolerances were constraints on the antennas considered in the parametric analysis. With a few exceptions, in the final sets of computer runs the antenna lengths were limited to the shroud length of 48 ft. At 1300 MHz, this then fixed the azimuth resolution at 1 degree. In one of the exceptions, where an antenna folded in length was considered, a resolution of ½ degree was indicated. The improved resolution reduced the clutter cell size, but the net gain on swath was only slight (see Columns C and D of Table 11).

Costs

(U) The antenna cost figures are based on detailed cost estimates for reflector type antennas. It is to be understood that these cost figures are only estimates and will be modified as firm information becomes available from industry sources relative to specific types of space qualified antennas. The costs represent the total estimate for research, development, test and evaluation. The antenna RDT&E costs further include fabrication of an engineering model, a flight prototype, and two flight qualified antennas.

(S) The costs for the solar prime power supply are based on various industrial information sources. The cost of the satellite solar power system is projected at one million dollars per kilowatt of primary power for solar panels with only one controlled axis for solar orientation.

(U) Figure 11 is an estimate of anticipated RDT&E costs for the transmitter. The values shown in Fig. 11 are based on the remotely related costs of current AEW radar systems together with estimates of the increased costs for higher reliability and qualification of a system for a space environment. Numerous inquiries have been made of industry representatives as to estimated cost of transmitter systems.

(U) The data processor and receiver were grouped together and cost values were estimated for the several systems under consideration.

Weight

(S) The weight of the antennas will be a function of the size, the materials used, the stresses to which it will be subjected during launch and in space, and the packaging and degree of erection which may be required. An initial estimate, based on space erectable antenna designs, is based on Fig. 6.

(U) The weights of the transmitter systems have all been based on a conservative value of 1 pound per watt of average radiated power. Fig. 10 shows weights and powers for a number of existing and proposed radar system transmitters. These weight values include all associated equipment such as modulators, power supplies, transmission lines, and protective circuitry.

(U) The receiver and data processor are considered together in weight estimates. The bulk of the weight is associated with the solid state processor. For the systems in Table 11, a constant value of 250 pounds was used. This initial gross estimate is considered to be conservative for the amount of data storage required for the particular systems being considered.

Reliability

(U) The intra-system comparison of reliability was of a gross nature and was based on consideration of the peak and average power requirements of the transmitter; and the size and degree of complexity associated with the erection of antennas and associated feeds. Reliability is to be assured through the use of low power and the specification of simple systems. Unused weight allowances will be considered for the addition of redundant sub-system elements for the improvement of reliability.

Candidate Systems

(S) Table 11 lists the parameters for five different real aperture sidelooking radar systems. The system in Column A requires two satellites equally spaced in an orbital plane, while the remaining columns list parameters for systems based on three equally spaced satellites. The chief differences besides the number of satellites are:

1. "A" requires twice as much peak and average power as the other listed systems.

2. The "A" and "E" systems do not require folding of the antenna.

3. The "B" and "C" systems require two folds of the antenna in the vertical dimension.

4. The "D" system requires one fold in the horizontal antenna dimension.

5. The "A" system has an approximate 9% swath overlap, the "B", 37%, and the remaining systems an approximate 16%.

6. The "A" system is the most expensive and the costs of the remaining systems have a variance of about 5%.

7. The "E" system frequency is 2900 MHz, all other systems in Table 11 are specified at 1300 MHz.

(S) The costs in Table 12 are intended only as guides and are one of a number of factors used in judging and selecting a preferred system. The important element of the cost figures is that the same approach and weighting has been applied to all of the systems being compared. Specifically, the cost figures shown in Table 12 represent RDT&E plus unit costs required to launch the initial constellation of satellites. The values are undoubtedly low and will be revised upwards as better cost information becomes available.

(S) Systems "B" and "C" are identical systems. The difference between the two is that the "C" system represents a more conservative approach towards the allowable minimum grazing angles, and is restricted to a 5 degree minimum as compared to the 2.4 degrees of the "B" system. The result of this conservative approach is a reduction in the range swath from 615 to 520 n.mi., or almost a 100 n.mi. loss in swath range. The "C" system with a swath of 520 n.mi. exceeds the minimum swath required for contiguous equatorial coverage by 16%.

(S) System "D" is not regarded as a serious candidate because of serious concern with the reliability of unfolding and erecting such a long, narrow antenna and associated distributed feed. The system is included in the table to show the effect of reducing antenna height and increasing length. The cross-sections of the antennas in "C" and "D" are approximately comparable. As a result of the increased length, the azimuth resolution of the "D" system is ½ degree compared to the "C" system 1 degree. The improvement in azimuth resolution decreases the size of the clutter cell and results in a slightly greater detection range swath.

(S) The "E" system is not a seriously proposed system. It is an example of the results which can be achieved through the reduction of safety factors, and the specification of laboratory "state of the art" performance for long periods of time in a space environment. It is through the high risk reduction of losses and improvement in sensitivity that the "E" system becomes theoretically feasible for operation at 2900 MHz. Additional major differences between the low risk "C" and the high risk "E" systems are shown in Table 13.

TABLE 12

REAL APERTURE SIDELOOKING RADAR SYSTEMS COSTS

SYSTEM	A	B	C	D	E
NUMBER OF SATELLITES	2	3	3	3	3
ANTENNA RDT&D	1.1	1.6	1.6	2.0	1.1
TRANSMITTER RDT&E $M	4.0	3.0	3.0	3.0	3.0
DATA PROCESSOR AND CONTROL RDT&E	2.0	1.5	1.5	1.5	1.5
ANTENNA UNIT COST	.12	.12	.12	.25	.12
TRANSMITTER UNIT COST	1.0	.8	.8	.8	.8
DATA PROCESSOR/CONTROL UNIT COST	.4	.25	.25	.25	.25
PRIME POWER UNIT COST	4.5	2.3	2.3	2.3	2.3
INITIAL CONSTELLATION, TOTAL COST	18.9	15.5	15.5	16.0	15.0

TABLE 13

REAL APERTURE SIDELOOKING RADAR SYSTEMS

FACTORS IN LOW VS. HIGH RISK APPROACH

Factor	Low Risk System	High Risk System
Receiver $\overline{NF}$	5.7 dB	1.5 dB
Swath Coverage	16% Overlap	No Overlap
System Degradation	3.0 dB	1.5 dB
Allowance for Satellite Roll	Vertical Beam Shape Accommodates $\pm\frac{1}{2}°$ Roll	Vertical Beam Shape Does Not Allow For Any Roll
Minimum Grazing Angle	5° Limit	2.4° Limit

(U) There is an inconsistency in Table 12 in that the cost values assigned for the "E" system do not include a recognition of the much greater cost and risk associated with the "state of the art" system.

Comparison of Candidate Systems

(U) Table 12 is related to Table 11, and in a comparison of systems, the two tables should be considered together. It is to be understood and emphasized again that there are numerous systems with a theoretical capability of providing the detection coverage required. The general system objectives are to provide the required coverage with the least risk, lowest cost, and highest reliability. System "C", the recommended system in Tables 11 and 12 will be used as a baseline system.

(S) System "A" which uses only two satellites is significantly more costly than System "C". The System "A" antenna does not require erection after launch, but this positive feature is more than offset by the requirement that the "A" system operate at double the peak and average power levels of the "C" system. So, from a power and reliability standpoint, and from a consideration of costs, the "C" system is regarded as being markedly superior to the "A" system.

(S) Systems "B" and "C" are identical systems. The difference between the two is the limit on the minimum grazing angles and the resultant swath over which a 200 square meter fluctuating ship target can be detected. The "C" system is the more conservative system and is designed to perform with a 5 degree limit on grazing angle. Because of the questions which still remain with regard to tropospheric anomalies and target re-radiation characteristics at very shallow grazing angles, the "C" system with the more conservative limit is preferred.

(U) The "D" system with greater azimuthal resolution provides a slightly greater range swath. The extreme length-to-height ratio and the complications of unfolding and providing a distributed line feed for such an antenna, result is an evaluation that the "D" system is significantly less reliable than the "C" system.

(S) The "E" system is the one which is based on the maintenance of outstanding and extreme performance capabilities for the duration of the satellite life. Safety factors are non-existent or completely unrealistic and this system is judged to be too advanced for consideration within the present time frame.

The Selected Real Aperture Radar System

(U) The selected candidate for the Real Aperture Radar systems is the "C" system of Tables 11 and 12. The prime positive features of this system are simplicity, moderate power requirements, realistic assessment of system losses and performance, and a resultant high reliability together with relatively low cost.

(U) In the order of difficulty, the problems associated with this system are the development of reliable equipment: the transmitter, data processor, antennas and feed, and the receiver. Remaining associated problems which are common to all systems are: determination of the practical limits on the minimum grazing angle; verification of the target model; development of accurate cost data; and acquisition of meaningful reliability data.

CASE III - SYNTHETIC APERTURE SIDELOOKING RADAR SYSTEMS

Background

(S) The objective of the Case III preliminary parametric analysis[4] was to present a feasibility study of the sidelooking synthetic aperture radar concept for ocean surveillance. Three modes of operation were considered in this analysis, and each mode required the use of a coherent radar system in which the receiver had available to it a reference signal from which the transmitter waveform was derived.

(U) A coherent focused mode of operation required that coherence exist during the entire time that a target was illuminated by the azimuth beamwidth of the physical antenna, which corresponded to the coherent integration time, and that the synthetic aperture be focused at all ranges of interest. The achievable azimuth resolution in this case was one-half the physical antenna length.

(S) For the Case III preliminary analysis, the permissible integration time was limited to an interval in which the random phase shift due to irregularities in the ionosphere was 0.8 radians or less. If a target were illuminated by the azimuth beam of the antenna for a time greater than the permissible integration time, then phase coherence could not be maintained acrcss the entire beamwidth. This problem was circumvented by analyzing a semi-focused mode of operation wherein the azimuth channel was divided into a number of Doppler filters, the return signal coherently integrated in each channel for the permissible time, and the outputs of the Doppler filter bank integrated noncoherently. The azimuth resolution achievable in this mode is somewhat degraded from that of the focused mode.

(U) Consideration was also given to the coherent unfocused mode wherein the synthetic aperture need not be focused. This procedure imposed a maximum length on the synthetic aperture and resulted in an azimuth resolution of $\frac{1}{2}\sqrt{\lambda R}$, where λ is the wavelength and R is the target range.

(S) The preliminary analysis was predicated upon the following assumptions:

1. That optimum data processing could be realized, that is, the synthetic aperture could be focused at all ranges;

2. The use of an ideal antenna elevation beamwidth, that is, the inner and outer bounds of the illuminated swath were assumed to be the 3 dB points of the vertical pattern and the gain was zero outside these limits.

Two loss factors were added to the general system losses used in the Case I and II programs; one being a 2 dB loss to account for the use of a hard limit system, and the other being a 0.5 dB loss to account for overlap of non-optimum Doppler filter bandwidths. The limitation on coherent integration time due to irregularities in the ionosphere varied with frequency as shown in Fig. 13. These assumptions limited the number of variables that influenced system trade-offs and permitted a more direct presentation of system trends.

(S) In the interest of continuity between this report and the preliminary analysis, a summary of the parametric trends determined in the preliminary analysis is shown in Table 14.

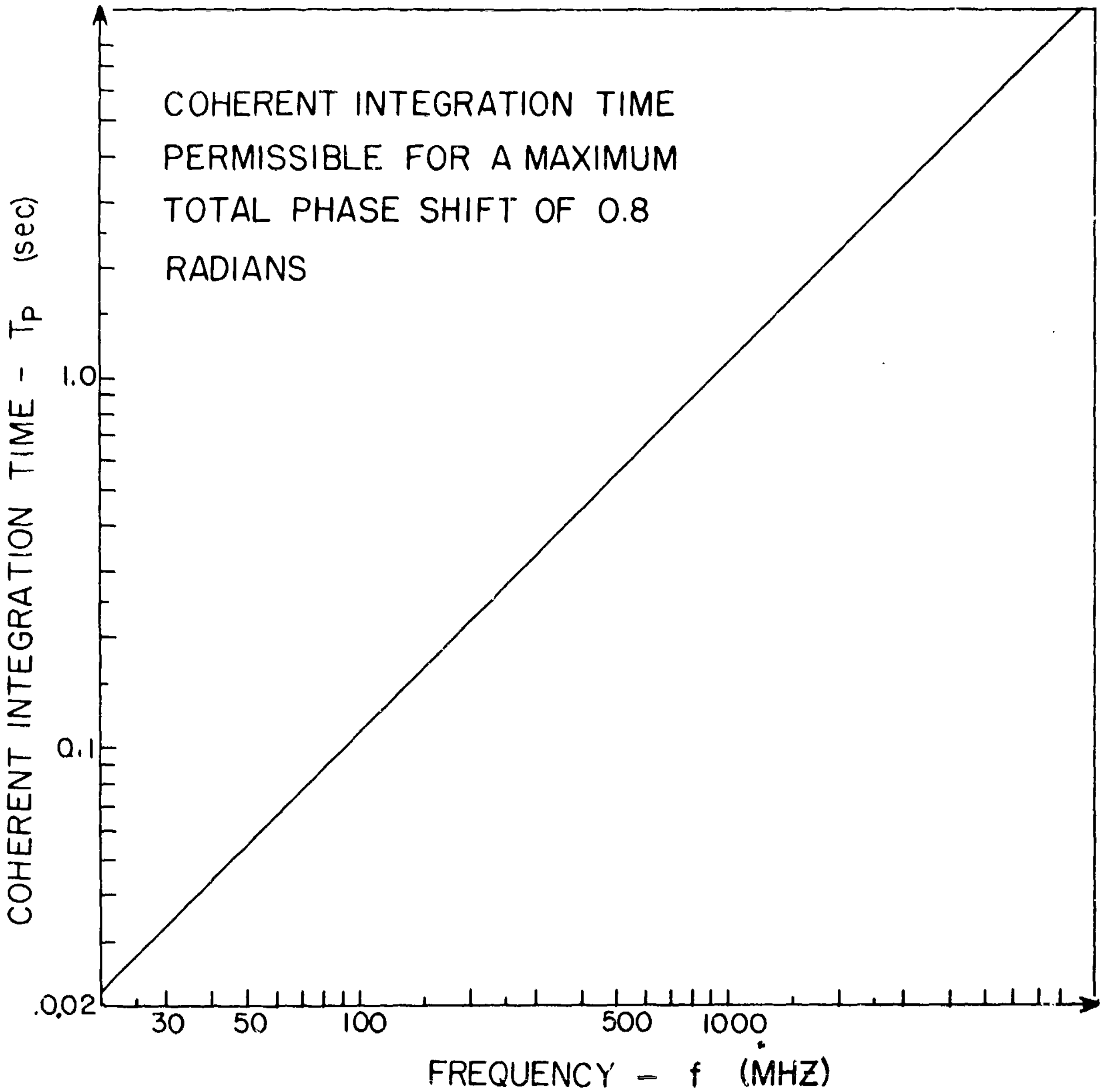


Fig. 13 - Allowable coherent integration time

TABLE 14

PRELIMINARY PARAMETRIC TRENDS - CASE III

Frequency ---------MHz	900 to 2900 for 200 n.m. altitude; or 1300 and 2900 for higher orbit altitudes
Orbital Altitude---nm	150 to 200
Swath Width--------nm	400 to 500
Antenna Size-------sq.ft.	Maximum allowable within constraints
Average Power------watts	Minimized at 1300 MHz
Pulse Width--------μsec	0.05 to 0.1

Frequencies below 900 MHz were eliminated from consideration because of excessive Faraday rotation losses as shown in Fig. 3 and 4. Considering altitudes significantly higher than 200 n.m. caused 900 MHz to also be discarded for the same reasons. For systems unambiguous in either azimuth or range, swath widths greater than 150 n.m. were not possible at 2900 MHz and above. This is due to the antenna constraints shown in Fig. 5, and the PRF required for unambiguous operation as imposed by the sampling theorem. Again, due to the constraints of Fig. 5, swath widths were limited to 300 n.m. for 1300 MHz. However, by accepting azimuth ambiguities, the swath widths tabulated in Table 14 were feasible. Average power minimized at 1300 MHz primarily due to the drop-out of Faraday rotation losses, and increases in effective system noise temperature which, in turn, reflects higher receiver noise figures and transmission line losses for the higher frequencies.

(S) It was concluded from the preliminary analysis, that either range or azimuth ambiguities must be accepted if swath widths large enough for effective ocean surveillance were to be realized. Completely unambiguous operation in both range and azimuth would require unrealistic antenna lengths of the order of 500 feet. This was due to the high PRF limitations imposed by the sampling theorem. The packaging and deployment problems associated with such antenna lengths would entail a high reliability risk. On the other hand, accepting both range and azimuth ambiguities would involve a severe ambiguity problem and require very complex processor circuitry to make target location possible.

Final System Analysis

Selection of Operating Mode

(S) As mentioned in the introductory statements of this report, one of the principle objectives of the final phase of this parametric study is to select, for each of the three radar categories, the system which will provide the best performance and highest reliability, hence, the least circuit complexity. In line with this philosophy, the emphasis for the Case III program has been concentrated on the unfocused mode of operation. The reasoning behind this choice of operating mode is set forth in the following paragraphs.

(S) The high degree of azimuth resolution obtainable with the synthetic aperture technique relies, primarily, on the successful design and mechanization of the data processor. Since the azimuth resolution achievable for the unfocused synthetic aperture is approximately an order of magnitude worse than that theoretically possible for the focused or semi-focused modes, it follows that the number of resolution cells to be processed would be reduced in proportion. The circuit complexity of the focused and semi-focused modes would be further increased by the need for correction of the quadratic phase errors, necessary for the focusing of the synthetic aperture, and Doppler compensating circuitry necessitated by the earth's rotation and spacecraft yaw. The latter circuitry would also be necessary for the unfocused mode, but not to as great a degree and with somewhat less expenditure of on-board fuel for proper control.

(S) Thus, for the very large swath widths necessary for effective ocean surveillance, the selection of the unfocused mode would greatly reduce the degree of circuit complexity and density involved in the mechanization of an on-board digital data processor. This, in turn, would lower the reliability risk over the long period of unattended operation contemplated for the mission.

Revised Constraints

(U) In the final phase of the Case III analysis program, more realistic views were taken with regard to the data processor, as already discussed, the antenna length, and the antenna elevation beamwidth pattern.

(S) The antenna lengths considered were limited to those considered to be mechanically feasible in the L and S-band frequency range. To obtain adequate swath widths, a beam shaping function, described by Eilbert[9], was incorporated in the computations for the antenna elevation beamwidth.

(S) From conclusions reached in the preliminary analysis, the number of trial system configurations was reduced to two, namely; the unambiguous azimuth/ambiguous range system; and the ambiguous azimuth/unambiguous range system. The original intent of the final phase of the analysis was to concentrate on the optimization of these two configurations. However, as the analysis developed, it became more and more obvious that an optimum solution for the type of system to be recommended was extremely sensitive to the digital data processor design. In the time available, it was not possible to analyze the details of all possible methods of processor design. Therefore, the method of approach discussed in the data processor section of this report was utilized to determine the processor requirements.

System Ambiguities

(S) Computer solutions were found for the unambiguous azimuth/ambiguous range configuration which provided adequate swath coverage, 500 to 700 n.mi. for a three satellite constellation with average power requirements ranging from 250 to 500 watts. However, to reduce the number of range ambiguities to an acceptable number, an antenna of considerable length was required. For example, a radar platform at an orbital altitude of 200 n.mi., utilizing an antenna length of 100 feet, and illuminating a 500 n.m. swath would result in six range ambiguities as shown in Fig. 14. This, of course, was due to the high PRF required by the sampling theorem for the unambiguous azimuth condition.

(S) With the method of data processing considered in this analysis, such range ambiguities would have to be resolved prior to processing. This could be accomplished with pulse coding techniques, PRF stagger, or spatially resolving them with multiple antenna elevation beams. All such remedies complicate either the electronic circuitry or the antenna design and would, in any case, add to the reliability risk.

(S) The ambiguous azimuth/unambiguous range configuration was considered to be the least complex. This approach exhibited the following advantages: no range ambiguities to be resolved; a relatively short antenna, requiring a minimum of folding; and only a single correlator channel would be necessary in the data processor. However, the problem of resolving the azimuth ambiguities remained. The difference in this case, as compared to that of range ambiguities, was that the ambiguities were confined to a region defined by the azimuth beamwidth of the antenna instead of the elevation beamwidth; a distance of several miles compared to several hundred miles. Hence, the problem of resolution should not be as complex.

(S) Obviously, to operate in an unambiguous range configuration, a low PRF is required. For a swath width of 500 n.m. and an antenna length of 50 feet, the required PRF is approximately 80 PPS, whereas the sampling theorem requires a PRF of 1000 PPS for an unambiguous sampling rate. This leads to approximately 12 azimuth

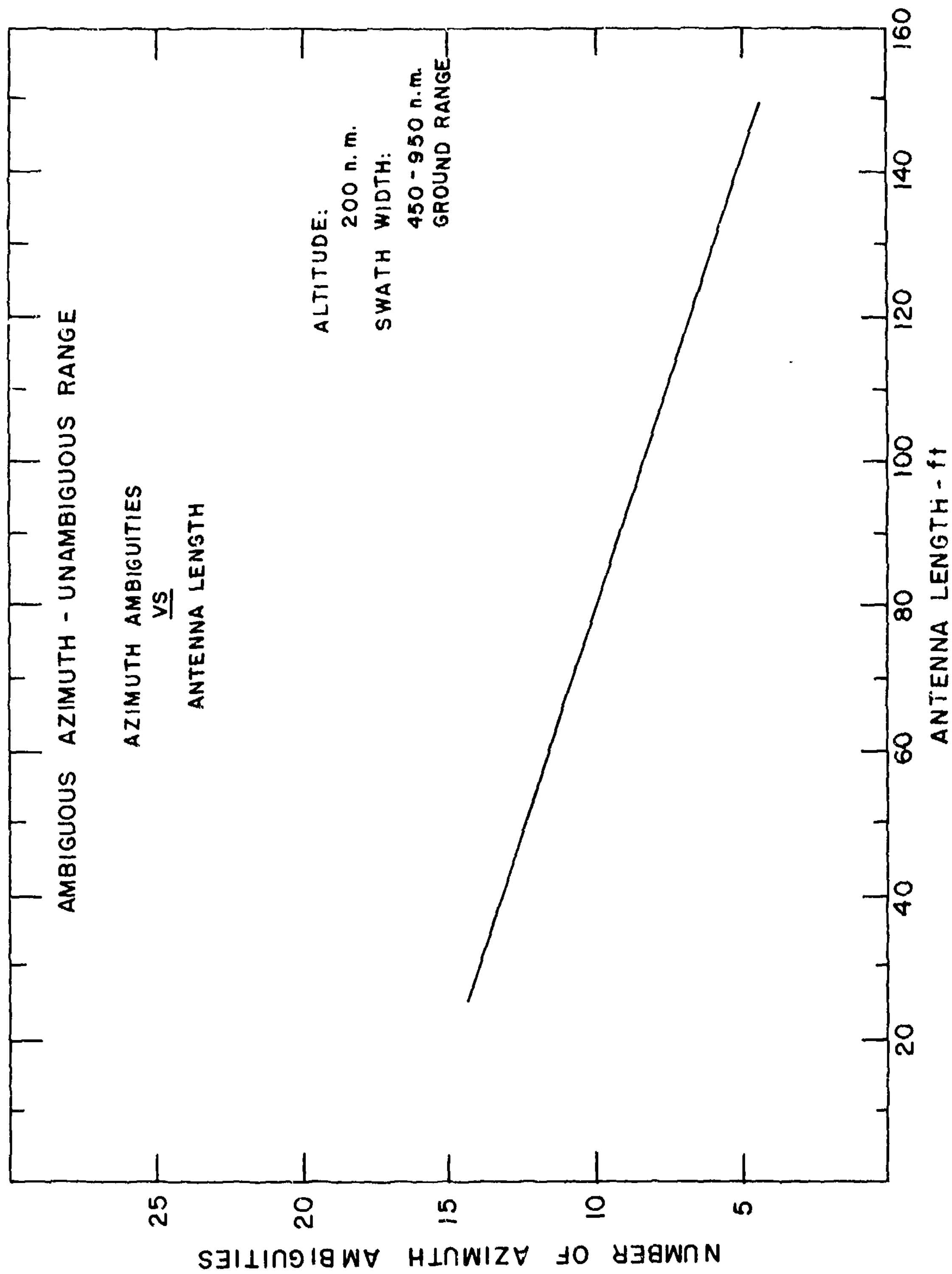


Fig. 14 - Range ambiguities

ambiguities as illustrated in Fig. 15. The low PRF, of course, implies that the Doppler history of the target will be undersampled. The undersampling procedure assumes that the surface of the sea, not occupied by the target, is a source of noise and its relected intensity is of no interest in ship detection. The undersampling would result in azimuth ambiguities intolerable for land or ship imaging radars, but it may be feasible for ship detection purposes only[13]. However, should azimuth ambiguities be intolerable, then a means of resolving them must be utilized. Perhaps beamsplitting in the data processor could be implemented. If this is not feasible, then some means of post-processing the ambiguities at a ground station could be used at the cost of increasing the load on the telemetering link.

Matrix of Possible Solutions

(S) For the Case III program, the type of system which would best fulfill the principle objectives of the overall parametric study would be an unfocused synthetic aperture radar operating in the ambiguous azimuth/unambiguous range configuration. As implied in the background discussion previously presented, the unfocused mode of operation would require the least complexity in data processor mechanization and antenna design. Hence, it would result in the minimum reliability risk.

(S) A matrix of the parameters representing three possible systems which would satisfy the study objectives is shown in Table 15. The criteria for each system is that it be capable of the detection of a fluctuating ship target whose effective radar cross-section is 200 sq. mi. with a probability of detection of 0.9, and with a probability of false alarm of 10^{-10}. Each of these systems meets the swath coverage requirements, 700 n.m., for a two satellite sidelooking constellation. A single sidelooking sensor is selected for the same reasons discussed in the Case II descriptive analysis. Each of the systems listed in Table 15 also meets the requirements of radar weight as a function of orbital altitude and system prime power for a Titan III-C launch vehicle as shown in Fig. 2.

Orbital Altitude

(S) The orbital altitude of 200 n.m. was selected from one of the family of curves represented by Fig. 2 as being nearly optimum for subsequent determinations of sensor weight and prime power requirements. For an altitude of 200 n.m. and a two satellite constellation, the selected swath width of 700 n.mi. provided a safety factor of approximately 4% over the minimum required for contiguous coverage at the equator.

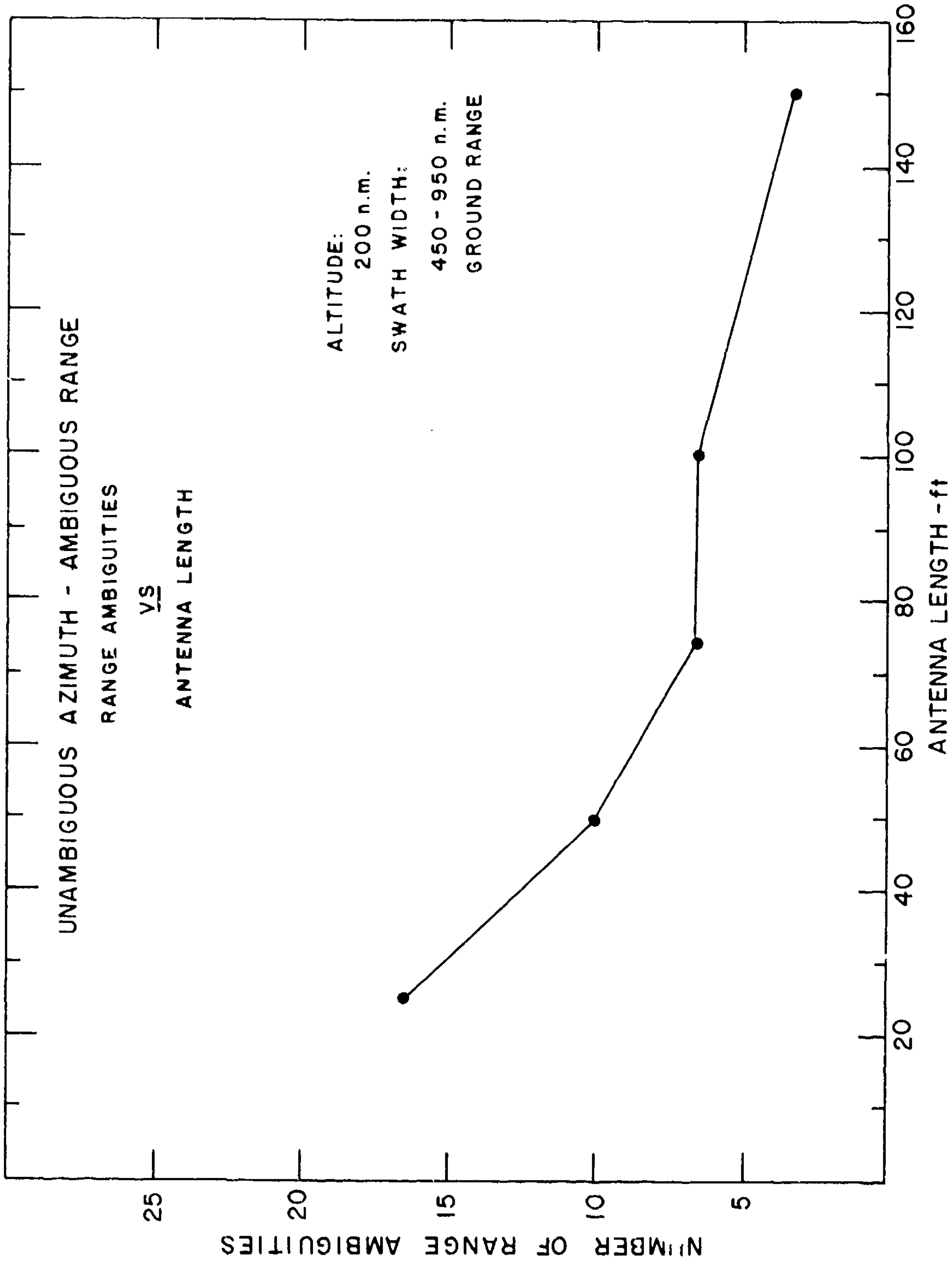


Fig. 15 - Azimuth am' guities

TABLE 15

CASE III - TRIAL SYSTEMS

Orbital Altitude - 200 N.M. Swath Width - 700 N.M.

<u>Radar Sensor</u>			
Frequency, MHz	900	1300	2900
Average Power, watts	500	500	500
Eff. Pulse Width, μsec.	0.1	0.1	0.1
Pulse Compression	300/1	300/1	300/1
PRF, pps	70	70	70
Peak Power, Kw	240	240	240
Target Cross-section, sq. meters	200	200	200
Antenna Length, ft.	48	48	48
Antenna Height, ft.	26	15	10
Antenna Area, sq. ft.	1300	750	500
<u>Data Processor</u>			
No. Range Cells	83,615	83,615	83,615
No. Azimuth Channels	78	65	44
Data Rate/Sub-channel	46.8	46.8	46.8
Power Requirement, watts	4409	3716	2598
<u>System Totals</u>			
Prime Power, Kw	6.5	5.8	4.7
System Weight, lbs.	1900	1470	1160
System Cost, Millions	32.0	30.3	28

Frequency

(S) From the preliminary conclusions discussed in the background statement, an operating frequency of 1300 MHz appeared to be optimum. However, based on the subsequent selection of a 200 n.m. orbital altitude and the choice of an ambiguous azimuth configuration, it is possible to again consider operating frequencies of 900 and 2900 MHz in addition to 1300 MHz. The matrix of Table 15 therefore, presents the parameters for possible systems operating at 900, 1300 and 2900 MHz respectively.

Average Power

(S) For the final phase of the Case III analysis program, solutions of the radar equation were found in terms of a predetermined swath width which was consistent with reasonable antenna lengths and average power requirements. The complexity and cost of the development of a space qualified transmitter was recognized. It was felt that the solar arrays necessary for supplying the attendant prime power and the problems associated with heat dissipation could be adequately handled with an average power requirement of 500 watts.

Pulse Width

(S) Narrowing the pulse width from the selected value of 0.1 μsec to 0.05 μsec would have little effect on reducing the average power requirement and would add further to the complexity of the data processor. It is narrow enough to keep clutter to a reasonable level. It is wide enough to ease peak power requirements and to simplify bandwidth requirements on associated radar circuitry.

Pulse Repetition Frequency

(S) To determine the unambiguous range to a target, the PRF is fixed so that a sufficient length of time elapses after the transmission of a pulse to allow target returns from the far edge of the swath to be received prior to the next pulse transmission. For Case III, the PRF is calculated so that the receiver is blanked at or near the time of ground returns due to the altitude ring and thus prevents clutter return from beneath the spacecraft from deteriorating desired target information.

Pulse Compression and Peak Power Considerations

(S) A pulse compression ratio of 300:1 is considered to be realizable for chirp techniques. Higher values could be attained through pulse coding techniques but would complicate still further the already complex data processor circuitry.

(S) The choice of pulse width, PRF, and pulse compression ratio dictate the peak transmitter power required of the system. The resulting peak power of 240 kw is within the 300 kw set as the maximum feasible value from the standpoint of X-radiation and voltage breakdown.

Antenna Size

(S) Since the synthetic aperture is inherently complex electronically, it is desirable to avoid further system complications by specifying an antenna which could be packaged to fit within the dimensions of the satellite shroud and which would require no unfolding or unfolding only in one dimension.

(S) One of the principle differences between the three systems shown in Table 15 is that of antenna height. The height decreases from 26 ft. at 900 MHz to 10 ft. at 2900 MHz, since, for a constant elevation beamwidth, antenna height varies directly with wavelength. Therefore, the antenna area requirements are considerably less at 2900 MHz.

Data Processor Requirements

(S) The properties of the data processor bear heavily upon the choice of the final preferred system. Since the effective pulse width of each of the systems is the same, the number of range bins to be processed is, likewise, the same for each system.

(S) However, the processor power requirements vary considerably between the three systems. Power requirements are a direct function of the number of azimuth channels necessary to process the Doppler signal returns. Note that the number of azimuth channels necessary to cover the azimuthal beamwidth of the antenna decreases from 78 at 900 MHz to 44 at 2900 MHz. Since the antenna length is the same for each system, the azimuth beamwidth of the physical antenna varies directly as the wavelength. Thus, the processor power required at 2900 MHz is nearly a factor of two less than that required at 900 MHz and approximately two-thirds that required at 1300 MHz.

System Totals

(S) In estimating the system total prime power requirements, a 25% efficiency is allotted to the transmitter and its associated circuitry. For 500 watts of average power, therefore, the transmitter prime power requirement is 200 watts for each system. To this is added the data processor power requirement and an estimated value of 110 watts for the receiver and other auxilliary equipment. It can be seen from Table 16 that the prime power requirements for each system varies directly with the processor power requirement and is least for the 2900 MHz system.

TABLE 16

COMPARISON OF PROCESSOR REQUIREMENTS

Radar Parameters	S. L.	F. L.	S. A.
Swath, N. M. or Scan Angle	488-940	±36.25°	300-1000
Range Sweep, N. M.	452	226	700
Range Resolution, ft.	50	50	50
Azimuth Beamwidth, deg	1.0	1.37	0.49
No. Azimuth Beam Positions	1	56	44
No. Beams Per Integ. Interval	1	7	44
Azimuth Resolution, N. M.	9-16	16-21	.07-0.2
Range Cells	55.5K	27.5K	83.6K
Signal Processor			
Size, cu. ft.	0.25	0.75	3.65
Weight, lbs.	14	21	238
Power, watts	50	200	2350
Central Processor			
Size, cu. ft.	0.4	0.5	0.6
Weight, lbs.	50	67	85
Power, watts	150	200	250
Storage, Kbits	300	400	500
Totals			
Size, cu. ft.	0.65	1.25	4.27
Weight, lbs.	64	88	323
Power, watts	200	400	2600

(S) Weight estimates for the antenna systems are based on Fig. 6 which gives the antenna weight in pounds as a function of antenna aperture area in square feet. The antenna weight estimates for the three systems of Table 15 are as follows: 920 lbs at 900 MHz; 570 lbs at 1300 MHz; and 370 lbs at 2900 MHz. The weights for the transmitter systems have been based on a conservative value of one pound per watt of average power. Since the average power for each system is 500 watts, the transmitter weight is 500 lbs. Weight estimates for the data processor are based on an estimated parts count of the electronic components and bulk storage devices necessary to perform the processor function. Processor weights for the three systems are estimated as follows: 470 lbs at 900 MHz; 400 lbs at 1300 MHz; and 299 lbs at 2900 MHz. A total of 10 lbs is added to the above weight estimates to accommodate the receiver and other auxilliary electronic equipment.

(S) Total system costs are only estimates and will be revised as more firm information is made available through industry. For the Case III systems, the cost figures include an estimate of research, development, test and evaluation of an engineering model, a flight prototype, and two space qualified systems. The antenna cost is based on a detailed analysis of several representative reflector type antennas. The cost estimates for the transmitter chain are made using the guidelines set forth in the Case II system descriptive analysis and Fig. 11. The costs associated with the research, design, and development of an on-board digital data processor which will reliably perform the extremely complex functions required for synthetic aperture operation are estimated to be several orders of magnitude greater than that required for the Case I and II radar sensors. The costs for the solar prime power supply are based on information from several industrial sources. The cost of the satellite solar power system is projected to be one million dollars per kilowatt of total prime power required for each radar system.

Preferred System Selection

(S) As seen in Table 15, each of the candidate systems have the following common radar parameters: orbital altitude, swath width, average power, peak power, effective pulse width, pulse repetition frequency, and antenna length. The major differences appear in the antenna height dimensions (hence, its area), data processor properties, system weights, and system costs.

(S) Although the 900 MHz system is acceptable for the selected altitude of 200 n.m., it is a borderline case insofar as Faraday rotation losses are concerned. Furthermore, the parameters pertaining to antenna weight, processor circuit complexity, prime power requirements, and cost make this system the least desirable of the three.

(S) The 2900 MHz system is selected as the preferred system for the Case III synthetic aperture radar. From Table 15 and the previous discussion of system parameters, the selection of the 2900 MHz system over that at 1300 MHz is relatively obvious. The salient features of the 2900 MHz system can be summarized as follows:

(a) the antenna will require no post-launch unfolding mechanisms, hence simplifying the antenna feed problems;

(b) it exhibits the least complexity in data processor design, hence requires the least processor power;

(c) it is the lightest in weight primarily because of the small antenna aperture area required;

(d) it requires the least total system prime power primarily because of the smaller quantity of processor circuitry required; and

(e) it is the least expensive since it requires the least prime power, hence, it requires the least cost for the solar array prime power source.

(U) It must be borne in mind that the component parts of this system must be designed with an inherently high degree of reliability. In the order of difficulty, the problem areas associated with this system are as follows: the data processor, transmitter chain, antenna, and receiver. The mechanization of a digitized synthetic aperture data processor will constitute the most difficult problem area of any of the three radar types considered in the overall parametric analysis.

RADAR PROCESSOR

(U) The characteristics of each radar system and an assumed target environment were utilized to determine initial estimates of processing and storage requirements. These estimates consider the primary processing functions of signal integration, target discrimination and bulk data storage in terms of the major hardware requirements. The basic functional block diagram of the radar processors is shown in Fig. 16.

(S) The first processing function considered is the integration and real time storage of the radar signal return. The Case I and II systems are noncoherent and require storage in real time of the detected video signal from one or more range sweeps. Case III requires additional complexity since coherent signals from the radar I-F are used and both range and azimuth storage is necessary. Case I requires the storage of seven consecutive range sweeps corresponding to seven adjacent beam positions accumulated over a period of 95 scans. The real time storage is then seven times the numoer of range cells in a single range sweep. For this case, the magnitude of the range walk caused by the forward motion of the vehicle required compensating shifts of the stored data during integration.

(S) Case II requires the storage of only a single range sweep since only one beam position is used. There are more range resolution cells in this range sweep than in a single range sweep of Case I, although the total number of cells stored is greater for

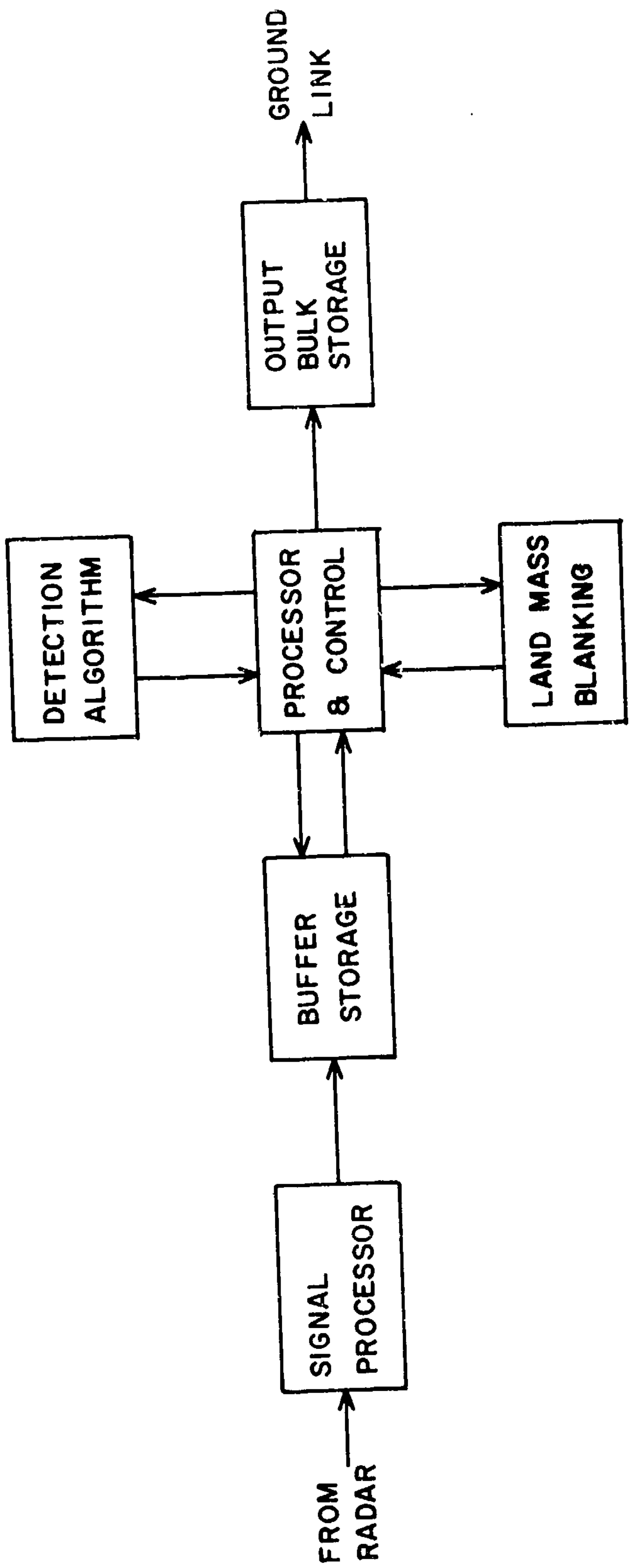


Fig. 16 - Block diagram of basic radar processor

Case I. The amount of range walk for Case II is small and requires minor compensation.

(S) Case III requires the storage of a large number of range sweeps corresponding to the locations of the elements of the synthetic array. Since mixed integration is used, storage of both the coherent and noncoherent signals is required. This results in a storage requirement which is at least an order of magnitude greater than that required for either Case I or II.

(U) Metal Oxide Semiconductor (MOS) static shift registers were used as the storage medium in determining hardware requirements. These devices provide a flexible real time storage medium that is suitable for this application. Multiplexing of these devices was utilized to obtain the lowest power dissipation.

(U) The estimate of size, weight and power for the signal processor includes provision for A/D converters, adders, gates, flip-flops, multiplexers and other circuitry.

(S) Following integration, a threshold detection is performed on the integrated returns for each resolution cell. The resulting detections are placed in the Buffer Storage in the form of words containing the location and amplitude of each detection. The size of the Buffer Storage for each case is determined by the number of resolution cells scanned during a single integration period. For Case I, seven beam positions consisting of 27,5000 range bins each are scanned during an integration period. In Case II, while only one beam position is scanned, three beam positions consisting of 55,500 range bins each are required for proper interlacing and formatting of the data. In case III, 44 beam positions consisting of 83,600 range bins each are utilized to generate the synthetic array and are placed in the Buffer Storage. For the purpose of estimating this storage requirement, a figure of 15 ships/1000 sq. n.m. was applied to the area represented by the resolution cells handled in the Buffer. An allowance was made for an occasional small land mass that might not be gated out at the receiver.

(S) The detections stored in the buffer are scanned by the processor. Utilizing the detection algorithm, the processor resolves the detections composed of targets, false alarms and clutter into valid ship targets. These targets together with location information are stored as words in the Bulk Storage. A figure of 2.6 ships/orbit per nautical mile of swath for a two orbit period was used to estimate the bulk storage requirement.

(S) The storage required by the Buffer, the Detection Algorithm, the output Bulk Store, and the Land Mass Blanking instructions was used to select an available aerospace computer. This provided an estimate of the size, weight and power of the data processor portion of the radar processor.

(S) The parameters and processor estimates for the Case II real aperture sidelooking radar are shown in Table 16, together with the Case I forward looker and the Case III synthetic aperture sidelooker.

RELIABILITY

(U) A preliminary estimate of the probability of success of the three preferred systems discussed in the previous descriptive analyses has been made. The reliability predictions are made by comparing the components of each of the preferred systems with similar equipments whose published failure rate data has been compiled from past experience.

(U) The quality and reliability of electronic components have shown consistent improvement since the onset of the space age. It is reasonable to assume that the quality of components designed in 1966, for example, will be considerably improved by 1970. Since there is a time lag of three to five years between component design and its published failure rate data, it is safe to assume that the reliability estimates for the preferred systems tend to be pessimistic. As more published data becomes available, the reliability predictions will be revised accordingly.

(S) The environment in which an equipment operates naturally affects its reliability. From operational data of other satellite borne electronic equipments it has been determined that the stress on a well designed system is no greater in orbit than on the ground. This, if course, presupposes that problems of heat dissipation have been solved and that only space qualified materials have been used.

(S) The computations of the probability of success values for the preferred systems are based on the following assumptions:

(a) failures occurring during a component's early life and wear out periods are not considered;

(b) calculations are based on a worst case basis, that is, all components are assumed necessary for successful operation;

(c) the components are operating during that portion of their lifetime when the probability of failure during any short time period is equally probable, i.e., a constant failure rate assumption,

(d) that all system components have demonstrated, through adequate environmental testing, their ability to survive the pre-launch and launch phases of the mission.

(U) Probability of success and mean-time-between-failure (MTBF) calculations are based on information derived from the Failure Rate Data (FARADA) Program and Mil. Specification MIL-HDBK-217A, and other sources. The MTBF represents a measure of the degree of reliability designed into a system. It does not take into consideration laxity in quality control and is not a guarantee of failure free operation.

(U) The probability of successful operation P_s is defined as

$$P_s = e^{-\lambda t} \quad (1)$$

where λ is the failure rate in failures per million hours and t is the mission time period. In this analysis, P_s is the probability of having zero failures during time t. Since the reliability estimates are made on non-redundant system components, the MTBF is the reciprocal of the sum of the failure rates for each sub-system, that is,

$$\text{MTBF} = \frac{1}{\lambda_1 + \lambda_2 + \ldots\lambda_n} \quad (2)$$

(S) The goal to be achieved for the useful mission lifetime of the selected system is, ideally, one year or 8760 hours. This number would represent 100% duty cycle if all systems operated continuously for that period of time. A more realistic duty cycle is obtained by comparing the total surface area of the globe to the surface area contained within longitudinal lines which are within 20 degrees of the North Pole and 30 degrees of the South Pole. This would result in a duty cycle of 40%. This duty cycle is assumed to affect only components pertaining to the transmitter final amplifier, high voltage power supply, pulse forming networks, and the duplexer. The remainder of the system would operate continuously. Duty cycles of 20 and 10% are also considered for which the entire system is assumed to be operating for periods of 1752 and 876 hours.

(U) Operational reliability block diagrams for the Case I, II and III preferred systems are shown in Figs. 17, 18 and 19. The diagrams are not intended to reflect an actual system design but are used to illustrate the relationship between sub-systems and the assumption that the failure of any one sub-system would cause total system failure. The numbers within each block in the diagrams represent the failure rate of that particular sub-system.

(U) The individual sub-system and total system failure rates for each of the cases considered are summarized in Tables 17, 18 and 19. The failure rates for all subsystems are given in column A. The failure rates shown in column B reflect the 40% duty cycle for the duplexer, TWT, high voltage power supply, pulse transformer, pulse transformer network, and pulser.

(U) In the subsequent summary, probability of success and MTBF predictions are given for four operating conditions:

ELECTRONIC SCAN FORWARD LOOKING RADAR

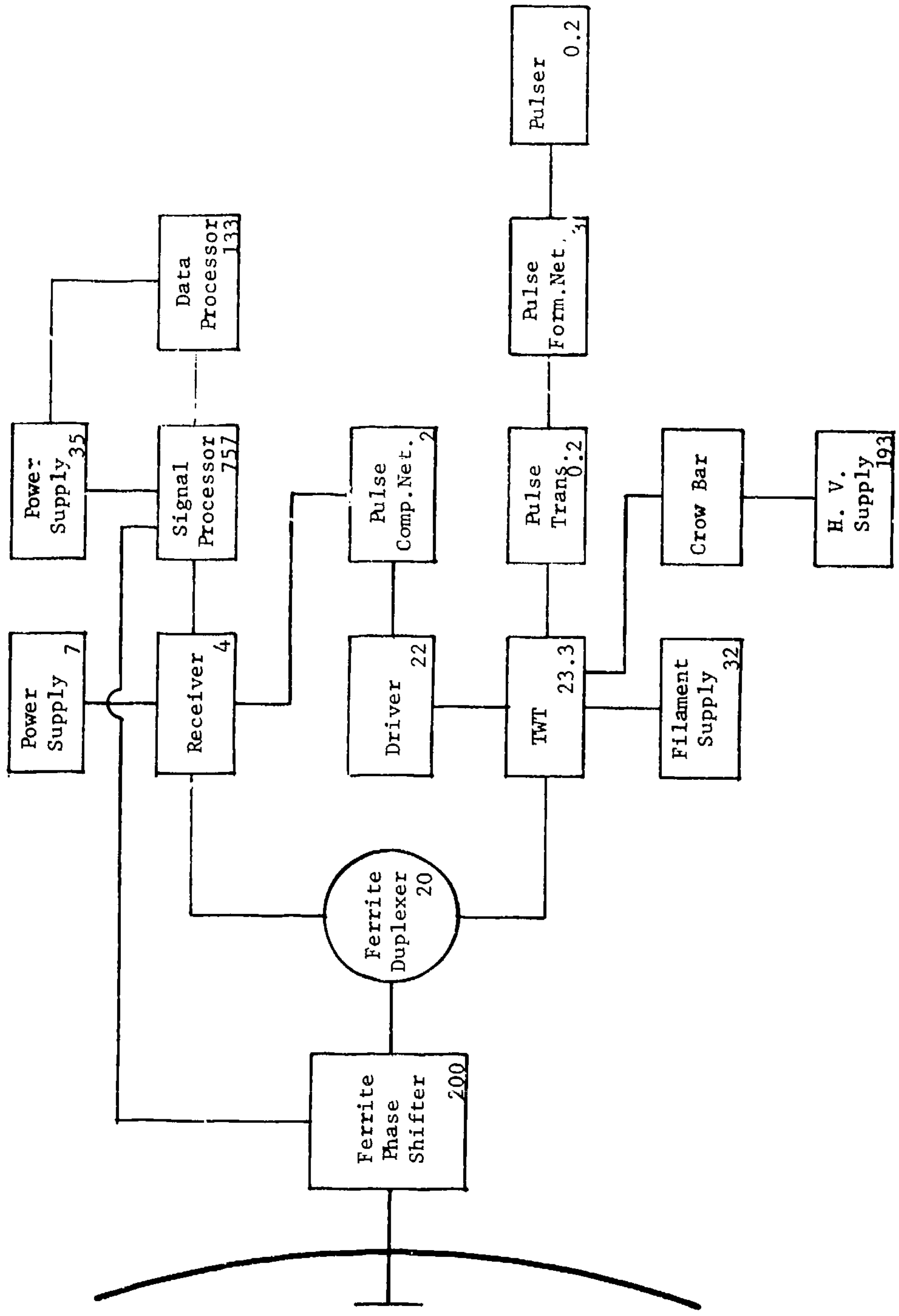


Fig. 17 - Reliability block digram for electronic scan radar

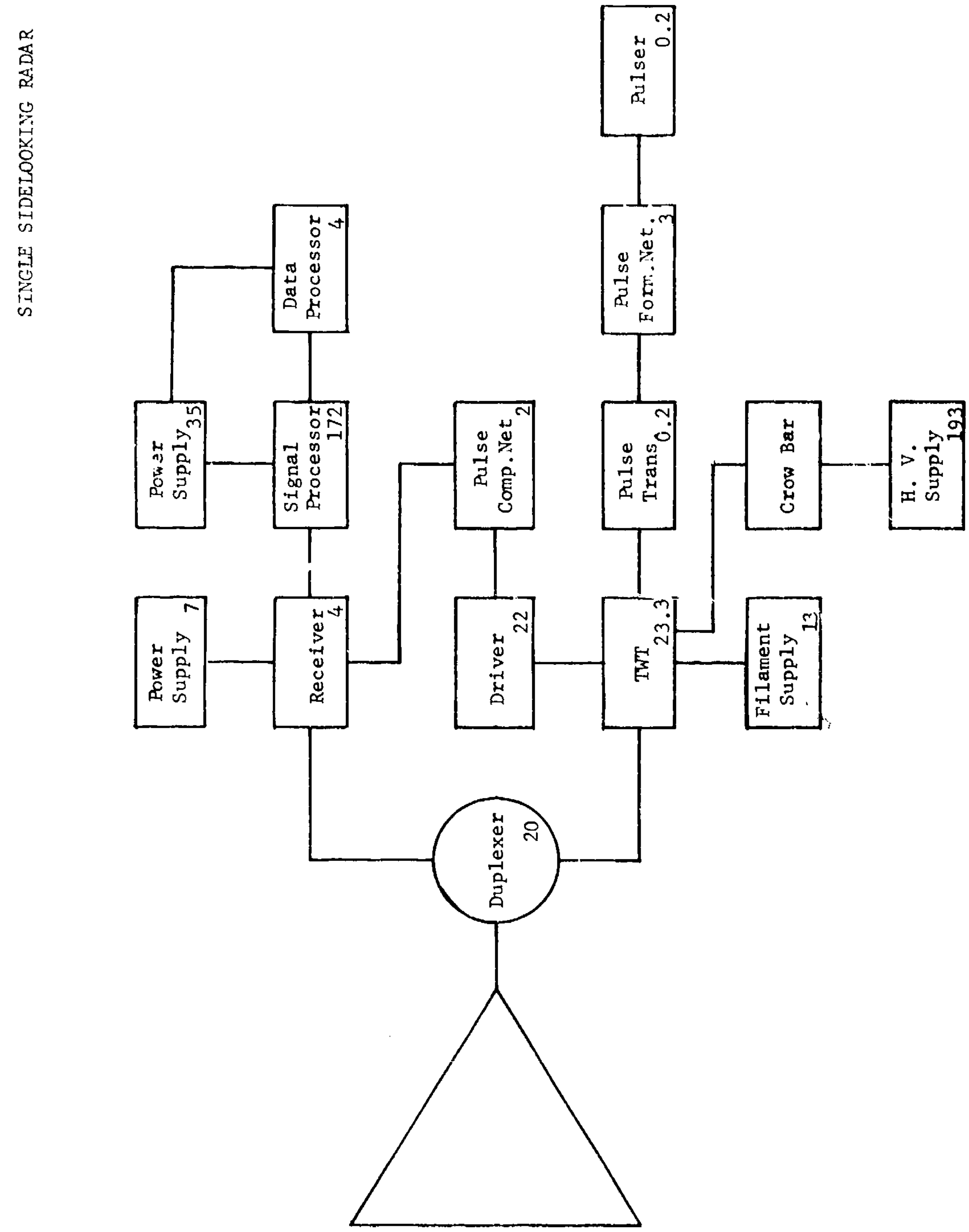


Fig. 18 - Reliability block diagram real aperture sidelooking radar

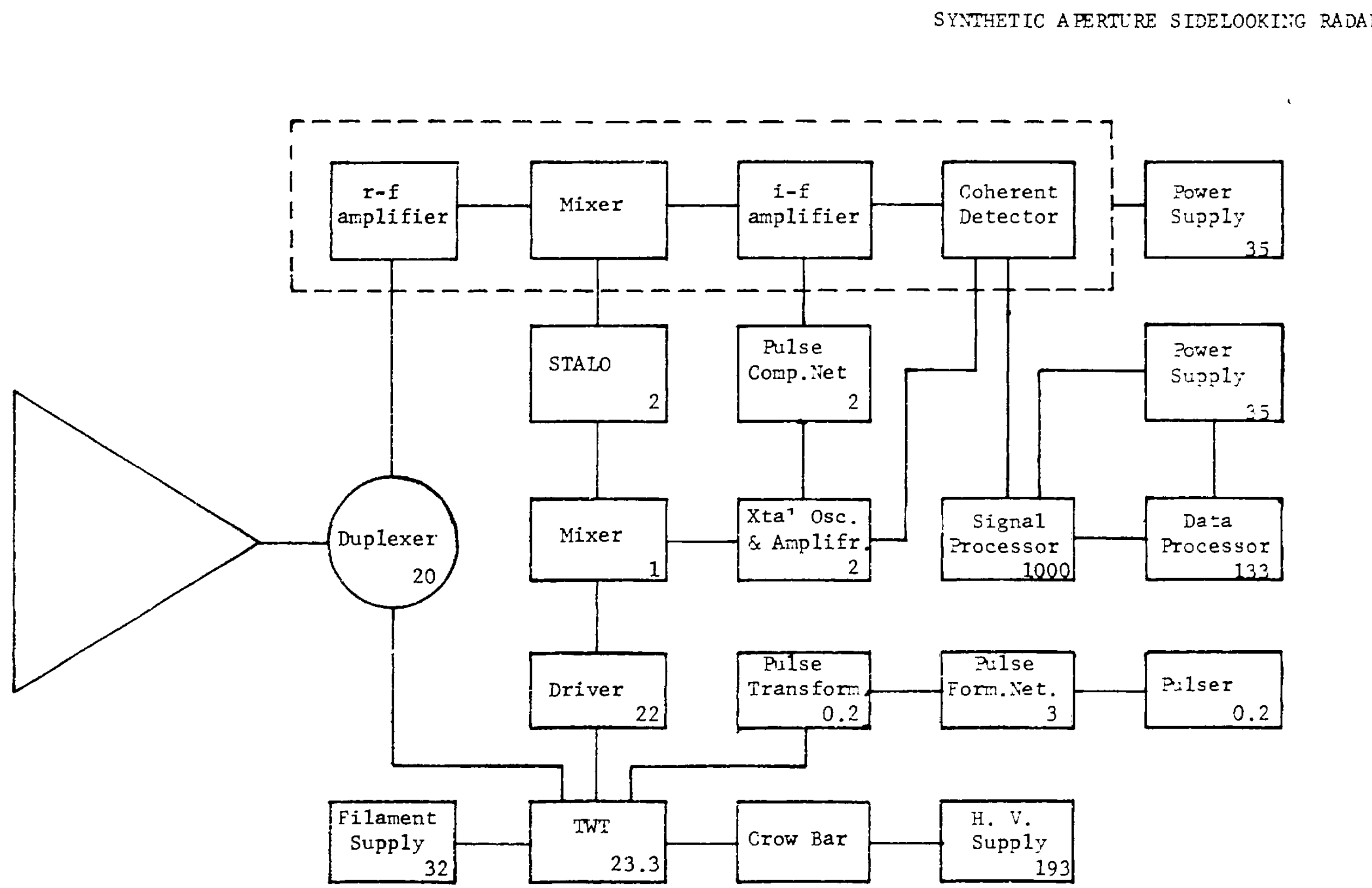


Fig. 19 - Reliability block diagram for synthetic aperture sidelooking radar

TABLE 17 - FAILURE RATES FOR CASE I

Sub-System	Failure Rates - λ A	Failure Rates - λ B
Ferrite Phase Shifter	200.0	80.0
Duplexer	20.0	8.0
TWT	23.3	9.3
High Voltage Power Supply	193.0	77.2
Pulse Transformer	0.2	0.1
Pulse Forming Network	3.0	1.2
Pulser	0.2	0.1
Filament Supply	32.0	32.0
Driver	22.0	22.0
Pulse Compression Circuitry	2.0	2.0
Receiver	4.0	4.0
Receiver Power Supply	7.0	7.0
Signal Processor	757.0	757.0
Data Processor	133.0	133.0
Processor Power Supplies	35.0	35.0
Failure Rate Totals - λ_T	1,431.7	1,167.9

For 100% duty cycle: $\lambda_T = 1{,}431.7/10^6$; $t = 8760$ hrs.

$$P_S = e^{-12.5} = .00033\%; \quad MTBF = \frac{1}{\lambda_T} = 699 \text{ hours}$$

For 40% duty cycle: $\lambda_T = 1167.9/10^6$; $t = 8760$ hrs.

$$P_S = e^{-10.23} = .0036\%; \quad MTBF = \frac{1}{\lambda_T(.4)} = 856 \text{ hours}$$

For 20% duty cycle: $\lambda_T = 1{,}431.7/10^6$; $t = 1752$ hrs.

$$P_S = e^{-2.51} = 8\%; \quad MTBF = \frac{1}{\lambda_T(.2)} = 3500 \text{ hours}$$

For 10% duty cycle: $\lambda_T = 1{,}431.7/10^6$; $t = 876$ hrs.

$$P_S = e^{-1.25} = 28\%; \quad MTBF = \frac{1}{\lambda_T(.1)} = 6990 \text{ hours}$$

TABLE 18 - FAILURE RATES FOR CASE II

Sub-System	Failure Rates - λ A	Failure Rates - λ B
Duplexer	20.0	8.0
TWT	23.3	9.3
High Voltage Supply	193.0	77.2
Pulse Transformer	0.2	0.1
Pulse Forming Network	3.4	1.2
Pulser	0.2	0.1
Filament Supply	32.0	32.0
Driver	22.0	22.0
Pulse Compression Circuitry	2.0	2.0
Receiver	4.0	4.0
Receiver Power Supply	7.0	7.0
Signal Processor	172.0	172.0
Data Processor	133.0	133.0
Processor Power Supplies	35.0	35.0
Failure Rate Totals - λ_T	657.1	502.9

For 100% duty cycle: $\lambda_T = 657.1/10^6$; $t = 8760$ hrs.

$P_S = e^{-5.76} = 0.34\%$; MTBF = 1546 hours

For 40% duty cycle: $\lambda_T = 502.9/10^6$; $t = 8760$ hrs.

$P_S = e^{-4.41} = 1.2\%$; MTBF = 1987 hours

For 20% duty cycle: $\lambda_T = 657.1/10^6$; $t = 1752$ hrs.

$P_S = e^{-1.133} = 32.2\%$; MTBF = 7610 hours

For 10% duty cycle: $\lambda_T = 657.1/10^6$; $t = 876$ hrs.

$P_S = e^{.5666} = 56.8\%$; MTBF = 15,460 hrs.

$$\text{MTBF} = \frac{1}{\lambda_T\ (.1)} = 15{,}460 \text{ hrs.}$$

TABLE 19 - FAILURE RATES FOR CASE III

Sub-System	Failure Rates - λ A	B
Duplexer	20.0	8.0
TWT	23.3	9.3
High Voltage Power Supply	193.0	77.2
Pulse Transformer	0.2	0.1
Pulse Transforming Network	3.0	1.2
Pulser	0.2	0.1
Filament Supply	32.0	32.0
Driver	22.0	22.0
Pulse Compression Circuitry	2.0	2.0
Receiver	6.0	6.0
Mixer	1.0	1.0
Receiver Power Supply	35.0	35.0
Crystal Osc. & Amplifier	2.0	2.0
Signal Processor	1000.0	1000.0
Data Processor	133.0	133.0
Processor Power Supplies	35.0	35.0
Failure Rate Totals - λ_T	1497.7	1363.9

For 100% duty cycle: $\lambda_T = 1497.7/10^6$; $t = 8760$ hrs.

$P_S = e^{-13.12} = .00027\%$; MTBF = 669 hours

For 40% duty cycle: $\lambda_T = 1363.9/10^6$; $t = 8760$ hrs.

$P_S = e^{-11.95} = .006\%$; MTBF = 734 hours

For 20% duty cycle: $\lambda_T = 1497.7/10^6$; $t = 1752$ hrs.

$P_S = e^{-2.64} = 7.14\%$; MTBF = 3340 hours

For 10% duty cycle: $\lambda_T = 1497.7/10^6$; $t = 876$ hrs.

$P_S = e^{-1.321} = 26.7\%$; MTBF = 6600 hours

1. all subsystems operating at 100% duty cycle and the failure rate total of column A;

2. using the concept of 40% duty cycle and the failure rate total of column B;

3. all subsystems operating at a 20% duty cycle;

4. all subsystems operating at a 10% duty cycle.

SYSTEMS COMPARISON AND SELECTION

(U) In the preceding sections of this report, a preferred system was selected for each of the major system types considered in the NRL parametric analysis. In the discussion which follows, these three selected systems will be compared with one another. First, a consolidation and review of the advantages and disadvantages of each of the three systems is in order. The listed advantages and disadvantages pertain to the specific candidate system and not to all systems within a given class or category. As an example, the particular antenna proposed for the candidate real aperture sidelooker requires unfolding in the vertical dimension and this is regarded as disadvantage and presents a reliability problem. However, not all potential theoretical real aperture sidelooking systems require that antennas unfold, and the antenna in the general case is not necessarily a reliability problem or disadvantage.

TABLE 20

SYSTEM ADVANTAGES AND DISADVANTAGES

FORWARD SCAN

Advantages

a. Swath width not too dependent on grazing angle

b. Antenna does not require folding

c. Provides coverage along ground track

d. 100% coverage of earth readily obtained

e. Sensitivity to spacecraft attitude stabilization is minimal

f. Coverage close to land-sea interface is more efficient

Disadvantages

a. Data processor rather complex because of range tracking

b. Azimuth position accuracy poor because of non-continuous scan

c. Most complex antenna feed

REAL APERTURE SIDELOOKER

Advantages

a. No antenna scan required

b. Azimuth position accuracy good

c. Simplest data processor

d. Highest probability of success (most reliable)

e. Least expensive

Disadvantages

a. Antenna must be folded

b. No coverage along ground track

c. 100% earth coverage is difficult

d. Ground swath is sensitive to spacecraft stability and grazing angle

SYNTHETIC APERTURE SIDELOOKER

Advantages

a. Best azimuth resolution

b. No antenna scan

c. Antenna does not require folding

Disadvantages

a. Must accept azimuth ambiguities

b. Data processor is quite complex and requires very high power (several kw)

c. If data processing is split to resolve ambiguities on the ground, the complexity of the ground station is considerably increased and the spacecraft data processor power requirements are still quite high

d. No coverage along ground track

e. Ground swath is sensitive to spacecraft stability and grazing angle

f. Lowest probability of success (highest risk)

(S) The parameters of the three candidate systems are shown in Table 21. The first, or Case I System is the Forward Scan Radar. The Case II System is the Real Aperture Sidelooking Radar, and the Case III System is the Synthetic Aperture Radar. Significant differences between the three systems are:

1. The Case I and III systems are specified for orbital altitudes of 200 n.m., while the Case II system is specified for an altitude of 150 n.m.

2. The Case I and II systems operate at 1300 MHz and the Case III system at 2900 MHz.

3. The Case II antenna requires folding while Case I and III antennas do not.

4. Case I and II are specified for more conservative minimum grazing angles.

5. Case I has 17% overlap, Case II 16%, and Case II 4% swath overlap.

6. Case I and III require two equally spaced satellites, while Case II requires three.

7. The Case I and II systems are essentially equal in cost while the Case III system projected cost is nearly twice as much as either of the other two systems.

8. The Case II system has the highest reliability, while the Case III is the lowest.

(S) Table 22 represents an initial and gross estimate of cost factors for the three systems. In the RDT&E costs, the antenna value includes the costs for an engineering model, a prototype, and two flight qualified antennas. The other RDT&E costs do not include an allowance for the production of flight qualified units.

(U) Table 23 is a matrix for the comparison of various key factors of the three candidate systems. The letter designators are relative indicators of: A, the best, the least complex, and the most readily achieved; B represents a relatively intermediate level or position; and C represents the lowest or more difficult. The preponderance of higher level ratings is associated with the Case II system, while the lowest overall rating is assessed to the Case III system. The Case I system is at an overall intermediate level.

(S) Table 24 is yet another table for the comparison of the three systems. In this two-part table, a judgment is first made on the degree of difficulty in developing the tabulated system elements, and then a second judgment is made on the degree of risk for the same system elements to provide one year of operational life in a space environment.

TABLE 21

OCEAN SURVEILLANCE RADAR SYSTEM PARAMETERS

PARAMETER	CASE I	CASE II	CASE III
ALTITUDE, N. M.	200	150	200
FREQUENCY, MHz	1300	1300	2900
AVG. OUTPUT POWER, W	530	500	500
PK. OUTPUT POWER, KW	190	200	240
AZIMUTH BEAMWIDTH, DEG.	1.4	1.1	0.5
ANTENNA LENGTH, FT	36	48	48
ANTENNA HEIGHT, FT	11	22	10
PULSE REPETITION FREQ., PPS	92	83	70
EFFECTIVE PULSE LENGTH, μSEC	0.1	0.1	0.1
FAR GRAZING ANGLE, DEG.	6.0	5.0	2.3
FAR SLANT RANGE, N. M.	880	770	1075
FAR GROUND RANGE, N. M.	840	740	1030
SWATH, N. M.	800	522	700
RADAR SENSOR SYSTEM WEIGHT, LBS.	2300	1370	1300
NO. OF SATELLITES	2	3	2
SENSOR PRIME POWER, KW	2.5	2.3	4.7
INITIAL SYSTEM COST, $M	16.1	15.5	28.7
RELIABILITY (NORMALIZED)	0.65	1.0	0.53

TABLE 22

ESTIMATED SYSTEM COSTS

RESEARCH, DEVELOPMENT, TEST AND EVALUATION		CASE I FLR	CASE II SLR	CASE III SAR
ANTENNA		2.9	1.6	1.1
TRANSMITTER		3.0	3.0	3.0
DATA PROCESSOR & CPU		2.5	1.5	10.0
	($M)	8.4	6.1	14.1
UNIT COSTS				
ANTENNA		0.46	0.12	0.12
TRANSMITTER		0.8	0.8	0.8
DATA PROCESSOR		0.75	0.25	2.0
PRIME POWER SUPPLY		2.5	2.3	4.7
FIRST CONSTELLATION WITH RDT&E	($M)	16.1	15.5	28.7

TABLE 23

SYSTEM COMPARISON

FACTORS	CASE I	CASE II	CASE III
AZIMUTH ACCURACY	C	B	A
RANGE ACCURACY	B	B	B
ANTENNA, DEVELOPMENT	C	A	B
TRANSMITTER, DEVELOPMENT	B	B	B
RECEIVER, DEVELOPMENT	A	A	B
DATA PROCESSOR, DEVELOPMENT	B	A	C
PRIME POWER, DEVELOPMENT	B	A	C
COST	B	A	C
RELIABILITY	B	A	C

TABLE 24

SYSTEM COMPARISON

Difficulty of Development

SYSTEM	TRANSMITTER	RECEIVER	ANTENNA	DATA PROCESSOR
Case I	High	Moderate	High	Moderate-High
Case II	High	Moderate	Moderate	Moderate
Case III	High	Moderate-High	Moderate	High

Degree of Risk

SYSTEM	TRANSMITTER	RECEIVER	ANTENNA	DATA PROCESSOR
Case I	Moderate	Low	High	Moderate-High
Case II	Moderate	Low	Moderate	Moderate
Case III	Moderate	Moderate	Moderate	High

(U) In the above table, the transmitter is regarded as being essentially common to each of the subject systems. The receiver is essentially common to the Forward Scan and Real Aperture system, but must be developed to meet the coherence requirements of the Synthetic Aperture system.

(S) To summarize - The objectives of the NRL parametric analysis are to select the best system for the detection of ships at sea with a satellite borne radar sensor. The best system is that one which meets the specified detection and coverage requirement, with adequate safety factors, minimum developmental risks, high reliability, and a minimization of costs. The system is not required to have growth capability, however, the selected system does offer a real potential for growth to a more sophisticated and higher performance system.

(U) Each of the candidate systems discussed in this section has a potential for accomplishing the specified primary job of ship detection. The selection is based on the combined evaluations of developmental risks, reliability, and costs for each of the systems.

(S) The Case III system is the most complex and most costly, involves the most risk, is judged to be the potentially least reliable of the system types considered, and is the first system type to be disqualified. This is a time qualified judgment based on today's state of the art. It is possible that in the next few years, advances in engineering and materials development will permit the specification of reliable, cost-effective, synthetic aperture satellite borne ship detection radar.

(U) The Case I and II systems are for practical purposes equal in costs. These approximately equal cost systems are not judged to be equal in complexity and reliability. The antenna and feed system of the Forward Scan system is determined to be much more complex, and as a consequence, less reliable than the comparable elements of the Real Aperture sensor. Further, the data processor for the Forward Scan is judged to be more complex and have a significantly lower mean time between failures than the processor for the Case II Real Aperture system.

(U) The Real Aperture Sensor is then selected for overall best reliability, minimum complexity, and minimum cost while providing the specified detection capabilities. Additionally, the system has a real growth potential in that the antenna, transmitter and receiver can be common to a growth system based on a new and more sophisticated data processor developed for synthetic aperture detection.

THE PREFERRED SATELLITE BORNE OCEAN SURVEILLANCE RADAR SYSTEM

(S) The preferred satellite borne ocean surveillance system is based on a constellation of three real aperture radars which are equally spaced in the same orbital plane at an altitude of 150 n.m. The parameters of each radar system are:

Frequency	1300 MHz
Average Radiated Power	500 watts/satellite
Peak Power	200 Kw
Effective Pulse Length	0.1 μsec
Antenna Size	48 x 22 ft.
Azimuth Beamwidth	1°
Vertical Beamwidth	2.4°
Minimum Grazing Angle	5°
Pulse Repetition Frequency	83 pps
Pulses in Beamwidth, Far Edge	282
Pulses in Beamwidth, Near Edge	96
Swath	520 n.m.
System Weight	1370 lbs
System Prime Power	2.3 kW

(S) An artist's conception of the presently envisioned form of the preferred radar is shown in Fig. 20. Once a stable orbit is achieved, the antenna would be deployed and locked to the erected position shown in the illustration. Solar panels would be erected and oriented to maximize illumination of the solar cells. The remainder of the radar system and housekeeping elements are enclosed within the remaining cylindrical section shown in the illustration.

Antenna

(U) With the parameters of the preferred radar system now established, it is possible to consider in somewhat more detail the type of antenna which should be used. This will not be a complete and final antenna specification; it is merely intended to show a likely antenna design which will satisfy the objectives and meet the constraints of system operation.

(S) The preferred system requires an antenna 48 ft. long by 22 ft. high operating at 1300 MHz. In addition, there is a requirement for beam-shaping in the vertical plane in order to cover a wide range of depression angles. There are a number of antenna types from which to choose, but conspicuous electrical and physical limitations promptly narrowed the choice down to two; the array and the parabolic cylinder.

(S) In Table 25, various factors are considered in comparing these two types. These factors include parameters common to any application (such as gain, beamwidth and sidelobe level), as well as factors of particular concern to spacecraft operation, such as weight and packageability. The array is unattractive because of its anticipated greater weight, and because of packaging problems. In Table 25, the only troublesome defect of the parabolic cylinder is aperture blockage. But this problem can be avoided by the use of an asymmetrical reflector. Therefore, this type antenna has been selected.

(U) In Fig. 21, the antenna is shown in its operating position attached to the spacecraft. The feed is a linear array of 128 waveguide horns, fed from the transmitter by a corporate network of coaxial line and stripline (depending on power levels). A Reflector Plate is incorporated as a suggested means of beamshaping (Ref. 9), although beamshaping can also be accomplished by altering the parabolic contour of the reflector. The estimated weight of the reflector, feed and support structure is 1000 lbs.

(S) Four hinges, two where the trusses connect to the parabolic reflector and one on both the outer and inner ends of the Reflector Plate, permit the antenna to be stowed. These trusses are conceived as deployable-type booms which pivot at the spacecraft interface. The trusses would be motor-driven for erection and would guide

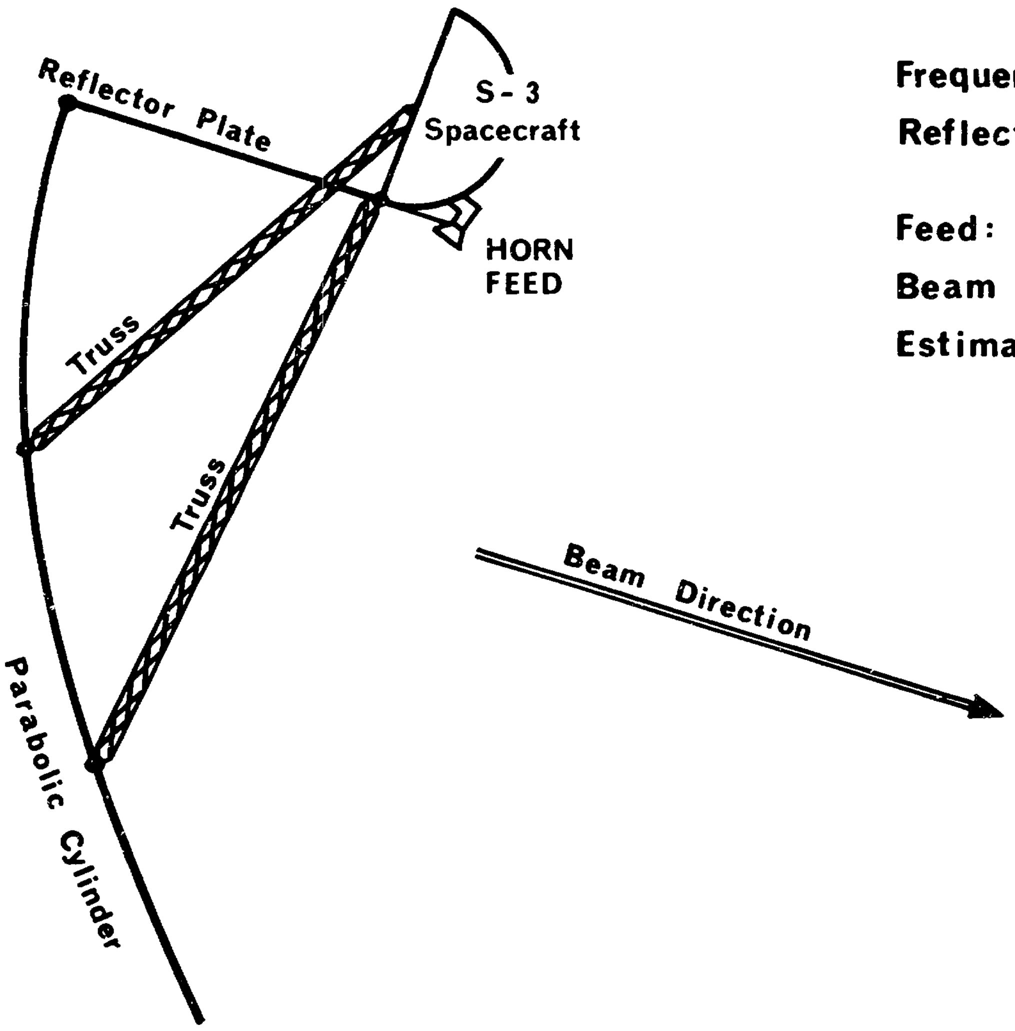
Fig. 20 - Artist's conception of preferred radar system

TABLE 25

FACTORS CONSIDERED IN SELECTING ANTENNA TYPE

(For aperture 48 ft. long by 22 ft. wide)

CONSIDERATION	ARRAY	PARABOLIC CYLINDER
Gain, Sidelobes and Beamwidth	All Achievable	All Achievable (Although sidelobe control is easier in the array)
Aperture Blockage	No	Yes
Weight	Heavy	Moderate
Cost	High	Moderate
Packaging (Which requires folding)	Very Difficult (May even be impossible)	Relatively Simple



Frequency: 1300 MHz
Reflector: Parabolic Cylinder
48 ft long x 22 ft high
Feed: 128 Horns
Beam Depression Angle: 17°
Estimated Weight: 1000 lbs

Fig. 21 - Sidelooking antenna

the deployment of the reflector. The horn feed is rigidly attached to the spacecraft. Fig. 22 illustrates the deployment of the antenna. From its folded position (a) against the flat rear side of the spacecraft, the three sections unfold on hinges through successive positions (b), (c), (d) and (e), until full erection is reached at (f). Although these deployment steps are controlled by the movements of the trusses, the details of truss erection are omitted in this schematic representation.

(S) Fig. 23 shows how three of these antenna/spacecraft units can be nested in the 12-ft-diameter shroud for S-3 operation.

Transmitter

(S) The transmitter poses a variety of problems; the biggest single problem is that of achieving the required MTBF in a space environment. Because of the frequency range of interest, conventional gridded power amplifiers tubes are not applicable. High power with a single or a relatively few solid state devices is not achievable; and the array approach toward developing high power with a large number of low level devices has been ruled out because of complexity, efficiency, and reliability. Also ruled out are those generators which do not have a potential for use in a coherent system. The most likely remaining power amplifiers are Klystrons, Traveling Wave Tubes (TWT), and Crossed-Field Amplifiers (CFA). Parameters of promising tubes of these three types are shown in Table 26.

TABLE 26

CANDIDATE POWER AMPLIFIERS

TYPE	CFA	TWT	ESFK
Dev. Required	Yes	Yes	Yes
Bandwidth	10%	10%	1-2%
Gain, dB	10	50	45
Voltages, KW	30	55	45
X-Radiation	None	Self-Shielding	Low
Weight, lb.	70	165	70
Dimensions	10"D x 17"	74" x 8½"D	< 1 ft^3
Protective Circuit	Complex	Mod/Complex	Least Complex
Efficiency, Overall	50%	45%	40%
Reliability	Cathode Problems	Good Reliab. Record	Good Potential
Related Tube Type	Q.K.S. 1397 Raytheon	Q.K.W. 1518CG Raytheon	L-5182 Litton

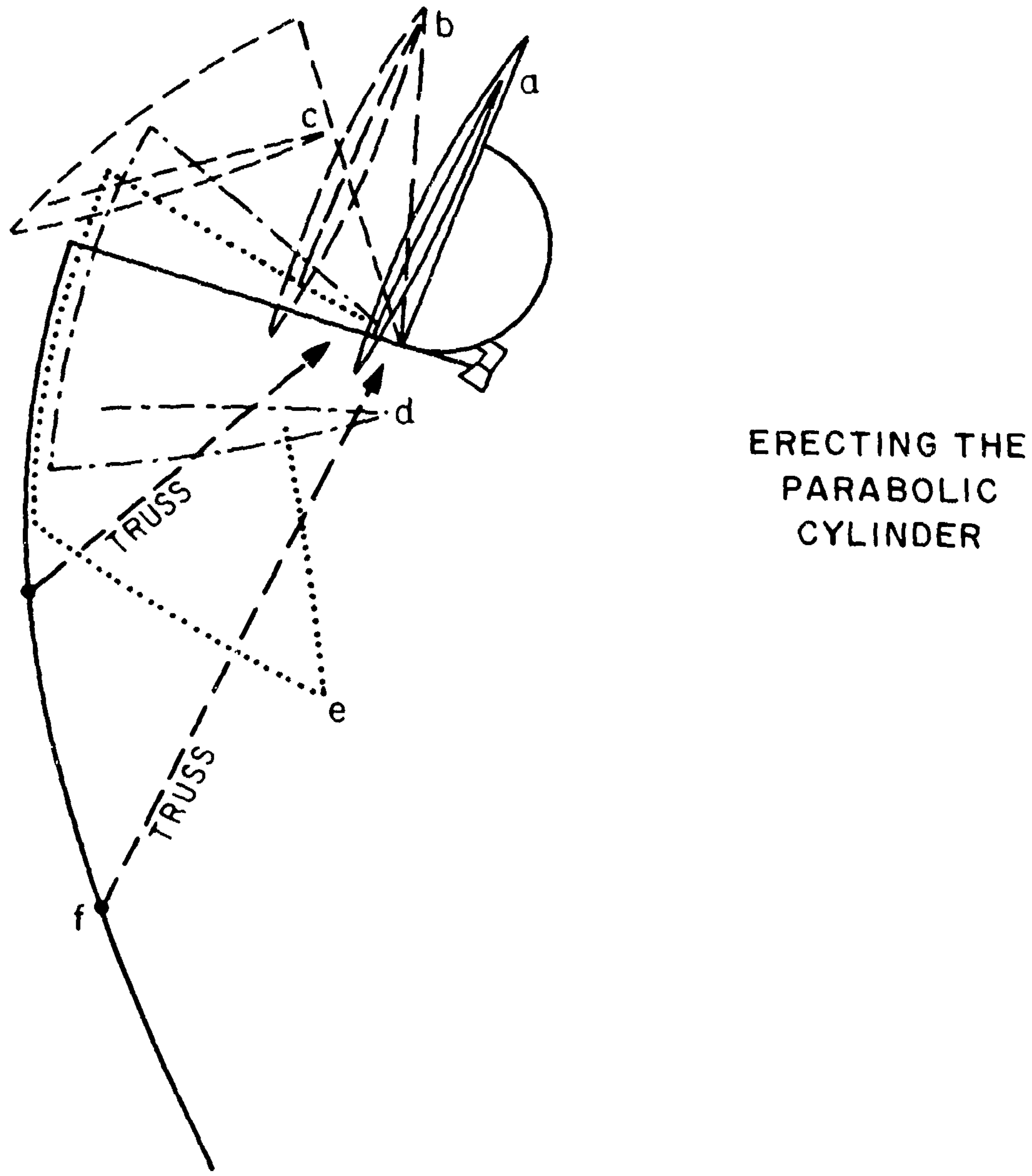


Fig. 22 - Erecting the parabolic cylinder

THREE SYSTEMS ENCAPSULATED IN 12-FT-DIAMETER SHROUD FOR S-3 OPERATION

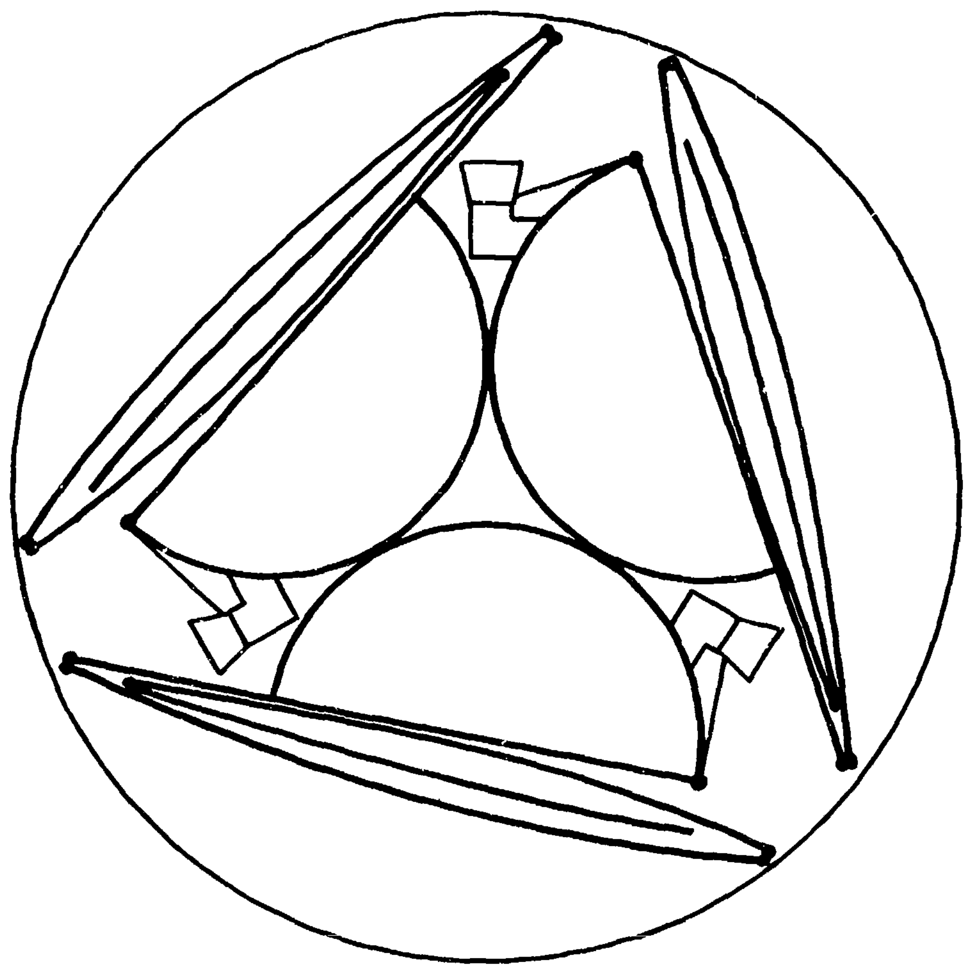


Fig. 23 - Three systems enclosed in a 12 ft diameter shroud

(U) Block diagrams of possible transmitter configurations based on these tubes are shown in Fig. 24, 25 and 26.

(U) The CFA of Table 26 is a low gain device, and as a consequence, requires as shown in Fig. 24, several intermediate stages to develop the required drive. The additional stages add to the complexity of the transmitter and result in a corresponding decrease in reliability.

(S) The TWT and ESFK (Electrostatically Focused Klystron) in Table 26 are both receiving serious consideration as possible power amplifiers for use in the satellite borne surveillance radar system.

The chief advantages of the TWT are:

1. Very high gain
2. High efficiency
3. Wide bandwidth
4. Demonstrated long life of a solenoid focused version

Major disadvantages are:

1. Heavy weight
2. Physical length of the tube
3. The necessity of a 2-year development program for a space-qualified, Periodic Permanent Magnet focusing
4. High developmental and unit costs

The chief advantages of the ESFK are:

1. High gain
2. Good efficiency
3. Light weight, compact size
4. Indicated long life capability
5. Modest cost and risk to develop space qualified units

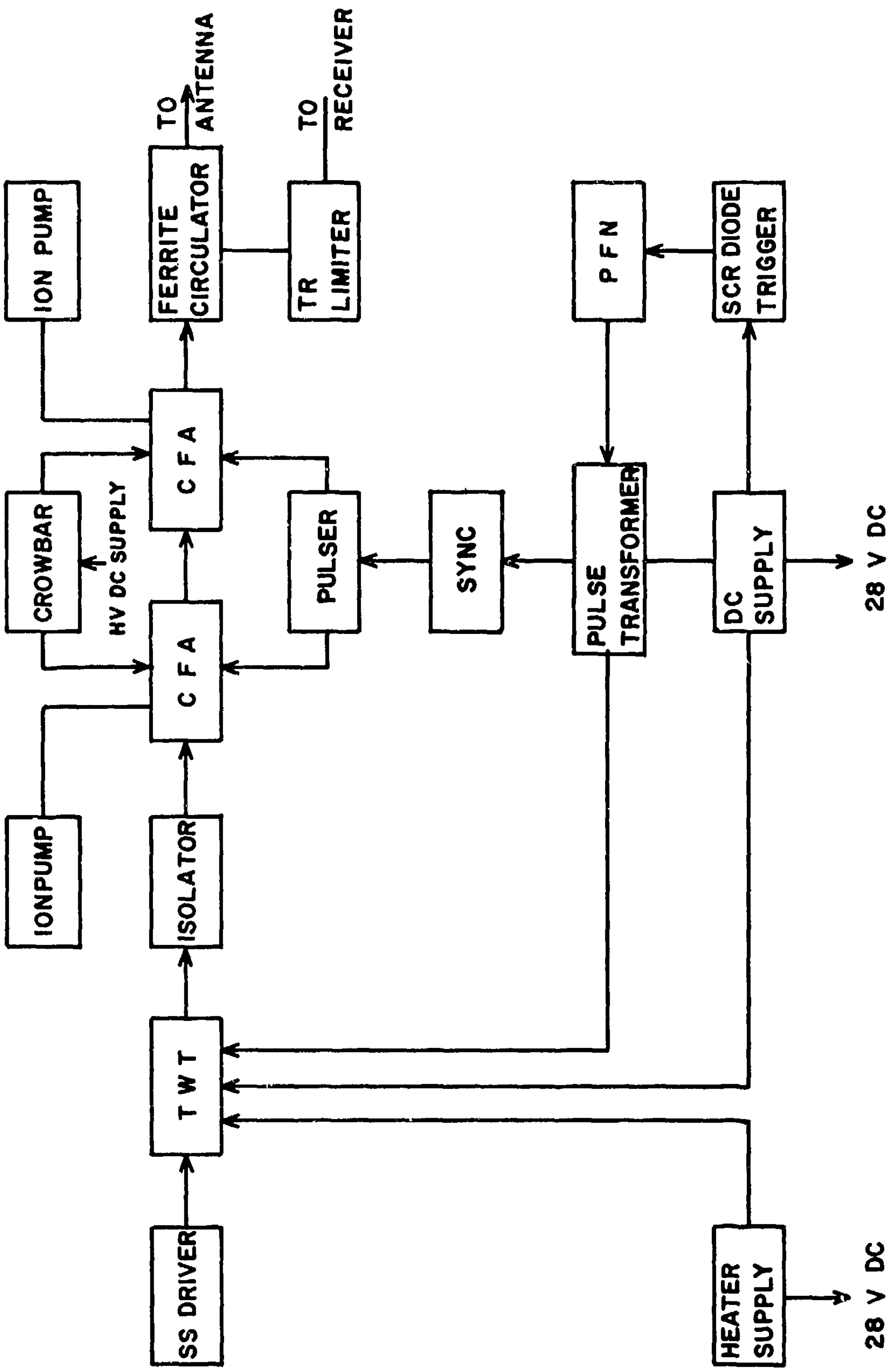


Fig. 24 - Block diagram of a typical CFA radar transmitter

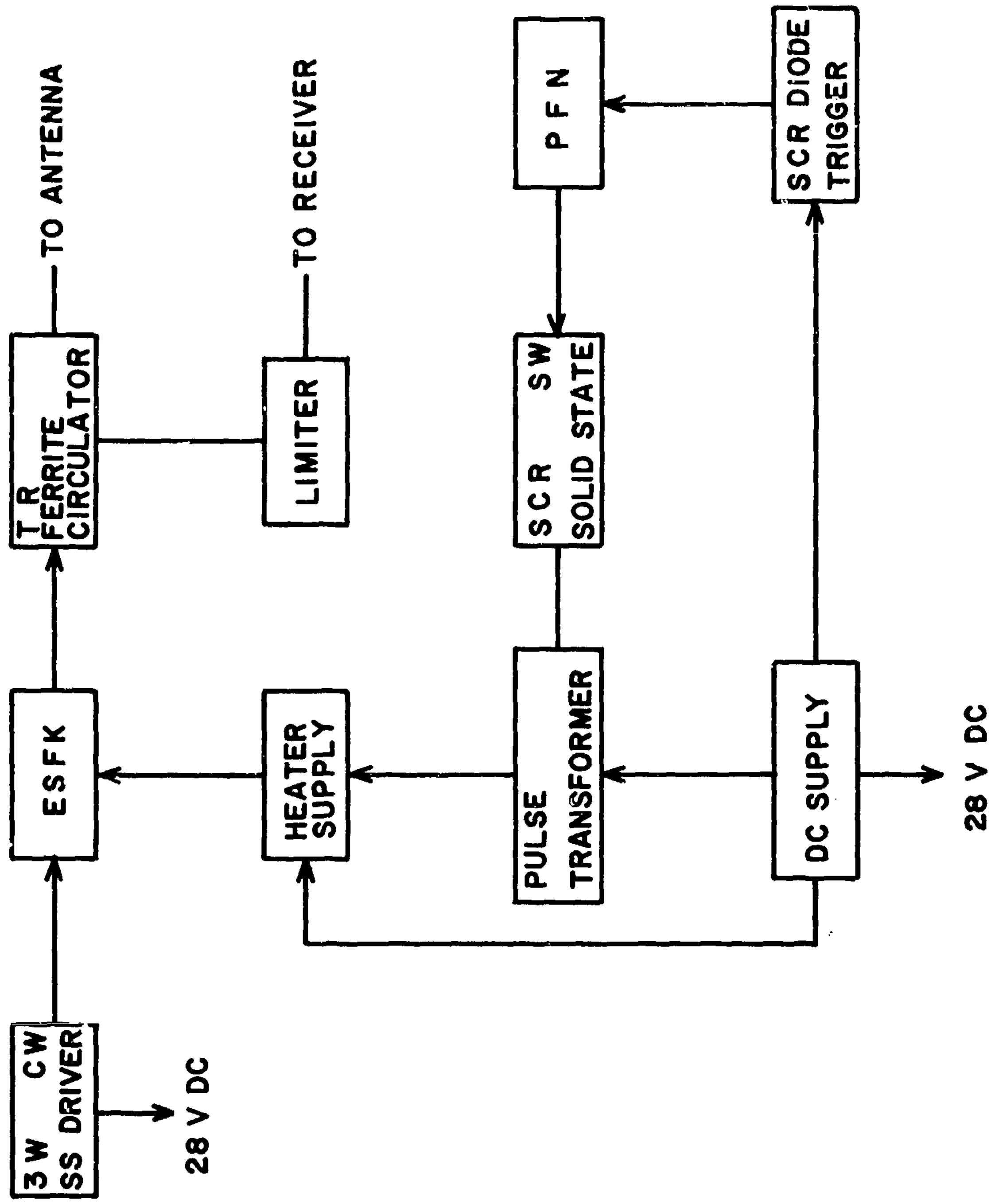


Fig. 25 - Block diagram of a typical ESFK radar transmitter

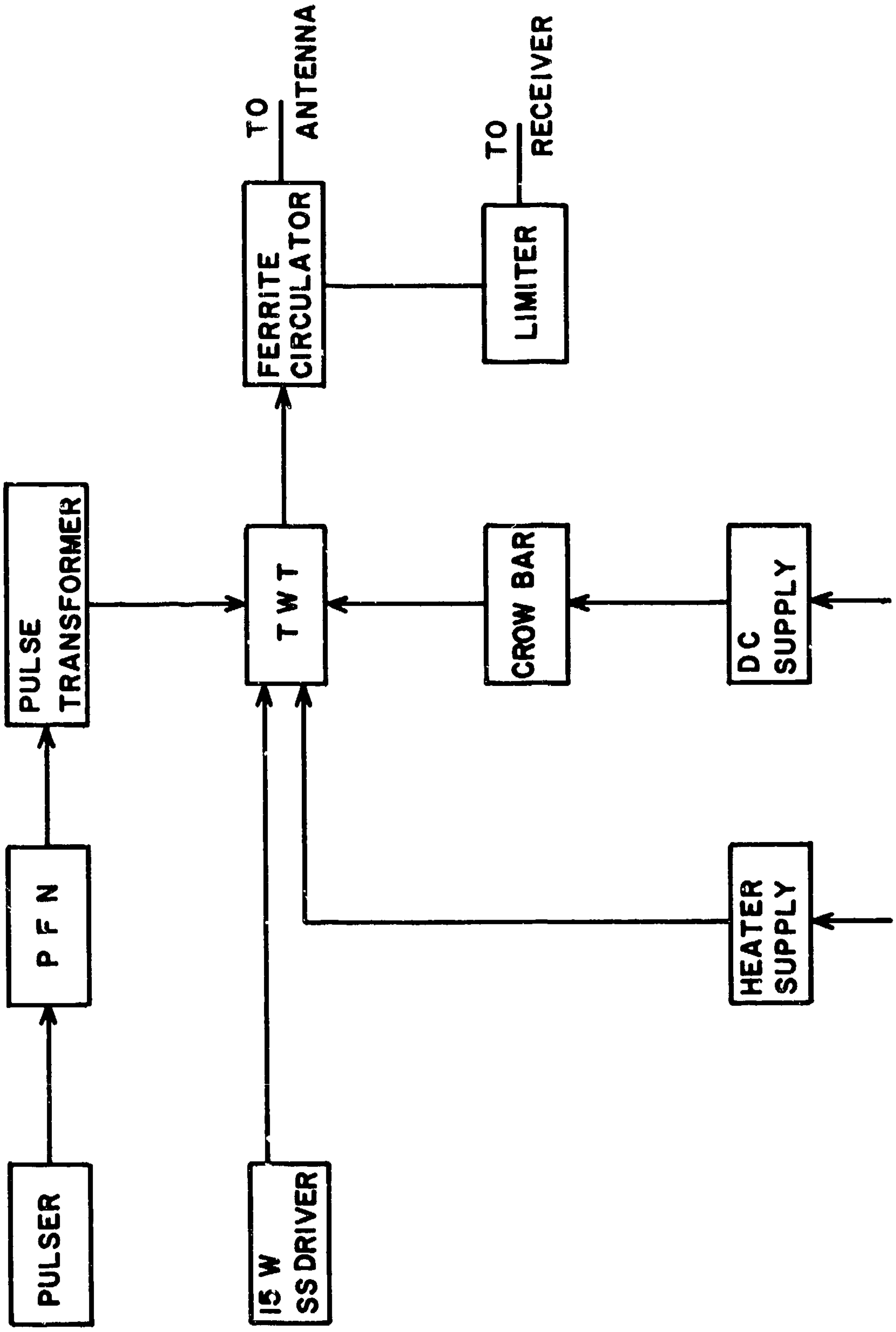


Fig. 26 - Block diagram of a typical TWT radar transmitter

Disadvantages are:

1. Limited bandwidth

(U) Neither the TWT or the ESFK has the excellent phase modulation sensitivity characteristics of the CFA, but modulation sensitivity is not the dominant factor in tube selection, and cost tradeoffs can be made relative to the specification ripple from the high voltage power supplies.

Receiver

(U) In this system the receiver consists of all components from the circulator to the video amplifier where the signal is passed on to the data processor. A block diagram of a typical receiver is shown in Fig. 27. The component of particular concern in the receiver is the low noise R.F. amplifier. This is the component which has the greatest effect on receiver noise figure. There are several possibilities for the low noise amplifier in this system, namely, a parametric amplifier (paramp), a travelling wave tube amplifier (TWT), and a solid state amplifier. All of these are capable of achieving noise figures low enough to satisfy the system requirements. Of the three types of amplifiers, the parametric amplifier is capable of the lowest noise figure, but the experience with parametric amplifiers in operational airborne systems indicates that their reliability in an unattended environment is poor. Unless the latest generation of paramps is significantly more reliable than their predecessors, the use of a paramp in the system would not be consistent with the reliability goals of the program. Of the other two devices, the TWT is not as sensitive to burnout as the solid state amplifier and therefore does not require as much protection from the limiter. The TWT however, is heavier and bulkier than the solid state amplifier.

(U) At the present time, it is planned to investigate each of these devices, i.e., the paramp, TWT and solid state amplifier to determine which one is the most suitable for the preferred radar system.

Data Processor

(U) The Processor for the Case II system represents the least development risk of the three systems investigated. The various processing functions involve circuitry which is presently available and which has, in most cases, been applied to systems now under development.

(U) The initial processing step (A/D conversion) would require a small development effort to achieve conversion rates of about 10 MHz for a parallel output of about 3 bits plus sign. This involves little development risk, since the components and techniques exist. A technique that meets the speed of conversion requirements, utilizing presently available circuitry, is under development at NRL.

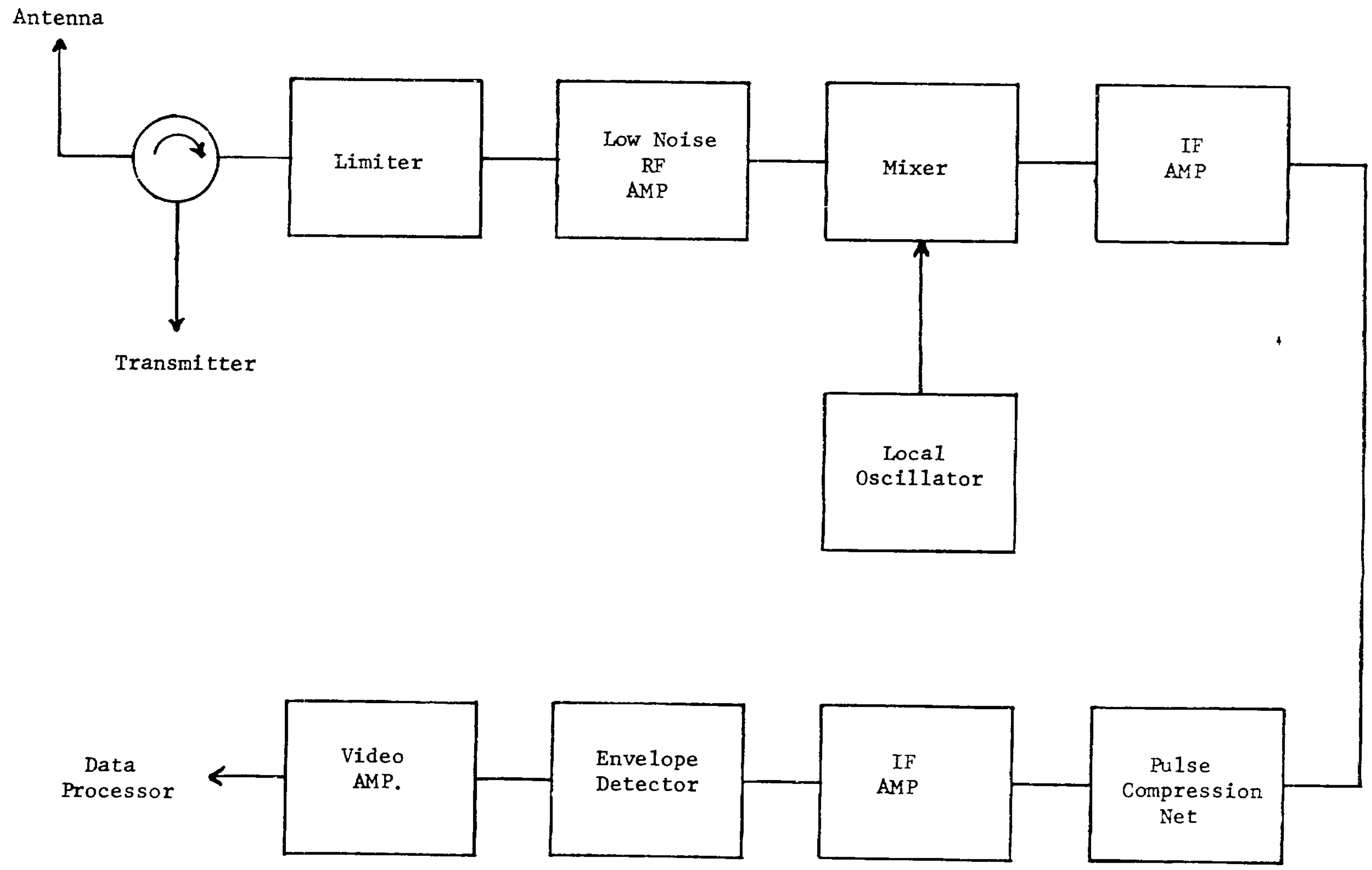


Fig. 27 - Block diagram of a typical receiver

(U) Digital integration of the converted data involves real time storage of about 55,500 range bins. While other techniques exist, shift register storage is an effective method which is more flexible and avoids some of the mechanical problems associated with other devices. Recent advances in I. C. technology have made available statis MOS shift registers with packaging densities which make this technique attractive. Currently under evaluation at NRL is a 200 bit device in a TO-5 package.

(U) Due to power dissipation and speed considerations, it will be necessary to apply multiplex techniques in order to utilize such devices at their present state of development.

(U) The integration of the stored range bins with the incoming data involves an adder of approximately 9 bits operating at a speed of 10 MHz. Such an adder can presently be implemented utilizing currently available high speed logic circuits. Multiple bit integrated circuit adder packages are available although there is some doubt as to their applicability due to speed and environmental considerations. Investigation is continuing to determine the availability of suitable devices.

(U) Preliminary investigation into the availability of aerospace computers both under development and in production, indicates that systems do exist that satisfy the storage capacity, speed, and format requirements of the Case II data processor within acceptable size, weight and power limits.

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SECRET
Security Classification

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1. ORIGINATING ACTIVITY (Corporate author) Naval Research Laboratory Washington, D.C. 20390	2a. REPORT SECURITY CLASSIFICATION SECRET 2b. GROUP 3

3. REPORT TITLE

OCEAN SURVEILLANCE RADAR PARAMETRIC ANALYSIS - Final Report

4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Work on the parametric analysis phase of this program has been completed; work on other phases of this program will continue.

5. AUTHOR(S) (First name, middle initial, last name)

Edward N. Carey; Richard L. Eilbert; Robert E. Ellis; Donald F. Hemenway; Albert E. Leef

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b. PROJECT NO. c. A37538/652/69/F48111704	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Department of the Navy (Naval Air Systems Command - Astronautics Division), Washington, D.C. 20360

13. ABSTRACT (Secret)

(S) The engineering analysis part of a program to determine the best type and the optimum parameters for a satellite radar system for ocean surveillance has been completed. Three basic radar system types were considered in the analysis, which were: a forward scan system, a non-coherent sidelooking system, and a coherent sidelooking or synthetic aperture system.

(S) Each of the basic systems was determined to have a capability of meeting the required probability of detection requirements. The parameters of the best of each of the basic system types were arrived at through a combination of computer aided studies to develop trends and optimize parameters, and the use of modeling data and constraints which were made uniform for all systems. The selection of the best single system was based on the application of a consistent set of factors to determine the relative development risks, reliability, complexity, and costs.

(S) The coherent sidelooking system was judged to be the least acceptable system type because of significantly higher development risks, complexity, and costs together with lower reliability.

(S) The real aperture sidelooking and the electronic forward scan system were determined to be nearly identical in projected costs. The real aperture system, though having only an insignificant cost advantage over the forward scan system, was judged as being less of a development risk, less complex, and more reliable. (Continued)

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Ocean surveillance Radar system analysis Forward scan radar Real aperture sidelooking radar Synthetic aperture sidelooking radar						

(S) The selected system, which was required to provide contiguous equatorial coverage, was based on a constellation of three real aperture sidelooking radars equally spaced in the same orbital plane at an altitude of 150 naut. mi. The major parameters of this system which would provide a 0.90 probability of detection on a 200 square meter fluctuating radar target with a 10^{-10} probability of false alarm are: 1300 MHz frequency, 500 watts average radiated power, 200 kW peak power, 83 pps, 0.1 microsecond effective pulse length, 1-degree azimuth resolution, 48 × 21 ft. antenna, and a range swath of 520 naut. mi. per radar.

UNITED STATES GOVERNMENT

memorandum

DATE: September 9, 1996

REPLY TO ATTN OF: Code 5304

SUBJECT: Declassification of NRL Memorandum Reports 1874 and 1966, Request for

TO: 1221.1

1. This memorandum is to request that the security classification of the two reports listed below be changed from a current classification of CONFIDENTIAL to UNCLASSIFIED.

NRL Memorandum Report 1874
Ocean Surveillance Radar Parametric Analysis
Case II - Noncoherent Sidelooking Radar
(Unclassified Title)
S. Angyal, D. F. Hemenway, and S. A. Zuro
April 1968

AD-391 513

NRL Memorandum Report 1966
Ocean Surveillance Radar Parametric Analysis
(Unclassified Title)
Final Report
E. N. Carey, R. L. Eilbert, R. E. Ellis, D. F. Hemenway
and A. E. Leef
March 1969.

AD-501 065

2. The above reports are more than 27 years old, and as one of the authors, I can see no need for continuing to maintain any classification on the subject studies, and recommend that they be designated as **UNCLASSIFIED** reports.

3. The above information was submitted to Code 1221.1 on a memorandum dated September 4, 1996. This re-submission is for the purposes of including the following statement :

Further, this memorandum requests that the subject reports be approved for public release: distribution unlimited.

Donald F. Hemenway
Donald F. Hemenway
Code 5304

Completed
2-7-2000
B.W.

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