NRL Report 7752

Cost Analysis of an OTH Radar System

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August 8, 1974

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NAVAL RESEARCH LABORATORY
Washington, D.C.

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER: NRL Report 7752	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): COST ANALYSIS OF AN OTH RADAR SYSTEM	5. TYPE OF REPORT & PERIOD COVERED: An interim report on a continuing NRL Problem
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): William B. Gordon	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Naval Research Laboratory, Washington, D.C. 20375	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: NRL Problem R02-46A, WF 12-111-704
11. CONTROLLING OFFICE NAME AND ADDRESS: Department of the Navy, Naval Air Systems Command, Washington, D.C. 20360	12. REPORT DATE: August 8, 1974
	13. NUMBER OF PAGES: 32
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report)
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE: XGDS-(3)-88

16. DISTRIBUTION STATEMENT (of this Report)

Distribution limited to U.S. Government Agencies only; test and evaluation; August 1974. Other requests for this document must be referred to the Director, Naval Research Laboratory, Washington, D. C. 20375.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Over-the-horizon radar
Cost analysis

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Ship-detecting (SD) land-based over-the-horizon radars are classed into two groups according to the power rating and complexity of their transmitting arrays. Type I SD systems are relatively lower powered, have little directivity in the vertical plane, and have minimal elevation-angle steering capability, whereas Type II systems are higher powered and employ transmit beams which are narrower and steerable in the vertical plane. This report is mainly concerned with a cost analysis of Type I systems, though the cost estimates obtained apply equally well to the receive end of either type of SD system. A cost analysis of Type II

(Continued)

20. Abstract (Continued)

systems and a performance analysis of both types will be the subjects of subsequent reports. The initial investment cost (excluding basing) for a Type I SD system will vary between $15 million and $27 million depending on the requirements on update times, dwell times, and other features. At present we would estimate that corresponding Type II systems would cost an additional $10 million to $15 million, the cost difference being approximately equally divided between increased costs for hardware and for engineering labor. (This cost estimate for Type II systems is rough and requires further study.) The annual operating cost of either type of SD system is estimated to be $3.7 million.

CONTENTS

LIST OF TABLES

PREFACE

Nothing in this report should be construed as representing anyone's final ideas concerning the optimal design of a ship-detecting OTH radar system. What we have attempted to do is to construct a cost breakdown of a "baseline" system which is sufficiently detailed and modular in character to be useful in estimating the costs of systems employing the same elementary subsystems as the baseline system. The baseline system and its modifications are meant to incorporate all of the necessary features of a ship-detecting system, with certain possible exceptions (concerning the transmitting arrays) discussed in the Introduction, but our present state of knowledge does not permit a determination of the precise optimal configurations of system parameters which would achieve a requisite system capability for ship detection and tracking.

For example, several reviewers have suggested that the update and noncoherent dwell times (given in Table 1) may be too long, that more frequencies might be necessary to provide the given range-coverage-per-scan, and that the occasions for which a signal bandwidth of 200 kHz might be used are so rare that this value might not be useful even for a "worst-case" analysis. Now, a decrease in the update time can be purchased by a corresponding proportional decrease in the noncoherent dwell time, and/or a decrease in the area of coverage, and/or an increase in the number of transmitting arrays. There are similar relationships between the number of frequencies used per scan and the other system parameters, and so on. The costs of most of these design modifications can be determined in a strictly straightforward manner from our charts, as is illustrated in Tables 11 and 12. There are other design modifications whose costs should be estimated with a bit more care. For example, the increased costs of increasing the number of frequencies used per scan might be partially compensated by multiplexing in the signal processing subsystem (i.e., if the range coverage for frequency is reduced then one could use each of the signal processing units shown in Fig. 5 to process several of the receive beams.) At any rate, we expect that the results of more experimental and analytical work undertaken in the near future will clarify these issues and render possible a more precise determination of system parameters.

COST ANALYSIS OF AN OTH RADAR SYSTEM

INTRODUCTION

Scope of Study

This is the first of two reports on the cost analysis of land-based OTH radar systems designed specifically for the detection and tracking of surface vessels, and is part of a study currently being undertaken to determine the optimum mix of radar platforms (including satellites and high-altitude aircraft) to be used in ocean surveillance. Even though ship-detecting (SD) systems might only be fabricated by adjoining the necessary features to OTH systems designed with the capability of detecting missiles and aircraft, a cost study of systems designed specifically for ship detection has utility because, first, a detailed cost analysis can be used to estimate the incremental cost of adding on a ship-detection capability to an aircraft-and-missile-detecting (AMD) system and, second, the cost of an SD system might prove to be sufficiently low to justify the construction of system designed specifically for this purpose.

Ship-detecting (and other) OTH systems will be classified according to the complexity and power rating of their transmitter arrays. Type I systems, the subject of this report, are relatively low powered bistatic CW systems whose transmitting arrays have little directivity in the vertical plane and have minimal elevation-angle steering capability. Type II systems, a subject of a later report, are higher powered, may be either CW or pulsed systems, and employ complex transmitting arrays consisting of six or more 500-to-800-foot-high columns, each containing ten or more dipole elements. A Type II system would thus transmit a beam which is about 10° wide and steerable in the vertical plane. Both types of systems are assumed to employ long receiving arrays (4000 ft long or longer) and involve the use of many simultaneous receive beams. References 1 and 2 describe a Type II system. The SRI WARF array is an example of a Type I SD system, and Refs. 3 through 5 describe this system and the experimental results obtained with it to date.

A detailed analysis of the precise ship-detection and tracking-performance capabilities of either of these two types of systems would be premature at the present time, and in this report we shall merely review some of the technical issues involved in their design.

The detection ability of an SD OTH system is limited by sea clutter, and it has been determined that ship detection requires the use of doppler processing, so that the target doppler has to compete with only a narrow spectral component of the clutter return. The limiting effect of sea clutter on ship detection also requires that the receive beams be made as narrow as possible, and this implies the use of extremely long receiving

Note: Manuscript submitted April 22, 1974.

antenna arrays (4000 ft long or longer). Another special feature of SD systems, which is important because of its effects on cost, is the use of rather long coherent integration times of up to 30 seconds or more. (The use of long coherent integration times is implied by the fact that the system employs doppler processing for the detection and tracking of slow targets, a ship's doppler at HF frequencies being on the order of 1 Hz.)

These last two considerations (narrow receive beams and long coherent-integration times) suggest that the signal and data-processing subsystems of an SD system providing a large area of coverage must be designed to process many simultaneous receive beams, a factor which would tend to increase costs. This effect is somewhat mitigated because the update (frame) times required of an SD system are measured in hours rather than in minutes or seconds as is the case for AMD systems.

Thus both types of SD systems are similar at their receive ends: both employ long receive-antenna arrays and use complex doppler processing of the outputs from many simultaneous receive beams (and the cost analysis presented in a later section can be used to estimate the initial-investment cost and annual operating expenses at the receive end of either type of system.)

We now have to consider the rationale behind the design differences between the two types of SD systems at their transmit ends. An AMD system is designed to detect targets whose radar cross sections are on the order of 1 m^2, whereas the radar cross sections of ships are several orders of magnitude larger. Moreover, once a critical signal-to-noise ratio is achieved, the detection ability of an SD system is thereafter limited by sea clutter, and the signal-to-clutter ratio is not affected by increasing the transmitter power. These considerations might suggest a Type I design, employing a cheap, simple, and relatively low powered transmitting array and putting the burden of reliable ship detection at the receive end (using longer receive arrays, more sophisticated signal processing, etc.). The level of performance that one might hope to achieve with a Type I system is suggested by Fig. 1. The spectra depicted in this figure apparently represent averages for the area covered by the present SRI WARF array, and the solid line labeled "reduced clutter" represents the spectrum that might be obtainable with certain system improvements. (In particular, the "reduced clutter" spectrum presupposes the use of a 10-km receive array, which represents a 6-dB improvement over the present 2.5-km WARF array.)

On the other hand reliable ship detection might require a Type II design to achieve further reduction in clutter power and a sharpening of the spectra around the principal (Bragg) lines. These improvements might be obtained in the following two ways:

- Use of the lowest possible frequency to illuminate a given area of interest with an acceptable signal-to-noise ratio. This might require a higher power transmitter, a transmitting array with more gain in the vertical dimension, and an elevation-angle steering capability.

- Reduction of multipath, which is due to the possibility that the backscattered return with a given time delay may contain the returns from several different discrete clutter-resolution cells corresponding to rays which refract from different layers in the ionosphere but have the same optical path length. The contribution that the multipath phenomenon makes to the broadening of the doppler spectra is currently under study at NRL. The reduction of this multipath effect would require a very tall transmitting array with a large vertical directivity [6,7].

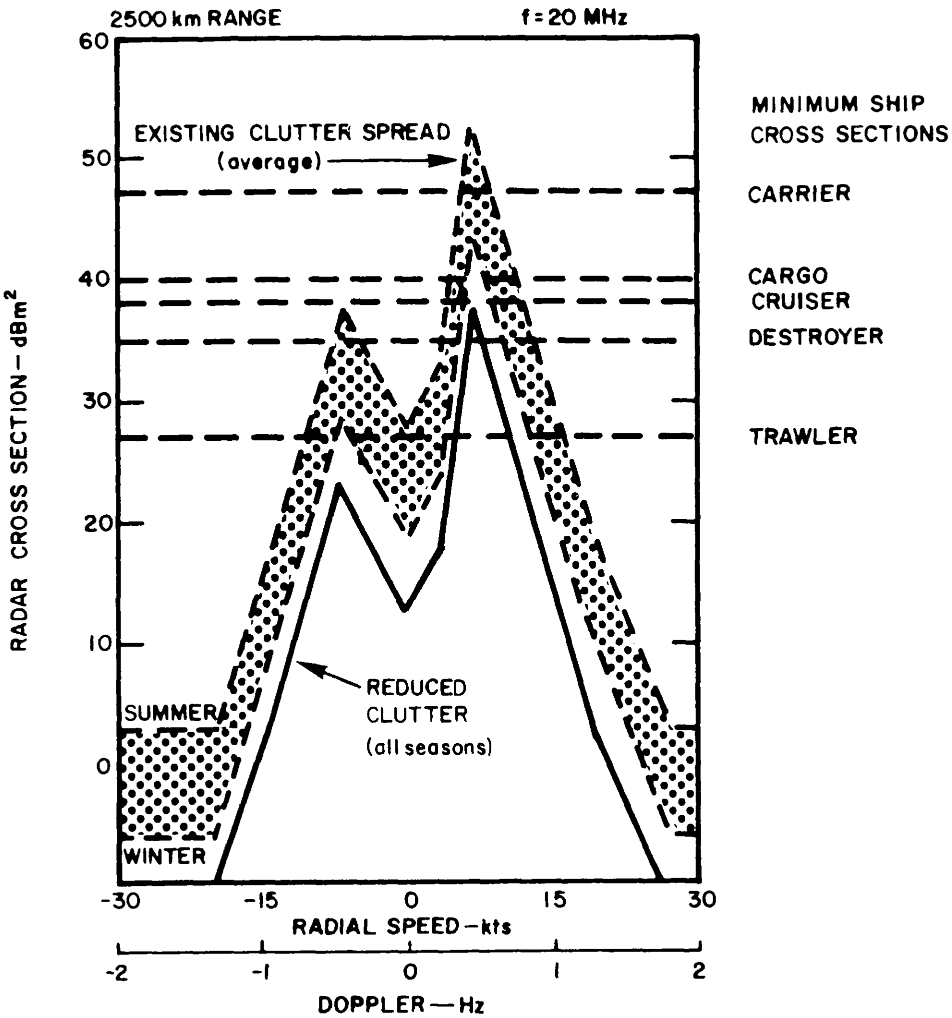

Fig. 1 — Comparison of current and future sea-clutter-spectrum magnitudes with the expected minimum ship-cross-section magnitudes (reproduced from page 83 of Ref. 5)

The remainder of this report is primarily concerned with obtaining cost estimates of Type I SD systems, though the cost estimates apply equally well to the receive end of either type system. The cost and performance capabilities of both types of systems will be treated further in subsequent reports.

Comparison of Costs of Different Systems

From time to time the cost estimates which we shall obtain for SD systems will be compared to the costs and cost estimates for AMD systems which have appeared in the technical literature. Type II SD systems and AMD systems are very similar, since they both employ high-powered and complex transmitters, and based on the literature, in particular a Mitre study of the CONUS system [2], we estimate that a Type I SD system costs about

$10 million less than an AMD system whose complexity is equivalent to that of the SD system at the receive end. At present we would judge that the cost difference between corresponding Type I and Type II systems falls roughly between $10 million and $15 million. This last estimate is rough and requires further study.

The proportion of these cost differences which can be attributed to differences in the costs of hardware and engineering labor are approximately equal. Type I systems are cheaper because the use of only low to moderate power and a bistatic CW mode of operation permit the use of "standard" HF equipment (equipment whose design and installation require only straightforward engineering development). *In this report the term "standard (equipment)" is not synonomous with "off-the-shelf (equipment)" and all the cost estimates presented in this study are based on the use of equipment which satisfy the relevant Military Specifications.*

Uncertainties in System Design

It was just remarked that the main factors tending to decrease the cost of a Type I SD system (in comparison to an AMD system) are the use of low to moderate power and a bistatic CW mode of operation, which permit the use of standard HF equipment, and it was earlier remarked that the main factors tending to increase the cost of an SD system are the size and complexity of the antenna arrays and the necessity of processing many simultaneous receive beams. However the cost analysis of a Type I SD system is not as straightforward as these remarks might suggest, because of uncertainties in system design.

The principle uncertainties and their mutual relationships are shown in Fig. 2. The figure requires some explanation:

- At present it is not quite clear how long the receiving antenna can be made without losing coherence in the received signal or exactly how narrow the receive beams must be for reliable ship detection. The number of simultaneous receive beams is inversely proportional to the update time and inversely proportional to the (receive) beamwidth. An operational study is underway to determine the requirements on update time, which will probably vary between 1 and 3 hours.

- The number of receive beams is also roughly proportional to the noncoherent dwell time, which will probably vary between 5 and 15 minutes. Variations in the noncoherent dwell time will affect the number of simultaneous receive beams to be employed but have only a small effect on the *per-beam* cost of the signal processing system. In a later section it will be shown that variations in the coherent dwell (or integration) time also have a small effect on per-beam costs, provided that this quantity is measured in minutes; since an upper bound to the coherent dwell time has been pretty firmly established at about 30 seconds, variations in this quantity have not been listed as an uncertainty in system design.

- Throughout this study it is assumed that the system is designed to scan an area which lies within 250 to 500 n.mi. of a given point, such as the center of a task force. (Hence the total range coverage per scan will vary from 500 to 1000 n.mi.) This central point may vary from day to day or even from scan to scan, but it is assumed that the extent of the area of coverage is fixed during a given scan. The term *azimuthal coverage*

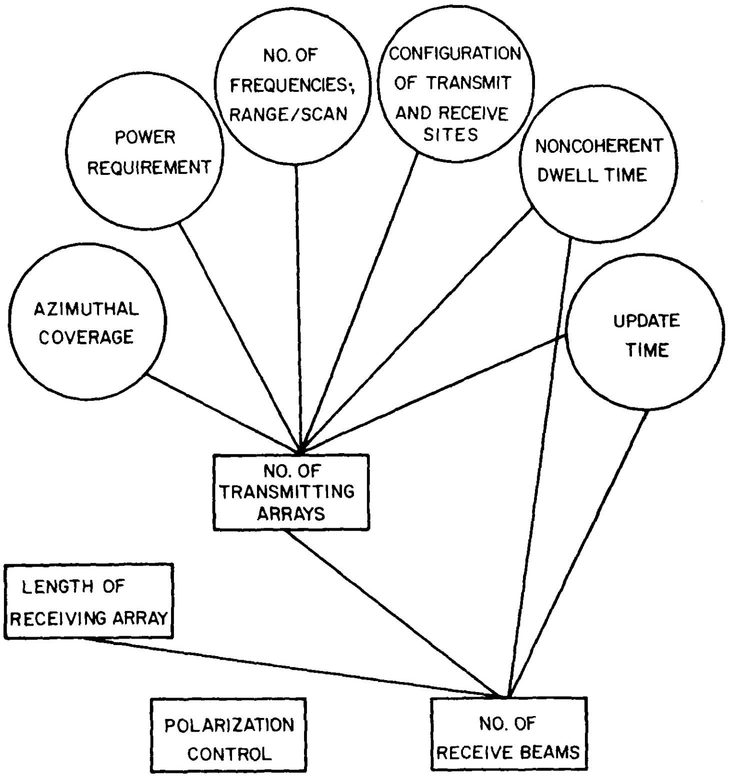

Fig. 2—Uncertainties in system design. The items in rectangles have a direct effect on costs.

refers not to the extent of the area covered during a given scan, but rather to the maximum angle off boresight at which the radar can be effectively aimed. Hence the azimuthal coverage has no effect on the maximum number of simultaneous receive beams, but it does have an effect on the number and complexity of antenna arrays.

- Throughout this study it is assumed that the system will employ low to moderate transmitter power. Hence variations in transmitter power will have only a small *direct* effect on cost, as indicated in the figure. However variations in the power requirement can have a large indirect effect on cost, as will be explained.

- The maximum number of simultaneous receive beams which can be contained within a given fixed transmit beam is determined not only by the transmitted and received beamwidths, but also by the geometry of the situation. For example, a fixed 6° transmit beam might accommodate only six 1/2° receive beams (Fig. 3)! For the case shown in Fig. 3 a 10° transmit beam would be necessary to accommodate 12 1/2° receive beams. (Twelve receive beams are about the minimum number of receive beams which are imposed by the constraints on dwell times, update times receive beamwidths, and range coverage per scan.) This geometrical effect could be mitigated by placing the two sites along a line running through the center of the area of coverage. However this arrangement might not be feasible for reasons of geography and economy. (Also it might appear that

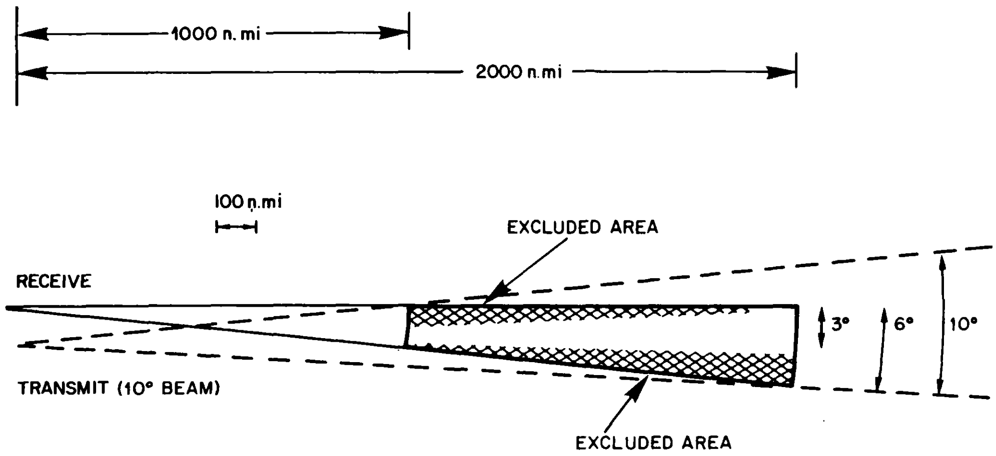

Fig. 3—Geometry of a bistatic configuration

such a configuration of sites might result in range ambiguities of the same type as occur in monostatic CW systems, however at the low PRF's employed in ship detection such range ambiguities have no practical importance in SD systems, as will be discussed further in a later section.)

- If the range coverage per scan is to be more than 500 n.mi., then it will probably be necessary to employ two or more frequencies to provide sufficient illumination on the area being scanned. In fact, our *baseline* SD OTH system will employ two independent transmitter arrays, each radiating up to 200 kW of power at different frequencies and each providing a range coverage per scan of 500 n.mi. (for a total of 1000 n.mi.). Each of the two transmit beams will be scanned independently and each will be covered with 12 receive beams (for a total of 24 simultaneous beams). If more than two frequencies must be used to provide sufficient illumination, then one must increase the number of transmitters or suffer a decrease in either the update time or noncoherent dwell time.

- The power requirement also has an effect on the number and complexity of the transmitting antenna arrays which will be required for a given extent of azimuthal coverage, due to the loss in transmitting gain which occurs as the scanning angle off boresight increases.

- The term *polarization control* refers to the possibility of employing elliptically polarized radiation whose vertical and horizontal components are individually controlled. This implies the use of crossed dipoles on the antenna arrays and would greatly increase the cost of the antennas and their associated RF equipment. Polarization control might be used to reduce target fading and for certain other reasons [8]. It will not be employed in the baseline system used as a basis for the calculations in the cost-analysis section, but its effects on cost will be included in the subsequent discussion of system modifications.

Brief Summary of System Costs

The initial-investment cost of our baseline Type I SD OTH system (summarized in Table 1 and described in a later section) is $15 million, which is considerably less than the corresponding costs for the higher powered AMD systems, which are generally estimated to be $25 million to $30 million.

(S) Table 1
System Description and System Parameters

Parameter	Description and Value
System type	Bistatic, FM-CW
Operating frequencies	5-40 MHz
Range coverage	500-2000 n.mi. on single-hop propagation
Range coverage per scan	Up to 1000 n.mi.
Azimuthal coverage	At least 60°
Transmitter array	Two 16-element log periodic arrays, each radiating up to 200 kW of power and having a 6° azimuthal beamwidth and 20-dB antenna gain
Receiver array	256 monopole elements spaced 10 m apart; 1/4° beamwidth at 29 MHz; directivity of 28 ± 5 dB
Coherent integration time	Up to 30 s
Dwell time	5 min
Update time	2 hr
dBJ rating	115 ± 7 dBJ
PRF	10 frequency sweeps per second
Signal bandwidth	200 kHz (corresponding to a range resolution of 0.4 n.mi.)
No. of range bins	Up to 2000 (per beam)
No. of simultaneous receive beams	24

The effects on cost of the various contingencies in system design will be discussed later. To avoid any misunderstandings which might arise from this overly brief summary, the reader should keep in mind the following explanatory remarks:

- The term *initial-investment cost* refers exclusively to the costs for the fabrication and installation of hardware and also the labor costs involved in engineering development, system integration, and computer programming, etc. This cost does *not* include such basing costs as site acquisition and improvement, buildings, roads, and other supporting facilities, which are highly variable and might run from $5 million to $20 million or more (and which are not included in the initial-investment cost of $25 million to $30 million estimated for a typical AMD system).

- The costs for the signal-processing subsystem turns out to be rather moderate ($3.6 million), and the most potentially costly items are the antenna arrays and associated RF equipment, and the labor costs described above.

- These costs are the costs for a first operational system. The costs for a second and all subsequent operational systems should be considerably less, because the engineering and programming labor costs for a second system should be greatly reduced.

The annual operating expense is estimated to be $3.7 million, and the estimated basing costs are (somewhat arbitrarily) set at $8.0 million, so that the estimated total 10-year system cost is estimated to be $60.0 million.

REVIEW OF LITERATURE OF OTH COST ANALYSES

Introductory Remarks

In reviewing the literature we should keep in mind that previous cost analyses are mainly devoted to AMD systems and that the cost of some items have undergone significant changes in recent years.

As a rough rule of thumb sufficient for purposes of comparison, many persons adopt a 6% annual rate of inflation for all hardware and labor costs. However, as we have already mentioned, the cost of computers has gone down. On the other hand, based on Department of Commerce figures (which are available in the form of computer printout only), since 1968 the annual rate of inflation for communication equipment has averaged somewhat less than 4% (Table 2). (The Commerce Department has no such figures on

(U) Table 2
Price Indices for Communication Equipment

Year	Price Index (1958 = 100)	Inflation From Previous Year
1968	95.8	—
1969	98.9	3.2%
1970	106.1	7.3%
1971	111.2	4.8%
1972	111.1	0.0%
		Av: 3.8%

computers, and a comparison of the costs of the current generation of computers with those of previous generations of computers would be an exercise of questionable value.) We have obtained no figures on engineering-labor costs, but based on Civil Service rates a 5% or 6% annual rate of increase would seem to be a reasonable estimate. Hence an inflation rate of 6% would seem to be a reasonable though somewhat conservative figure for the purposes of gross comparison between cost estimates performed in different years.

Literature Review

Before reviewing the literature, we again remind the reader that the term *initial-investment cost* is to be understood strictly in the sense defined at the end of the preceding section. The cost estimates discussed below are generally expressed in terms of dollar costs current at the date of the particular document listed:

- *SRI Technical Note 8, January 1968 [9]*. This SRI study is concerned with and AMD OTH system (apparently a monostatic system of the NRL Madre type) to be used in fleet air defense. Cost estimates are obtained mainly from empirically derived *cost-estimating relationships* which relate costs of various items to the system parameters of power, azimuthal coverage, and number of beams. Though many of the values given in this document are by now dubious, the document does have a valuable discussion of the various items appearing in system costs and data on the costs of basing. The estimated initial-investment cost of a 200-kW system with a single *transmitted* beam and 160° azimuthal coverage is (1967) $33.6 million, of which $19.6 million is for prime-mission equipment (Table 3).

(U) Table 3
SRI Prime-Mission-Equipment Cost Breakdown

Item	1967 Cost ($ millions)
Antenna (160° coverage)	9.1
Transmitter	4.0
Receiver	1.0
Signal Processing	2.5
Data Reduction	2.5
Display	0.5
	Total: 19.6

- *Mitre Technical Report 2274, December 1971 [2]*. This Mitre report is concerned with the design and cost analysis of the high-powered (1.8 MW) CONUS OTH radar system. This system employs four transmitter arrays (two high-band arrays and two low-band arrays), employs a planar receiving array of 512 elements, has a total angular coverage of 90°, and employs 32 simultaneous receive beams. The cost is summarized in Table 4. Both a monostatic and a bistatic mode of operation are contemplated (as indicated), and the study is not definitely committed to either a pulsed or CW system. An examination of the detailed cost breakdown in this Mitre report reveals that a considerable fraction of each item of the cost summary is charged to engineering development and programming costs. In fact the item"computer programming" does not contain all of the programming costs; additional programming costs are charged to other items, especially the signal-processor group.

Table 4
CONUS Baseline Cost Summary from Ref. 2;
RDT&E System Cost Summary of Prime-Mission-Equipment Items

Item	Cost ($ thousands)	
	Monostatic	Bistatic
Antenna group	3,400	3,400
Transmitter group	5,600	5,100
Receiver group	2,500	2,500
Signal-processor group	4,260*	4,260*
External calibration group	870†	870†
Data processor	1,140	1,140
Computer programming	4,925‡	4,925‡
Display group	1,290	1,290
Intersite communications	—	400§
	23,985	23,885

*Includes $300,000 for computer programming documentation.
†Includes $500,000 for beacons.
‡Includes $1,135,000 for computer-programming documentation.
§ Ten-year leasted-line costs at $40,000 per year.

- *CNA Study 1015, March 1973 [10].* This CNA study is concerned with the operational requirements and costs of various ocean-surveillance systems required for various (specified) naval missions. They find that for most naval missions those ocean-surveillance systems which employ OTH radars cost only about 1/3 as much as those systems which do not employ OTH. The cost estimates appearing in this CNA study are mainly derived from the SRI and Mitre studies cited above. (For example, except for one minor discrepancy which appears to be a transcription error, the initial-investment-cost estimates for a 90°, 1.8-MW system given in their Table VI agrees item-for-item with the corresponding cost estimates derived from the SRI cost-estimating relationships. The annual operating costs shown in Table VI also agree with those derived from the SRI cost-estimating relationships, except in two items involving military pay scales and expenses for utilities.)

- *NRL Studies, April 1972 and November 1972, [11,12].* In these studies OTH systems are classified according to their dBJ rating and P_D (probability of detection) for various sized targets. The estimated initial-investment cost for high-powered systems (with average power ratings of about 1.8 MW and angular coverages of 90°) are $25 million to $30 million.

- *AN/FPS-95 System.* Our sources on the costs for this system are not available for documentation; however we understand that the hardware cost was (1967) $33 million. The cost for site preparation ($21 million) was inordinately high because of the system's location on a marsh.

- *MCR Report 73-1007.* This MCR study was published and became available to the author only after the first draft of our report had been written. The results of this study will be compared with ours in the appendix.

- *Other Sources.* Other sources, which cannot be documented, consist of contractor proposals, vendor quotations, and the experience of workers in the field.

THE BASELINE SD OTH SYSTEM

System Description and System Parameters

The main features of the baseline system on which our cost analysis is to be based are summarized in Table 1. The various design contingencies, enumerated earlier, and their effects on cost will be further discussed in the final section.

The transmitter and receiver sites will be separated by at least 50 n.mi., and this might require the use of extremely accurate clocks at both sites for the proper signal gating [13,14]. Both sites will contain ionospheric-sounding equipment to determine the frequencies to be used to illuminate the area of interest.

Figure 4 illustrates the various functions performed at the receiver site, and Fig. 5 shows the signal-processing subsystem in some detail. The output from each receive beam is displayed on a cathode-ray tube (CRT) in the form of range-vs-doppler plots. (The signal processing involved in obtaining these plots is discussed in the next subsection.) The output of three (or more) contiguous beams is monitored by an operator, who will mark possible target returns. Coded information on target returns is passed to a central display via a data processor which will construct range-azimuth plots and perform certain other tracking operations. Officers and operators at central control consoles will monitor target tracks and environmental conditions (including interference and ECM activity) and perform such functions as the initiation of scanning programs, threat analysis, and the communication of information to intelligence centers and users.

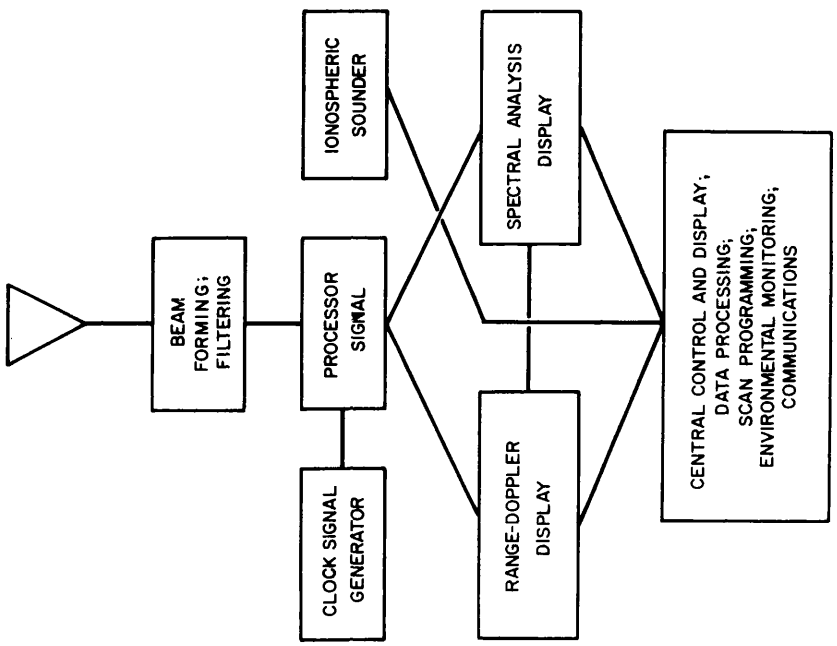

Fig. 4 — Functions at the receiver site

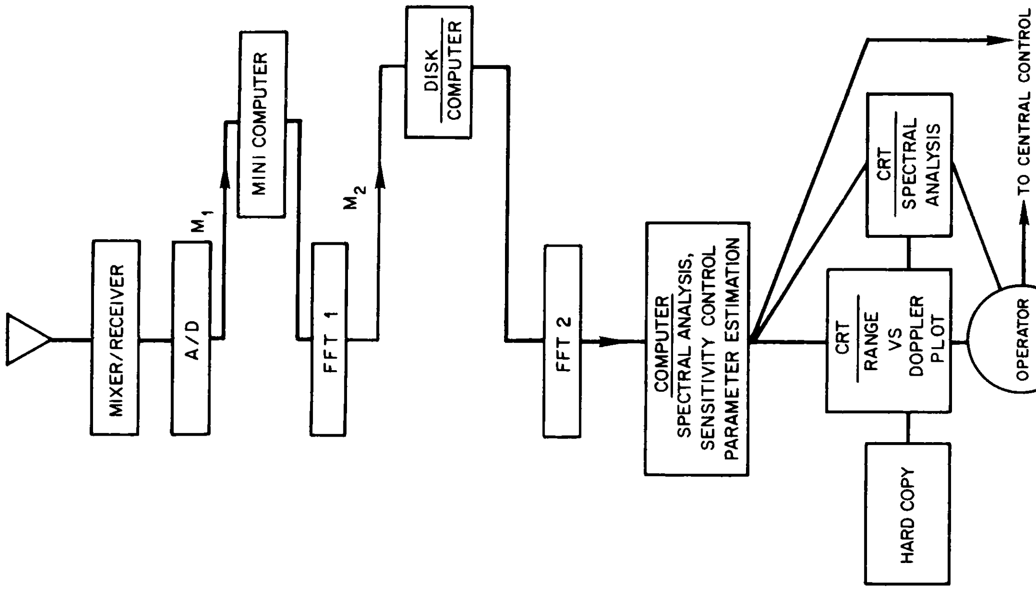

Fig. 5 — Signal processing subsystem (one unit per receive beam)

Information on the signal spectrum will be displayed at both the central and satellite consoles and used for sensitivity control, filtering, computation of target radar cross sections, and monitoring of environmental conditions. The output from each beam may also be stored as hard copy.

Signal Processing Requirements

A major concern of this report is to compute the per-beam cost of the signal processing unit, since there will be 24 or more simultaneous receive beams. The number of receive beams will depend on the requirements on update times and (noncoherent) dwell times. Some examples are given in Table 5.

The transmitted signal can be viewed as a train of pulses joined end to end. During each pulse (or sweep) duration period t_p(=0.1 s) the signal frequency is swept through the band $[f_0, f_0 + B]$, where f_0 is the carrier and B(=200 kHz) is the signal bandwidth, so that each pulse has the general form

$$S(t) = A \sin [2\pi(f_0 + kt)t], \qquad 0 \leqslant t \leqslant t_p,$$

where $k = B/t_p (= 2 \times 10^6/s^2)$. The sweep duration period t_p = 0.1 s corresponds to a nonambiguous range of 1.5×10^4 km. The pulse (or sweep) repetition frequency of $1/t_p$ = 10 Hz corresponds to a nonambiguous doppler of ±5 Hz, which provides sufficient doppler coverage for fast ships at the highest frequencies. The value of t_p must be made sufficiently small to provide adequate doppler coverage; on the other hand, large values of t_p provide large unambiguous ranges and, as we shall see, smaller signal-processing costs.

A plot of instantaneous frequency is shown in Fig. 6. Note that a range delay of $2r$ (light seconds) corresponds approximately to a frequency difference of $\Delta = 2kr$. The

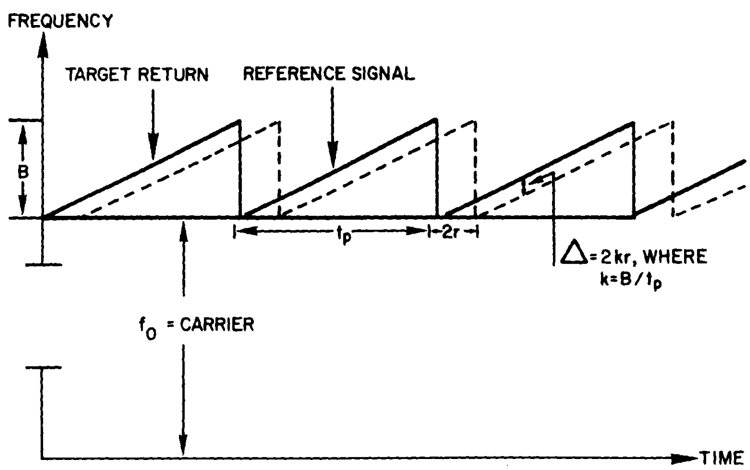

Fig. 6—Relationship of range delay $2r$ and frequency difference Δ

Table 5
Examples of Relations Between Number of Receive Beams per Transmit Beam and Requirements on Update Times and Dwell Times. The Computations Assume 240 (1/4°) Beams for 60° Coverage and a Coherent Integration Time of 30 Seconds.

Number of Receive Beams per Transmit Beam	Update Time (hr)	Noncoherent Dwell Time (S)	Number of Coherent Dwells
1	3	45.0	1.5
	2	30	1.0
	1	15	0.5
2	3	90	3.0
	2	60	2.0
	1	30	1.0
3	3	135	4.5
	2	90	3.0
	1	45	1.5
4	3	180	6.0
	2	120	4.0
	1	60	2.0
6	3	270	9.0
	2	180	6.0
	1	90	3.0
8	3	360	12.0
	2	240	8.0
	1	120	4.0
9	3	405	13.5
	2	270	9.0
	1	135	4.5
12	3	540	18.0
	2	360	12.0
	1	180	6.0

basic sequence of operations (Fig. 5) producing the range-vs-doppler plots can be represented as

$$M_1 \xrightarrow{\text{F.T. (rows)}} M_2 \xrightarrow{\text{F.T. (columns)}} M_3,$$

where M_1, M_2, and M_3 are matrices each having 300 rows and 4000 columns. Each of the 300 rows of M_1 corresponds to the filtered output from a single frequency sweep. The 300 rows correspond to the 300 sweeps contained in a 30-second coherent dwell. (The reason for 4000 columns will be explained shortly.) A Fourier transform on the rows of M_1, produces the matrix M_2. A Fourier transform on the columns of M_2 produces the matrix M_3, which is the range-vs-doppler plot.

More specifically, the signal from each receive beam is mixed with a properly gated reference signal, and the output is passed through a single-sideband receiver tuned to the proper frequency band (in our case about 20 kHz). The output from the receiver is then passed through an analog-to-digital converter, a minicomputer (where the samples are given the appropriate Hamming weights), and an FFT. The output of this FFT is the matrix M_2, whose elements must be stored, readdressed, and weighted before being passed to a second FFT, which computes the matrix M_3.

The use of just one single-sideband receiver to detect the output from the mixer implies that the maximum frequency difference Δ (Fig. 6) is $k2\delta$, where δ corresponds to the extent of the range coverage per scan. As was stated, we generally assume that at least two independent transmit beams will be employed, each providing a range coverage per scan of 500 n.mi. However, since there is some possibility of employing a single transmit beam in a floodlighting mode of operation, we shall set δ = 1000 n.mi. (converted to light-seconds) for purposes of costing. Hence Δ_{max} = 24,693 Hz. The data from each frequency sweep are sampled at a rate of $2\Delta_{max}$; hence there are 4939 samples per sweep. This is an inconvenient number, since it exceeds $4096 = 2^{12}$.

Equivalently, the target return from the jth range bin at r_j corresponds to the frequency difference $f_j = 2kr_j = 2Br_j/t_p$. But $r_j = j/2B$, so that $f_j = j/t_p$. Hence, if there are n range bins, the maximum difference frequency is n/t_p. The sample rate is therefore $2n/t_p$, so there are $2n$ samples per sweep. A signal bandwidth of B = 200 kHz actually corresponds to a range resolution of 0.405 n.mi., so that there are again 1000/0.405 = 2469 range bins and 2 × 2469 = 4939 samples per sweep corresponding to a range coverage per scan of 1000 n.mi.

The nominal figure of 4000 samples per sweep, which corresponds to a coverage of 810 n.mi., is used for costing. The difficulties involved in using more than 2^{12} samples per sweep might be overcome by using two receivers per beam (which would halve the data rate) or in some other way. Indeed, since it is not likely that a range coverage per scan of 1000 n.mi. can be provided by a single transmit beam employing a single carrier, this difficulty probably does not represent a real problem.

Further details and references on signal processing are given in Ref. 13 and 14.

COST ANALYSIS

Cost Analysis of the Baseline System

In Tables 6 through 10 we present the cost analysis of our baseline SD OTH system in a manner which facilitates modifications in these estimates which might arise from the various contingencies in system design discussed in the Introduction. Thus we keep hardware

(S) Table 6
Cost Summary for SD OTH Baseline System

Item	Cost	
	$ thousands	$ millions
Prime-Mission Equipment (PME)		
1. Transmitter-site prime-mission equipment	2290	
2. Receiver-site prime-mission equipment	7640	
3. Spares, standard equipment, and misc.	990*	
	10920	
Engineering Labor, Computer Programming, and Documentation†		
4. Engineering development, system integration, and documentation	3500	
5. Computer programming and documentation	600	
	4100	
Total initial investment cost, excluding basing	15020	15.0
Basing and Operating		
6. Basing		8.0‡
7. Annual operating expense		3.7
Ten-year operating expense		37.0
Total 10-year system cost		60.0

*Set at 10% of items 1 plus 2.
†These labor charges are figured in terms of what we shall call *nominal man years*, with 1 nominal man year corresponding to a cost of $50 thousand, half of which is charged to salaries and half to overhead. The overhead costs include fringe benefits, travel, and also supervisory and secretarial personnel. Hence each nominal man year corresponds to about 1.2 persons. There are 75 nominal man years charged to item 4 and 10 charged to item 5, the remainder of item 5 (20%) being charged to documentation costs.
‡As explained before, this is merely a nominal figure and the actual cost will vary according to the local conditions.

costs (the costs involved in the actual fabrication and installation of equipment) separate from engineering-labor costs, since one would imagine that the labor costs would be approximately the same for two different systems having the same degree of complexity. Also, these costs are costs for the first operational system, and the costs for engineering development and computer programming involved in a second and all subsequent systems should be considerably reduced.

Table 7
Cost Breakdown of Item 1 (Transmitter-Site Prime-Mission Equipment)

Item	Cost ($ thousands)
A. Two 16-element log periodic arrays	800
B. Twenty 20-kW transmitters	700
C. Cables, beam-steering equipment, and other RF equipment	480
D. Clocks and signal generators	250
Subtotal	2230
E. Ionospheric sounder*	60
Total	2290

*This item, unlike items A through D, is independent of system design; for example, it remains the same if the number of transmitters or arrays are varied.

Table 8
Cost Breakdown of Item 2 (Receiver-Site Prime-Mission Equipment)

Item	Cost ($ thousands)
a. Antenna array (256 monopole elements) and associated RF equipment (including beam steering)	1800
b. Clock and signal generator	100
c. Central display and control*	2000*
d. Ionospheric sounder	100
Subtotal	4000
e. Signal-processing group (Fig. 5):†	
24 mixer/receivers ($3500 each)	84
24 A/D converters	24
24 minicomputers ($6000 each)	144
24 FFT's (No. 1) ($22,000 each)	528
24 disk/computers ($40,000 each)	960
24 FFT's (No. 2) ($22,000 each)	528
24 computers ($25,000 each)	600
24 CRT displays and hardcopy ($32,000 each)	768
Subtotal	3636
Total	7640

*This is a rough estimate of the costs of a large computer, an unspecified number of displays, and communication equipment.
†The cost of these items is directly proportional to the number of receive beams. For example, a system employing 36 beams would cost $1818 thousand more (for a total of $5454 thousand).

Table 9
Cost Breakdown of Item 7 (Annual Operating Expense)

Item	Cost ($ thousands)
Maintenance of prime-mission equipment	990*
Utilities, including leased lines for intersite communications	250
Maintenance of grounds and buildings	50
Retraining	200
Continuing engineering development	750†
Military pay and allowances (Table 10)	1213
Civilian differential‡	200
Total	3653

*Set at 10% of items 1 and 2 (Table 6).
†Cost of 15 nominal man years (explained in the second footnote to table 6)
‡Accounts for the possibility that some personnel will be (higher paid) civilians.

The initial-investment cost is broken down into costs for prime-mission equipment, engineering labor, computer programming, standard equipment, spares, and miscellaneous. The highly variable costs for basing, consisting of costs for site acquisition, land improvement, transportation, etc., which we set at a nominal figure of $8 million, are excluded from the initial-investment cost. The annual operating expense consists of charges for military pay and allowances, maintenance, utilities and other expenses.

Again we remind the reader that our baseline system employs two independent transmitters and transmitter arrays, each capable of radiating 200 kW of power, one 256-monopole-element receiver array, and 24 simultaneous receive beams. The prime-mission-equipment costs for processing the 24 receive beams are shown in item e of Table 8.

We should mention that our cost analysis is based on the use of 14- or 16-bit machines which is more than adequate to provide sufficient dynamic range for ships as small as the AGI, whose radar cross section is about 400 m^2 [3].

Comparison with Costs of the CONUS Baseline System

The cost summaries of our SD system (Table 6) and the CONUS baseline AMD system (Table 4) should not be compared item for item, since corresponding items may represent quite different things. For example, in the CONUS report the "transmitter group" and "receiver group" contain subitems which are charged to the antenna arrays in this report.

Table 10
Personnel Breakdown and Cost Computation for the Item Military Pay and Allowances in Table 9

Personnel Category	Number per Shift	Number of Shifts	Number of Personnel
Operations Personnel at the Transmitter Site			
Shift supervisor	1		
Operators	2		
Guards	3		
	6	5	30
Operations Personnel at the Receiver Site			
Radar control officer	1		
Threat analyst	1		
Communicator	1		
Radar operators (one per three beams)	8		
Operator for ionospheric sounding	1		
Guards	6		
	18	5	90
Technical Support and Maintenance at the Transmitter Site			
Engineer	1		
Repairmen	3		
Maintenance	2		
	6	1	6
Technical Support and Maintenance at the Receiver Site			
Supervisor	1		
Engineers	2		
Programmer	1		
Repairmen	4		
Maintenance	4		
	12	1	12
Total Number of Personnel			138

Cost Computation Based on Data Given in Ref. 10:

15% x 138 x $16,869 = $ 349.2 thousand

85% x 138 x $ 7,360 = $ 863.3 thousand

$1212.5 thousand

An examination of the detailed cost breakdowns in the CONUS report [2, pp. 154-160] reveals that the bulk of the $9 million difference in the estimated initial-investment costs of the two systems consists of a $4-million difference in the cost of engineering development and computer programming, and a $3-million difference in the cost of transmitters. (In the CONUS cost summary $4.9 million is charged to programming, but the detailed cost breakdowns contain another $3.5 million charged to engineering development and programming.)

We believe these differences in estimated initial-investment costs are reasonable, because our baseline Type I SD system is a low-to-moderate-power system, so that the engineering involved in its design and implementation should be fairly straightforward.

Another $870 thousand in the difference between the estimated initial-investment costs of the two systems is attributable to the item "external calibration group" in the CONUS cost summary which has no analog in our cost analysis.

System Modifications

The estimated initial-investment costs for various modifications of our baseline SD OTH system are shown in Table 11. For each modification, item 3 (Table 6) is 10% of items 1 and 2. The effects on costs of employing polarization control are estimated by the simple device of multiplying the relevant subitems (antenna arrays and associated RF equipment) by a factor of 3.

For example, to obtain the cost of the system labeled C-P, we begin with Table 7 and proceed as follows:

Item A ($800 thousand) becomes $[(800 + 400) X 3] thousand	=	$3600 thousand
Item B ($700 thousand) becomes $(700 + 350) thousand	=	$1050 thousand
Item C ($480 thousand) becomes $[(480 + 240) X 3] thousand	=	$2160 thousand
Item D ($250 thousand) remains		$ 250 thousand
Item E ($ 60 thousand) becomes $(60 X 3) thousand	=	$ 180 thousand
The total (item 1 of Table 6) becomes		$7240 thouasnd.

Similarly for item 2 of Table 6 we obtain the following from Table 8:

Item a ($1800 thousand) becomes $(1800 X 1/2 X 3) thousand	=	$2700 thousand
Item b ($ 100 thousand) remains		$ 100 thousand
Item c ($2000 thousand) remains		$2000 thousand
Item d ($ 100 thousand) becomes $(100 X 3) thousand	=	$ 300 thousand
Item e ($3636 thousand) becomes $(3636 X 18/24) thousand	=	$2727 thousand
The total (item 2 of Table 6) becomes		$7827 thousand.

Adding 10% to the sum of Items 1 and 2 and then another $4100 thousand for items 4 and 5 (Table 6), we get the initial-investment cost of $20.7 million given in Table 11 for the modified system labeled C-P. These calculations for all the modified systems are given in Table 12.

Table 11
Estimated Initial-Investment Costs of Modified SD OTH Systems

System	No. of Transmit Arrays	Total Power (kW)	Length of Receive Array (ft)	No. of Receive Beams	Polar-ization Control	Cost ($ millions)
Baseline	2	400	8000	24	No	15.0
A	1	200	4000	6	No	9.9
B	2	400	4000	12	No	12.0
C	3	600	4000	18	No	14.1
AA	1	200	8000	12	No	11.9
CC	3	600	8000	36	No	18.1
A-P	1	200	4000	6	Yes	13.7
B-P	2	400	4000	12	Yes	17.2
C-P	3	600	4000	18	Yes	20.7
AA-P	1	200	8000	12	Yes	17.6
BB-P	2	400	8000	24	Yes	22.1
CC-P	3	600	8000	36	Yes	26.6

Table 12
Breakdown of Initial-Investment Costs for Each of the Modified Systems Listed in Table 11

Item	Cost ($ thousands)										
	A	B	C	AA	CC	A-P	B-P	C-P	AA-P	BB-P	CC-P
	Modified Values in Table 7										
A	400	800	1200	400	1200	1200	2400	3600	1200	2400	3600
B	350	700	1050	350	1050	350	700	1050	350	700	1050
C	240	480	720	240	720	720	1440	2160	720	1440	2160
D	250	250	250	250	250	250	250	250	250	250	250
E	60	60	60	60	60	180	180	180	180	180	180
	1300	2290	3280	1300	3280	2700	4970	7240	2700	4970	7240
	Modified Values in Table 8										
a	900	900	900	1800	1800	2700	2700	2700	5400	5400	5400
b	100	100	100	100	100	100	100	100	100	100	100
c	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
d	100	100	100	100	100	300	300	300	300	300	300
e	909	1818	2727	1818	5454	909	1818	2727	1818	3636	5454
	4009	4918	5827	5818	9454	6009	6918	7827	9618	11436	13254
Σ	—	—	—	—	—	—	—	—	—	—	—
+10%	—	—	—	—	—	—	—	—	—	—	—
+4100	9940	12029	14118	11930	18107	13680	17177	20674	17650	22147	26643

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APPENDIX A

COMPARISON WITH REPORT MCR-73-1007

A report has recently been published which contains the results of a study performed under contract to the Navy Material Command (Navy Space Project Office, PME-106), and which is devoted to a cost and performance analysis of an SD OTH system [A1]. As we have already mentioned, this MCR report became available to the author only after the first draft of the present report had been typed; hence this MCR report and our own represent two absolutely independent efforts.

The MCR system characteristics are reproduced in Table A1, and the cost analysis of this system is reproduced in Table A2. Since this MCR system employs three transmitters, each rated at 800 kW (for a total of 2.4 MW average power), and 40 receive beams, it will be compared to the system labeled CC described in Table 11 and costed in Table 12. The CC system employs three independent transmitters, is rated at 600 kW average power, and employs 36 receive beams.

A detailed comparison between estimated initial-investment costs of these two systems is given in Table A3. The estimated initial-investment cost for the CC system ($18.1 million) is less than 1/2 the estimated initial-investment cost for the MCR system ($41.7 million). The large difference between these two estimates should serve to emphasize a basic assumption made throughout this report: a Type I SD OTH system would employ only low to moderate power. The use of low to moderate power results in cost savings because it permits the use of standard HF equipment and because it entails only a straightforward engineering design of the antenna arrays and associated RF equipment. This might explain a large part of the difference ($15.5 million) in the first two items (engineering labor, transmitters) of Table A3.

Another significant portion of the difference ($6.9 million) in estimated engineering-labor costs may be due to our considering the costs for research currently in progress to be sunk costs.

The difference of $5.5 million in the estimated costs for support equipment and initial spares is due to these costs being taken to be fixed percentages of the prime-mission-equipment costs; the MCR report sets this percentage at 30% whereas we have set it at 10%.

The estimated prime-mission-equipment (excluding support equipment and initial spares) costs for the MCR and CC systems are $22.6 million and $12.6 million.

The authors of the MCR report state that their estimated initial-investment cost includes such basing costs as buildings, power, heating, air conditioning, etc., (but not the costs for land acquisition), but it is not clear how this is done since these items do not appear in their chart of accounts (Cf. pp. 14-18 of Ref. A1). Perhaps these basing costs were charged to other items in some sort of a pro rata basis. This might account for several millions in the difference between their estimated initial-investment cost and ours.

Table A1
OTH Radar Characteristics Reproduced from Ref. 41

Radar Type:	Bistatic
Frequency:	7 to 30 MHz
Radar Coverage:	90° sector,
Transmitters:	One for 7-13 MHz One for 12-20 MHz One for 17-30 MHz
Transmit Array:	16 vertical monopole elements, 625 feet long
Transmit Antenna Beamwidth:	20°
Transmit Antenna Gain:	20 db
Receiver Bandwidth:	200 KHz
Receiver Antenna Gain:	23 db at 13 MHz
Receiver Beamwidth:	.6° at 7 MHz
PRF (if pulse system):	40 Hz
Scan Rate:	3° per minute
Receive Beams:	40
Receiver Array:	210 vertical monpole elements, 11,800 feet long
Transmitter Power:	800 KW Ave/Transmitter; 2.4 MW total average power
Integration Time:	20 sec.
No. of Dwells per Resolution Cell:	10

Table A2
MCR Cost Summary Reproduced from Ref. A1

RDT&E COSTS ($ million)		ACQUISITION COSTS ($ million)		ANNUAL OPERATING COSTS ($ million)	
(a) Engineering & Tests	10.0	(b) Transmitter	9.6	Pay and Allowances	1.2
		(c) Transmitter Array	0.611	Facility Support	0.5
		(d) Receiver Array	0.42	Depot Support	0.1
		(e) Receiver Processing	10.0	Equipment Mod	0.2
		(f) Displays	2.0	Replenishment Spares	0.2
		(g) Initial Spares	4.5	Retraining	0.5
		(h) Support Equipment	2.25	Miscellaneous	0.2
		(i) Training	1.0		
		(j) Communication	0.3		
		(k) Installation & Checkout	1.0		
TOTAL	10.0		31.7		2.9

Table A3
Comparison Between the Cost Analyses of the Initial-Investment Cost of the MCR System (Table A2) and NRL System CC (Tables 11 and 12)

Subsystem	MCR Items from Table A2 and Corresponding NRL Items			Cost ($ million)		
	MCR Items	NRL Items		MCR	NRL	MCR Minus NRL
		Table	Items			
Engineering labor	(a) + (k)	6	4 + 5	11.0	4.1	6.9
Transmitters	(b)	12	B	9.6	1.0	8.6
Transmit array	(c)	12	A + C + D	0.6	2.2	(-1.6)
Receive array, processing, and display	(d) + (e) + (f)	12	a + b + c + e	12.4	9.4	3.0
Support equipment, spares, etc.	(g) + (h)	12	E + d + 3	6.8	1.3	5.5
Training; communications	(i) + (j)	—*	—*	1.3	—*	1.3
				41.7	18.1	23.6

*Included in annual operating expenses.

REFERENCE

A1. "Analysis of Over-the-Horizon Radar Performance" (U), MCR-73-1007, Navy Material Command, Navy Space Project Office, PME-106, Washington, D.C., 1973 (Secret).

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