NELC/TR 1853

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NELC/TR 1853

AD-909622

SHIPBOARD VHF/UHF ANTENNA DESIGN AND UTILIZATION CRITERIA

A technique is presented for establishing height, minimum mean gain, maximum standard deviation of gain, and trade-offs

M. S. Kvigne   Research and Development   5 January 1973

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PROBLEM

Develop a technique for finding design and location criteria for shipboard vhf/uhf naval communications antennas. Document the technique so that it is possible for an antenna engineer to establish, for any particular circuit, the minimum mean antenna gain, the maximum standard deviation of the antenna gain, the height of the antennas, and the trade-offs involved. Also indicate how the information developed can be used to analyze existing systems.

RESULTS

1. Findings of this study are presented to enable the antenna engineer to establish his own design and location criteria and the associated trade-offs. See RESULTS, DESIGN FINDINGS, in the report proper.

2. The results of the design section are described and examples are presented to show how to use them in the analysis of existing circuits. See RESULTS, ANALYSIS FINDINGS.

3. Conclusions are drawn about shipboard antenna design and location. See SUMMARY AND CONCLUSIONS – SHIP TO SHIP, SHIP TO AIR, and GENERAL.

ADMINISTRATIVE INFORMATION

This report covers work done from July 1971 through August 1972 by the Radio Technology Division under SF 14.222.004, Tasks 15347B, C (NELC B164). The report was approved for publication 5 January 1973. Program Manager was H. F. Murphy, NAVSHIPS 03525. Technical adviser was R. Pride, NAVSEC 6179C03.

The assistance of J. M. Horn and R. L. Goodbody is acknowledged.

Special thanks is given to W. M. Chase and C. W. Tirrell, who provided the appendix.

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INTRODUCTION

Up to now, there has been little documented guidance on the design and location of vhf/uhf antennas aboard ship for shipboard communications links. Antenna engineers have followed a basic rule: locate the antenna as high as possible for ship-to-ship circuits, locate it as low as practical (down to 17m above the water) for ship-to-air circuits in the 225–300MHz band, and try to maintain omnidirectional patterns in all cases. This rule can lead to ineffective design and positioning of antennas, especially when trade-offs and compromises with other systems are required, with the result that the communications link may not meet its requirements or its potential. Because of these problems, there is a need to develop better design and location criteria for shipboard communications antennas.

This report develops a technique by which effective criteria for the design and location of vhf/uhf communications antennas can be found and decisions on the various trade-offs involved can be made. The technique may also serve in the analysis of present vhf/uhf antennas and circuits.

When an antenna engineer is asked to design an antenna system for a particular circuit, he is generally given a list of circuit requirements which must be met by the system as finally installed. These requirements establish range, desired grade of service, and percentage of time (time availability) the circuit is to provide the desired grade of service or better. The grade of service, time availability, and range requirements establish a baseline from which to work. To perform a complete analysis, the engineer sums the rest of the gains and losses throughout the system. To the direct losses, such as basic transmission loss, coupler losses, and cable losses, the loss biases for the statistically varying items must be added to achieve the desired time availability. The difference between the sum and the required grade of service establishes the amount of gain the antenna system must provide. However, many engineers have only vague familiarity with the values of the individual parameters for a particular link, and are likely to have almost no knowledge of the trade-offs involved. In general, the result is a design that is governed solely by the basic rule in the first paragraph. On the other hand, if an antenna engineer could be given all the parameters, he could establish effective criteria for the antennas in the system based on the fact that after system installation the net system margin (dB above the required grade of service) must be $\geqslant 0$.

The research documented here provides antenna engineers with a knowledge of the values of the parameters of the summation. In addition, a general technique for obtaining antenna design and location criteria for shipboard Navy communications circuits is developed by theoretical analysis. This work also provides information on the trade-offs involved in assigning one parameter more importance than another.

Although this effort is directed toward developing shipboard antenna design criteria, it ignores the effect of complex ship electromagnetic environment upon the receiving capability – a major item in communication system design. To get valid design results, one should consider the communication system as a whole, and an appendix is included to indicate the effect of a complex shipboard environment upon a sample receiving system. The work done for the appendix was funded under another project but is documented here because it can have a major impact upon antenna design and utilization.

PROCEDURE

The procedure followed to deduce the vhf/uhf design and location criteria is given in the following paragraphs.

1. A list of CNO qualitative requirements for vhf/uhf communications circuits is completed in terms of circuit type, frequency, range, time availability, and grade of service.

2. A mathematical model of a typical naval vhf/uhf communications circuit is set up.

3. A computer program is developed to calculate basic transmission loss between two isotropic antennas.

4. By use of the mathematical model and the computer program, predicted vhf/uhf communication system performance relative to antenna performance is determined. Total communication system performance for typical Navy vhf/uhf systems is then predicted mathematically to see whether the actual performance requirements of paragraph (1) can be met in theory.

5. By use of the mathematical model and the computer program, the effect of each individual parameter on total system performance is found. This is then documented so that an antenna engineer can develop his own design and location criteria for a particular circuit of interest. This technique is also used to deduce trade-off guidance in weighting various individual parameters.

6. All the results and work done for the design criteria are studied to see which of the developed items would be of use to an antenna engineer analyzing a current vhf/uhf antenna system. This analysis is then documented.

VHF/UHF COMMUNICATIONS REQUIREMENTS

The following requirements for Navy vhf/uhf communications were extracted from the Naval Communications Mid-Range Plan (NC-MRP-82):

FREQUENCY

vhf: 30–76MHz, 115–162MHz

uhf: 225–400MHz

RANGE

ship-to-ship: vhf and uhf, 55.6km (30nmi)

ship-to-air: uhf, 556km (300nmi)

TIME AVAILABILITY (RELIABILITY)

vhf and uhf: 99% reliability, with median outage not greater than 10 minutes in any 24-hour period, calculated on an annual basis. Maximum single outage should not exceed 30 minutes.

GRADE OF SERVICE (PERFORMANCE)

plain language:	95% voice intelligibility
secure voice:	95% voice intelligibility
data link:	10^{-5} probability of error

These requirements are desired performance objectives, but NC-MRP-82 states that they may be relaxed where the objective is not economically feasible.

COMMUNICATION SYSTEM MODEL AND MATHEMATICAL ANALYSIS

The problem of finding design and location criteria for shipboard Navy communications antennas involves many variables. Prior to mathematical analysis, the performance terminology and the system model must be defined.

PERFORMANCE TERMINOLOGY

In this study the following standard terms and their definitions are used to indicate the performance of the circuit:

1. Grade of Service: That level of signal-to-noise ratio (SNR) or binary bit error rate (ber) that provides acceptable service.

2. Time Availability: The percentage of time that an acceptable or better grade of service is provided.

3. Service Probability: The probability that the specified, or better, grade of service will be achieved for the specified time availability. Service probability accounts for the uncertainties in the values of the parameters used to predict system performance. However, in this study no attempt is made to determine the magnitudes or the distributions of these uncertainties; 50% service probability has been assumed.

SYSTEM MODEL AND OTHER TERMINOLOGY

A typical naval vhf/uhf communications link first appears as an extremely large variety of interrelated items. However, this complex network can be broken up into a set of quantized functions interconnected in a particular flow pattern. This technique of quantization was used in setting up the communication model used in this study and figure 1 shows the model's quantized flow diagram. The following tabulation is an explanation of the pertinent details of each block.

1. Transmitter Modem. Supplies the transmitter with the appropriate modulation scheme – FSK, AM, DPSK, etc. It is a nonstatistical item.

2. Transmitter. A power amplifier that is capable of supplying the transmitting antenna system with the desired power at the desired frequency with the desired modulation. It is a nonstatistical item.

3. Transmitter Line Losses. The losses associated with the signal path between the transmitter and the transmitting antenna. These include coaxial-cable losses and losses associated with terminations and coupling devices at the ends of the coaxial line. Although these items may vary on typical ships in use, they are generally considered nonstatistical and are so considered in this study.

4. Transmitting Antenna. An antenna in free space may have a pattern which is easily and clearly characterized. However, installation

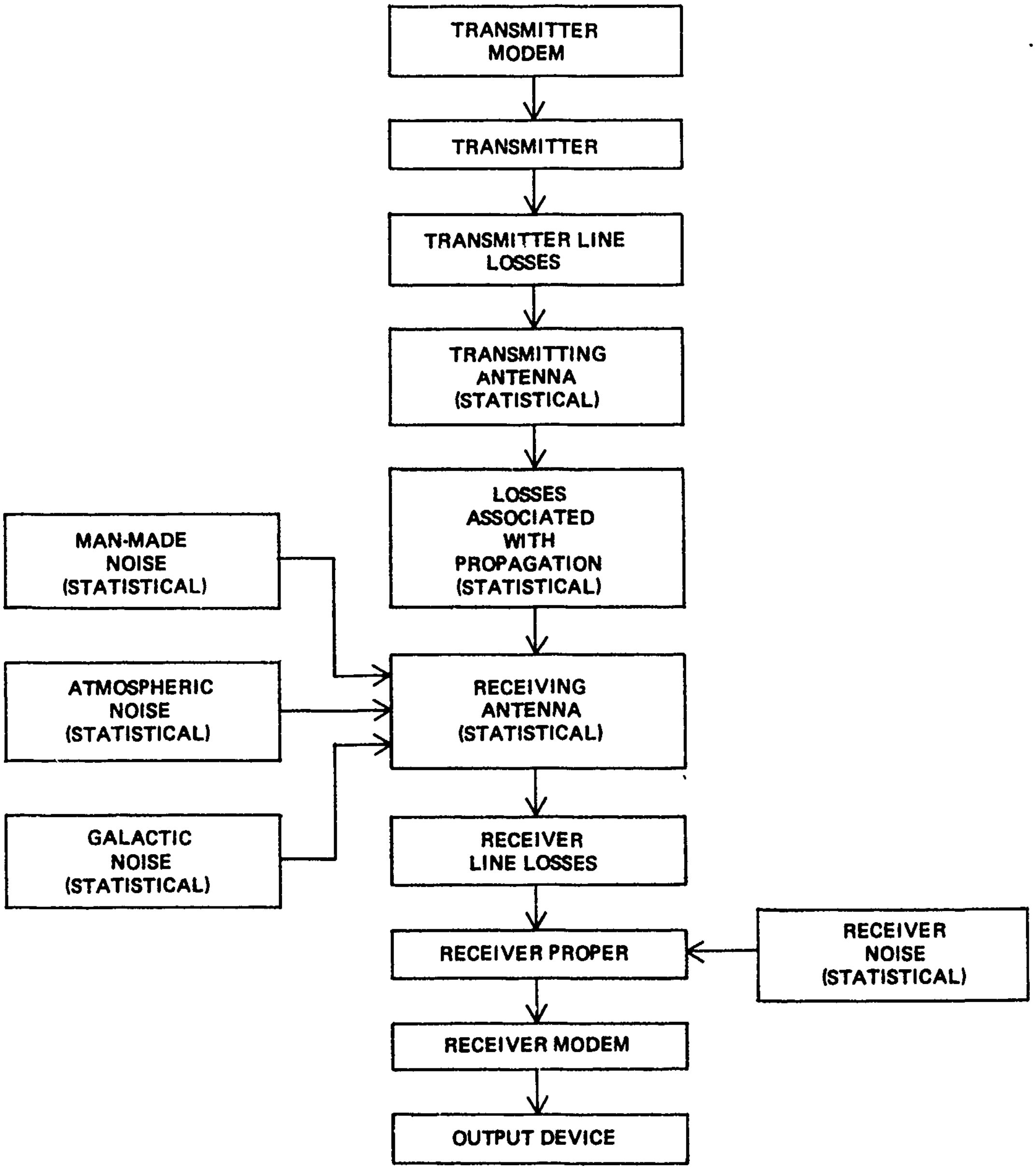


Figure 1. Communications system model.

aboard ship significantly alters this free-space pattern, and the resulting pattern is highly dependent upon location. Because of this pattern variability and the need to communicate in random directions, the transmitting antenna is characterized as a statistical device. Hence, in this study, the gain of a shipboard transmitting antenna is characterized as that of an antenna having a free-space pattern with a normal probability distribution. This is a realistic distribution and allows the antenna to be specified by its mean and standard deviation.

5. Basic Transmission Loss. In this study we employ the definition of basic transmission loss L_b given by Norton. Formally it is defined as

$$L_b = 10 \log_{10} \left(\frac{P_{ti}}{P_{ri}} \right) , \qquad (1)$$

where P_{ti} is the power transmitted by an isotropic radiator and P_{ri} is the power received by an isotropic receptor. Essentially, L_b is the loss the signal suffers while traveling between the transmitting antenna and the receiving antenna. This loss is dependent upon antenna aperture effects, basic free-space loss effects, the effects of direct and reflected waves, and surface-wave effects. Figure 2 shows the geometry used in making the calculation of L_b. L_b must be considered a statistical item because the sum of the direct, reflected, and surface waves is dependent upon atmospheric refractivity, and atmospheric refractivity varies greatly with time and position on the earth. Typically, the variations in L_b may be considered to be normally distributed with respect to time and have a standard deviation which is generally less than 5dB.

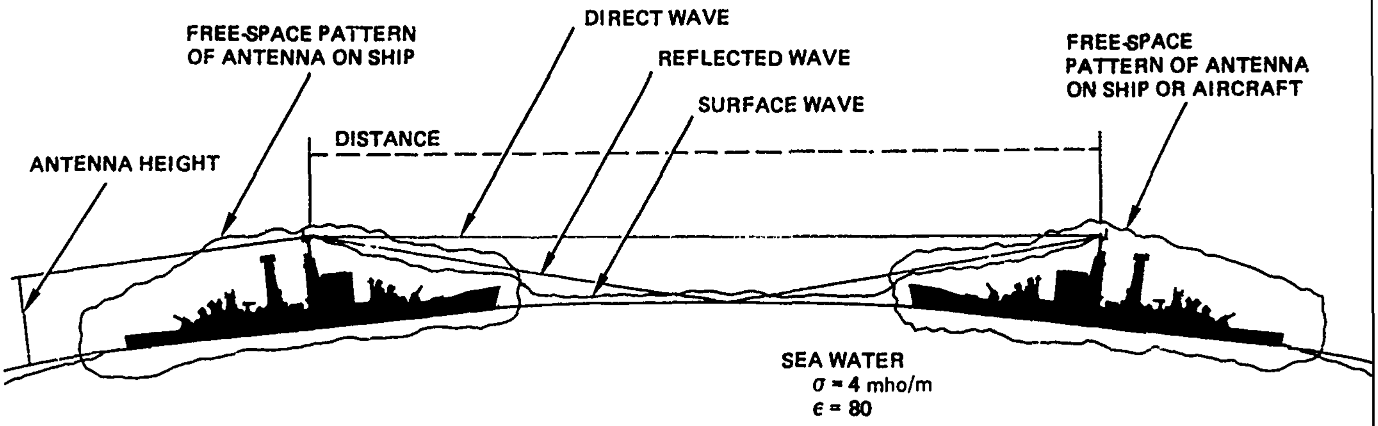


Figure 2. Geometry used to make calculations.

6. Noise. In this study noise is defined as any undesired power in the output. There are many sources of noise, and the characteristics of those that are of interest to this work are briefly covered in the following paragraphs:

> a. Man-made noise: Any signal power other than naturally generated and that is not the desired signal. This signal power may include interference from intermodulation products, other transmitters, etc., and hence may have a large mean value and a large amount of variation (see appendix). In a well designed system this type of noise is negligible, but in a poorly designed system it may be of major concern.
>
> b. Atmospheric Noise: Noise generated by natural causes in the atmosphere. The mean value of atmospheric noise falls off as frequency increases and, in general, its standard deviation is small at vhf and uhf. Atmospheric noise is important at the lower vhf frequencies where its mean value is greatest.
>
> c. Galactic Noise: Noise generated by natural causes in the galaxy, excluding earth sources. It is important only at the lower vhf frequencies and, in general, is not highly variable.
>
> d. Receiver Noise: Noise generated in the receiver. Receiver noise has a relatively constant average value, but may have a slight long-term variation resulting from improper receiver maintenance.

In this study, the particular source of noise is not important, but the magnitudes of the average value and standard deviation of the total noise power are of extreme importance. Hence, noise is considered a single parameter which is a summation of power from all sources. This single parameter has a probability distribution that can be represented as falling off approximately normally for values above the mean. Thus, for this model, noise may be considered to have a mean value and a standard deviation. In a well designed system for ships, it is felt that a reasonable value for the standard deviation of the noise is 4dB. This standard noise deviation will increase in less well designed systems.

7. Receiving Antenna. An antenna that receives the transmitted signal. It has the properties of the transmitting antenna characterized in paragraph 4. In addition to the attenuated transmitted signal, the receiving antenna receives noise and interference.

8. Receiver Line Losses. The losses listed in paragraph 3 are present in receiver lines. However, the losses in this case are associated with the system between the receiver and the receiver antenna. The receiver line loss is generally a nonstatistical item.

9. Receiver Proper. Essentially a narrow-bandpass amplifier, with amplification occurring at radio and intermediate frequencies. The receiver is generally a nonstatistical item.

10. Receiver Modem. Demodulates the received signal and converts it into useful information. It has some probability of error depending upon the SNR applied to the device.

11. Output Device. Displays the received signal in the desired fashion.

MATHEMATICAL ANALYSIS

The basic mathematical technique used to find vhf/uhf antenna design and location criteria is quite simple. However, the calculation of some of the parameters is involved and requires a digital computer.

Definition of the following terms is essential to the explanation of the mathematical technique.

P_T	Transmitter power in dBW
P_{LT}	Transmitter line losses in dB
G_{AT}	Mean free-space shipboard transmitter antenna gain in dB above isotropic
L_B	Basic transmission loss in dB
G_{AR}	Mean free-space shipboard receiver antenna gain in dB above isotropic
N_T	Mean total noise power in dBW
P_{LR}	Receiver line losses in dB
B(TA)	Bias needed to achieve the desired time availability (TA) in dB
GS	Grade of service

These are the terms used in establishing antenna design and location criteria. By summing these terms according to equation (2), the grade of service for a circuit can be established. The crux of the study is to establish from

$$P_T - P_{LT} + G_{AT} - L_B + G_{AR} - N_T - P_{LR} - B(TA) \geqslant GS, \qquad (2)$$

equation (2), a technique for finding shipboard antenna design and location criteria that will be a combination of necessary mean antenna gain, maximum permissible standard deviation of antenna gain, and minimum antenna height. Once the criteria are found, they can be used to establish requirements for location of antennas with respect to masts and other topside structures.

Some of the terms in equation (2) are established directly from circuit requirements (for example, GS) and transmitter and receiver specifications, and others are indirectly established. For most circuits, time availability coupled with circuit statistics leads to B(TA); N_T is generally established by the type of receiver or the limiting noise source; P_T is established by the transmitter; and P_{LT} and P_{LR} are established by the types of networks connecting the receiver or transmitter to the antenna. When all these things are known, the only items left to specify are the antenna heights, the mean gain of each antenna, and the standard deviation of the gain of each antenna. If these are specified so that for a particular physical arrangement the predicted grade of service is greater than or equal to required grade of service, antenna design and location criteria have been generated.

The term B(TA) should be explained in greater detail. As stated, many items in the model shown in figure 1 are statistical. If one desires to have a high percentage of confidence in the predicted grade of service, one must add a bias protection factor to overcome these statistical variations. The bias depends on the percentage of confidence, which is the same as the percentage of time the circuit is available, and the random variable chosen to represent the time-varying items in the model. For the communications model of this study, the random variables are assumed to be represented by independent normal probability distributions in the region of interest. Under these conditions, the random variable describing the whole circuit is normally distributed with a mean which is the sum of the individual means and a standard deviation that is the square root of the sum of the squares of the individual distributions. Hence, B(TA) can be represented by equation (3); σ_B is the standard deviation of the random variable representing the whole circuit and is given by equation (4). D(TA) is the standard normal deviate for the desired TA.

$$B(TA) = \sigma_B \, D(TA). \tag{3}$$

$$\sigma_B = \sqrt{\sigma_{AR}^2 + \sigma_{AT}^2 + \sigma_N^2 + \sigma_L^2} \tag{4}$$

where:

σ_{AR} = Standard deviation of receiver antenna free-space gain

σ_{AT} = Standard deviation of transmitter antenna free-space gain

σ_N = Standard deviation of the noise power

σ_L = Standard deviation of the basic transmission loss

The effects of B(TA) are discussed in greater detail in RESULTS, DESIGN FINDINGS.

At this point, a simple example will illustrate the technique for finding criteria and establishing trade-offs. Suppose the requirement exists for a 400MHz circuit with a 10dB grade of service for two ships 50km apart with fixed antenna heights of 30 meters. The circuit is to be available 85% of the time, the transmitter puts out 100 watts, the receiver is internally noise limited with a noise level of −140dBW, the line losses for each system are 3dB, and the transmission loss and total noise have standard deviations of 4dB each. It is desired to establish the mean gain, maximum standard deviation, and associated trade-offs for both antennas. Proceeding with the analysis, one begins to identify the values of terms in equation (2):

$$GS = 10\text{dB},\ P_{LT} = 3\text{dB},\ P_{LR} = 3\text{dB},\ N_T = -140\text{dBW, and } P_T = 20\text{dB}.$$

This leaves G_{AT}, G_{AR}, B(TA), and L_B unknown. A computer algorithm is developed that tells us that L_B for this geometry is 141dB. Then we have only the unknowns to solve for. Inserting these values into equation (2) yields equations (5) and (6).

$$20 - 3 + G_{AT} - 141 + G_{AR} + 140 - 3 - B(TA) = 10. \tag{5}$$

$$3 + G_{AR} + G_{AT} - B(TA) = 0. \tag{6}$$

B(TA) can be found from equation (3). For 85% time availability, the standard normal deviate is approximately unity, so B(TA) can be represented by equation (7).

$$B(TA) = 1\,\sigma_B = \sqrt{4^2 + 4^2 + \sigma_{AT}^2 + \sigma_{AR}^2}. \qquad (7)$$

Coupling this back into equation (6) yields equation (8), an expression which determines the antenna design criteria and the associated trade-offs.

$$3 - \sqrt{32 + \sigma_{AT}^2 + \sigma_{AR}^2} + G_{AR} + G_{AT} = 0 \qquad (8)$$

Since there are more unknowns than equations, the solution to these unknown terms is not unique; hence, the object is to choose solutions that yield physically realizable devices. In this case, one solution: if $\sigma_{AT} = \sigma_{AR} = 0$, $G_{AT} = -3\text{dB}$, and $G_{AR} = +\sqrt{32}$. Since $\sigma_{AT} = \sigma_{AR} = 0$ implies a perfectly omnidirectional antenna (which is difficult and expensive to develop), a better choice may be $\sigma_{AT} = \sigma_{AR} = 3\text{dB}$, and $G_{AT} = G_{AR} = 1/2\,(\sqrt{50} - 3) = 2.03$. There are many such possible solutions and there are many trade-offs to be made.

The previous example shows that it is possible to find antenna design and location criteria for every circuit by following the technique illustrated. However, the procedure is tedious and somewhat difficult to execute longhand. A computer can be used to perform the calculations, but although the procedure effectively simulates the system, the problem of how to present the data remains.

It was decided that a better method than presenting just the absolute design criteria for each Navy communication circuit would be to record the results so that an engineer could determine his own criteria for a particular circuit and understand all the ramifications. It was felt that the best way to do this was to record in graphical form the computer output data needed to find each term in equation (2) for all reasonable physical geometries. This method of presentation allows the engineer to understand the circuit and make trade-offs effectively without needing to run a computer program.

It was therefore decided to use a digital computer to aid in simulating the total circuit. By keeping all circuit parameters constant except one, and incrementing that constant through its range, the effect of the parameter was determined. This technique was particularly useful in finding the effect of various parameters on basic transmission loss.

Two computer programs for calculating basic transmission loss were investigated. The first was developed recently by a U.S. Government agency to simulate vhf and uhf communication circuits. It follows closely the analysis of Longley and Rice [1968] and Rice et al [1965]. This program includes all the terms in equation (2) and simulates the whole circuit. However, upon closer investigation, it was found to be excessively optimistic in its basic transmission-loss calculation for line-of-sight paths. Because of this optimism, a second program was considered – that of Berry and Chrisman [1965], of ESSA. It solves an integral for the field strength of the signal above a spherical earth by using one of three techniques, depending upon the geometry of the path. A saddle-point solution is used in the visible region, complex numerical integration in the penumbra, and a residue solution in the deep-shadow region. The field-strength solutions have been checked against Norton's curves [Barrick, 1970] and CCIR solutions [CCIR, 1955], and the results agree.

A comparison of actual measured loss over sea water with values computed by the above two methods was made by Cullen [1969]. The comparison indicates that the Berry and Chrisman method produces better results. For this reason, the method of Berry and Chrisman was chosen to calculate L_B in equation (2). However, before use in the present study, the Berry and Chrisman program was modified to calculate basic transmission loss as defined in equation (1), and several plotting options using a Calcomp plotter were incorporated.

RESULTS

The results of this study are presented in two sections, DESIGN FINDINGS and ANALYSIS FINDINGS, and each of these sections is further divided into two types of circuit links – ship to ship and ship to air. In the design section, an attempt is made to present the findings in a manner that will allow an antenna engineer to establish his own design and location criteria and the associated trade-offs. This is done by discussing the variation of each term in equation (2), or the pertinent circuit parameters and their effect upon the final system performance. An example is then covered for each circuit type which illustrates how to use the data.

In the analysis section, the results of the design section are discussed and examples presented to illustrate how to use these findings to aid in the analysis of existing circuits.

DESIGN FINDINGS

While trying to find design criteria for an antenna on ship, an antenna engineer must consider antenna gain as a random variable. This arises because (1) any antenna will have pattern variation, (2) communication is equally probable in any direction, and (3) the direction is time-varying. A reasonable approximation to the probability distribution of the gain is the normal distribution characterized by a mean and standard deviation. It is the goal of the antenna engineer to define the bounds of the mean and standard deviations of the distribution data. This section provides the data necessary to do this.

SHIP TO SHIP

The range of parameters of interest values can be obtained from physical constraints and circuit requirements. In the ship-to-ship case, range is less than 60km, frequencies are between 30 and 400MHz, antenna heights are limited to less than 60m, and transmitter power is less than 1000 watts.

BASIC TRANSMISSION LOSS. Calculations of basic transmission loss over sea water were performed by the Berry and Chrisman method for vertical polarization, a relative dielectric constant of 80, conductivity of 4mho/m, and smooth sea. The calculations were performed for intermediate receiving and transmitting antenna heights (30m) as a function of distance for the upper and lower frequency in each band of interest. The results are presented in figure 3. Only vertical polarization is presented, because the basic transmission loss for horizontal polarization is too great to make its use of any practical interest for the ranges and frequencies involved here.

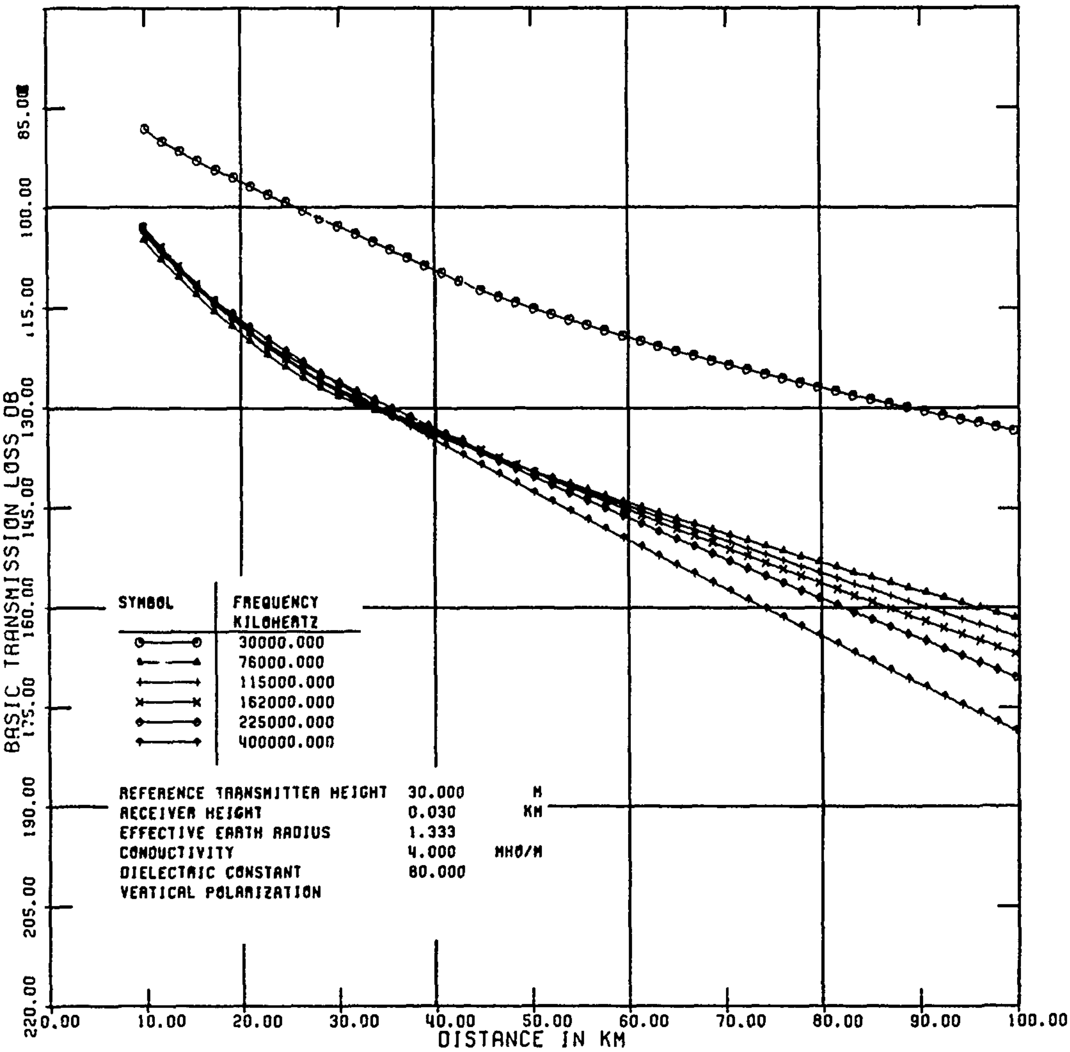


Figure 3. Basic transmission loss over sea water for 30m transmitter and receiver heights.

For heights other than 30m, a loss correction value must be added to the value shown in figure 3. Beyond about 25km, the correction for height is almost independent of distance for antenna heights less than 60m. The calculated correction values for other antenna heights are shown in figure 4, with one plot for each frequency. The plots are accurate to within 1dB. Linear interpolation can be performed between the curves for other frequencies and interpolation can be performed on the curves for other heights, with reasonably accurate results. It may also be noted that above a certain critical height, the height correction value is almost independent of frequency. Below this critical height, the height correction value is almost zero. A plot showing the critical height as a function of frequency is shown in figure 5.

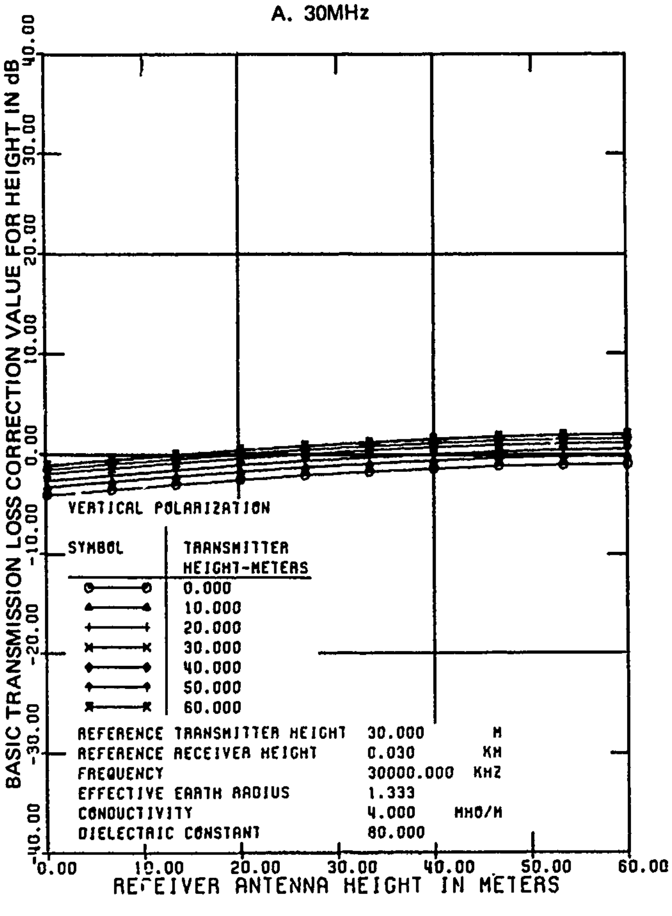


Figure 4. Loss correction values for other shipboard antenna heights.

B. 76MHz

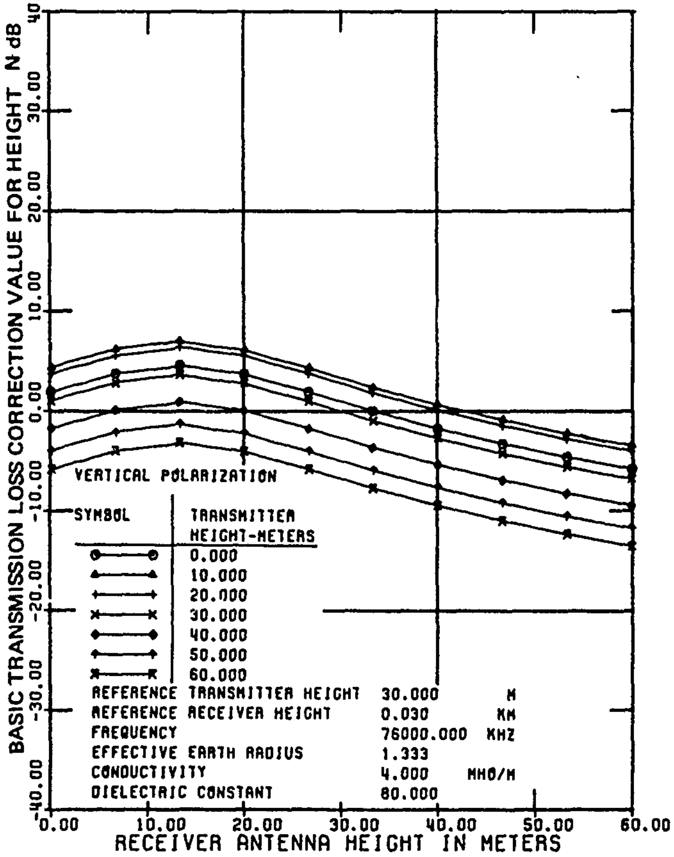
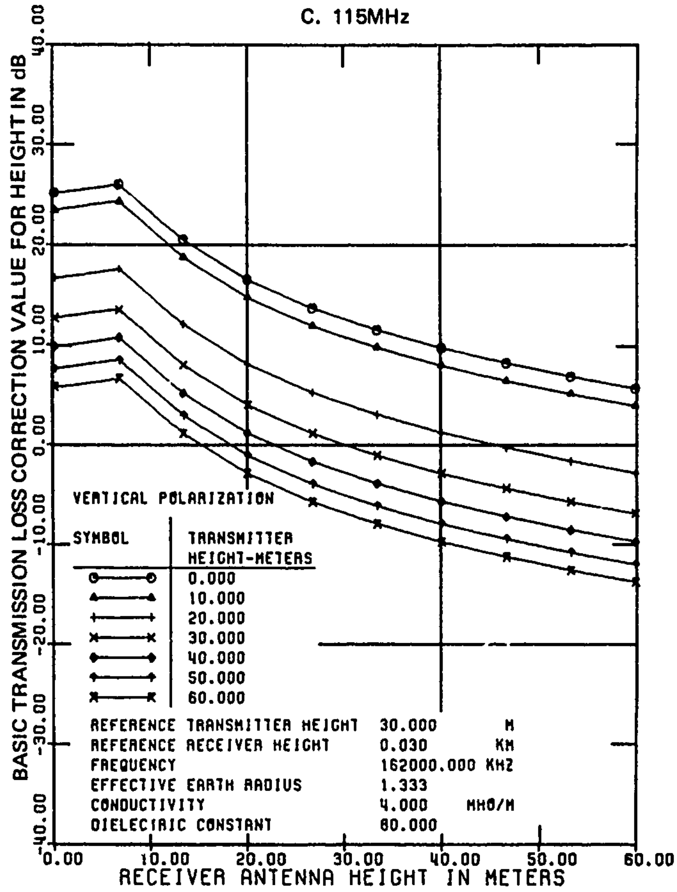
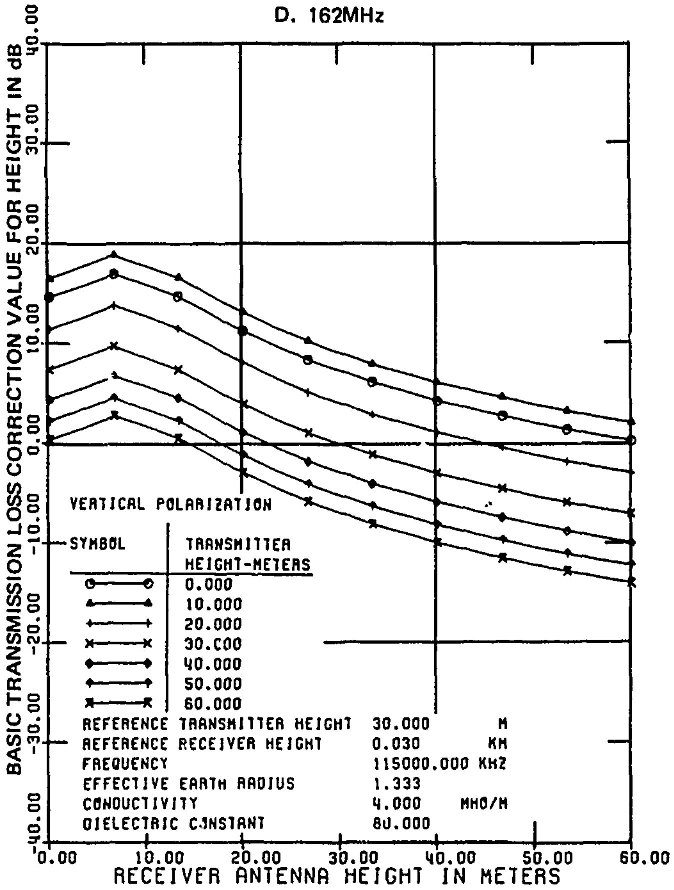


Figure 4. (Continued)



C. 115MHz

Figure 4. (Continued)



D. 162MHz

Figure 4. (Continued)

E. 225MHz

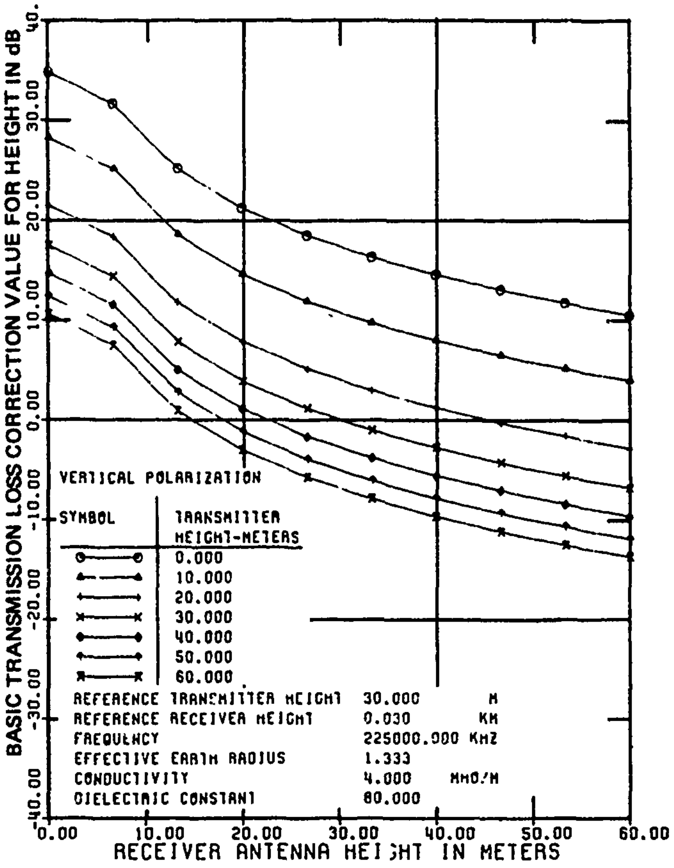


Figure 4. (Continued)

F. 400MHz

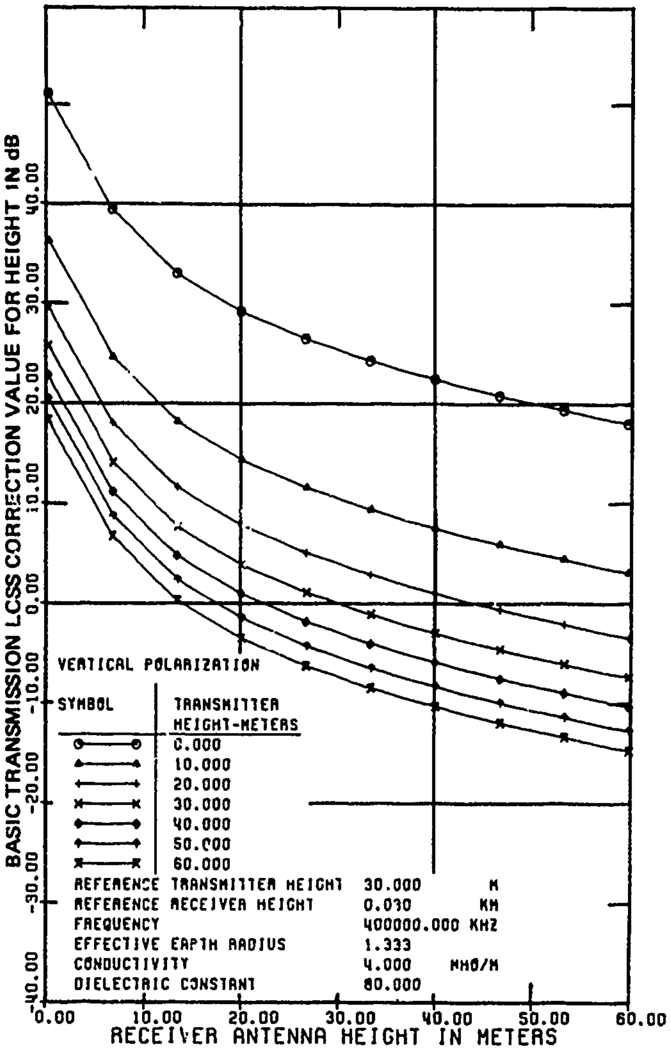


Figure 4. (Continued)

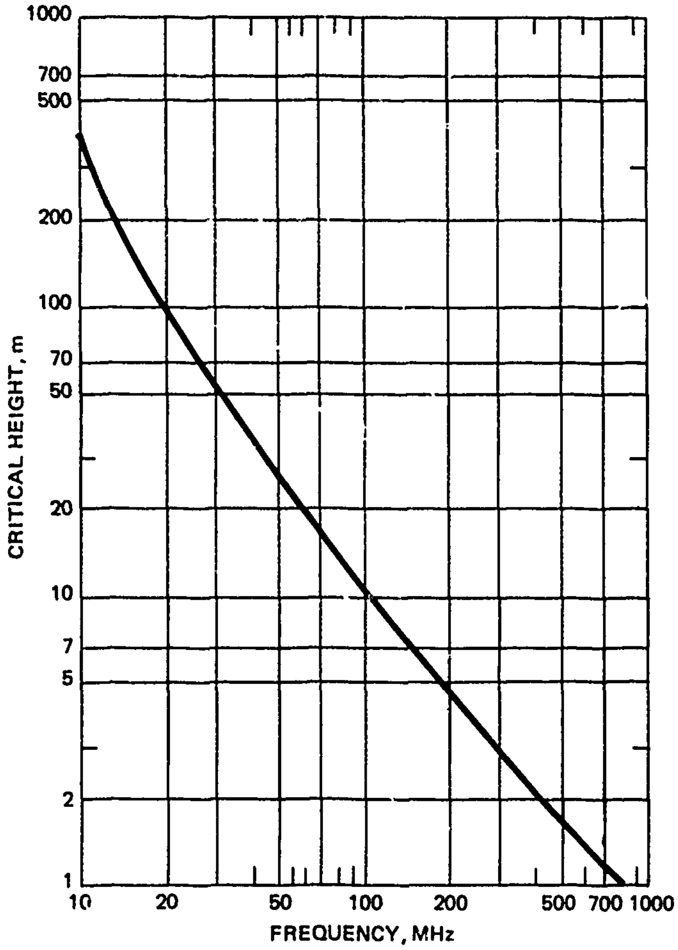


Figure 5. Antenna critical height.

The effect of frequency on basic transmission loss for a given set of parameters can also be determined from figures 3 and 4. This can be done by using these curves to calculate the loss for a given distance and pair of heights, and then plotting the loss versus frequency. An example of such a plot is shown in figure 6.

The variability of basic transmission loss can be broken down into two items: long-term power fading and short-term fading. Short-term fading is associated with tropospheric scatter propagation and multipath propagation. Diversity techniques other than polarization diversity [CCIR, v. II, 1970] can be used to combat this type of fading. However, for the distances and power in Navy ship-to-ship communications, scatter propagation presents basic transmission loss so great it is of no interest.

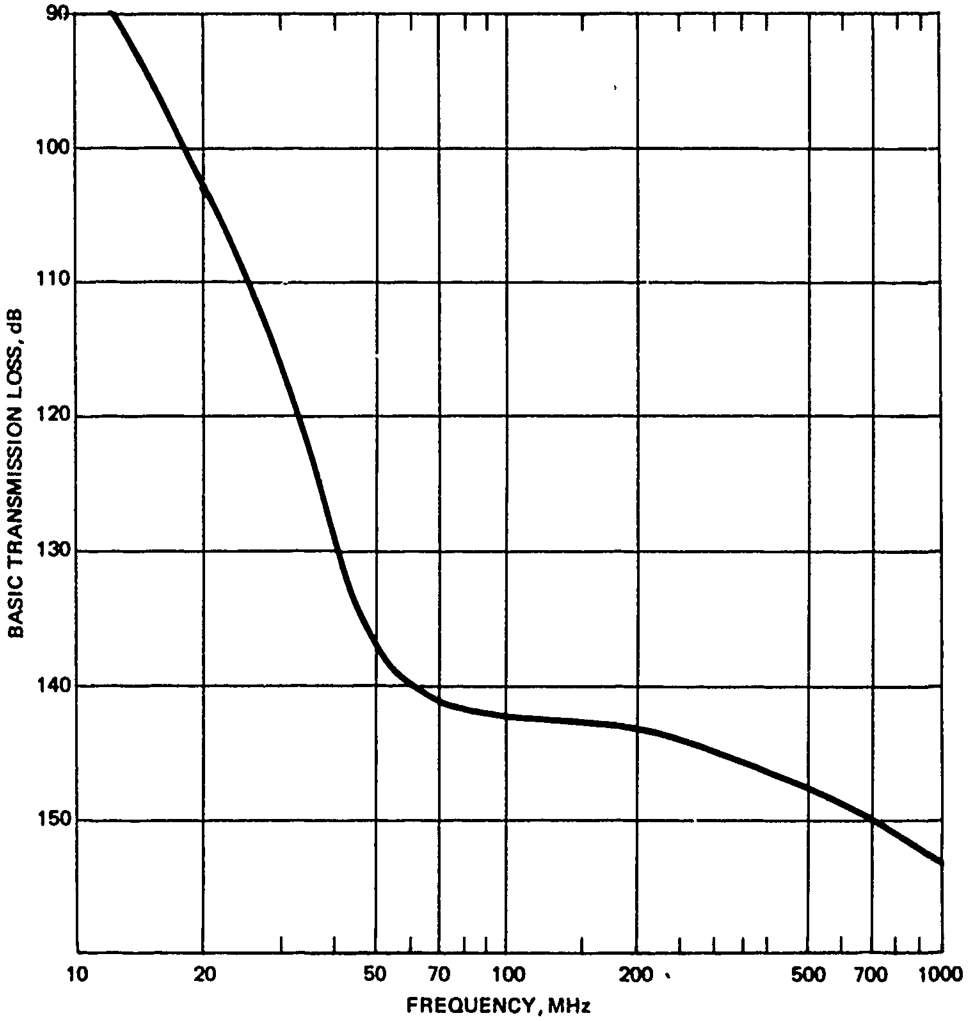


Figure 6. Basic transmission loss as a function of frequency for fixed geometry – 55.6 km separation, 30m antenna heights.

The fading of interest is long-term power fading. Long-term power fading is caused by changes in the atmospheric refractive index [CCIR, v. II, 1970], and cannot be countered by diversity techniques. According to Longley and Rice [1968], the average long-term sea-level atmospheric refractivity varies from 300 to 390 for all the world seas. In addition to this average variance, the daily variation may be as high as 90 [CCIR, v. II, 1970]. Using 300 and 390, a 50km distance, antennas at 30m, and a frequency of 400MHz, the computer calculation (Berry and Chrisman method) indicates the basic transmission loss changes from 143 to 141dB. This calculation assumes the refractive index has the same linear height profile all along the path and thus eliminates the possibility of ducting or any associated phenomena that could potentially increase the variation of the above calculations. Detailed empirical data indicate greater variation than the above sample calculations indicate [Rice et al, 1965]. Because of the above, it is felt that it is reasonable to consider the variability of the basic transmission loss to be normally distributed with a standard deviation of 3dB.

TRANSMITTER POWER AND LINE LOSSES (P_T, P_{LT}, P_{LR}). The values of these terms are calculated from parameters of specified equipment in the communication circuit. P_T is determined by calculating the power of the specified transmitter in dBW. Currently the maximum power capability in the uhf and vhf bands is 1000 watts, but most transmitters transmit less than 100 watts. If the power budget is being calculated on a per-tone basis for a multitone system, the effective transmitter power must be reduced according to the results of Smyth Research Associates [1965].

Line losses are calculated from line length, specified types and numbers of connectors used, loss per unit length, and multicoupler or tuner losses. These losses can vary from installation to installation and are to some degree a function of antenna height. A typical multicoupler loss is less than 3.0dB, and typical line lengths are on the order of 30 meters for both transmitter and receiver. Loss per unit length for various types of cable used in these frequency bands is shown in table 1 along with the insertion loss for various multicouplers. Table 1 indicates that a typical value of P_{LT} or P_{LR} s between 2 and 5dB.

TABLE 1. INSERTION LOSS OF CABLES AND MULTICOUPLERS, dB.

Freq Device	50MHz	225MHz	400MHz
30.48m of 1/2" Spir-O-Foam 331/v cable	0.55	1.22	1.71
30.48m of 1-5/8" Heliax HJ7 - 50A	0.15	0.3	0.42
30.48m of RG - 17	0.62	1.8	2.5
30.48m of RG - 9		3.1	4.4
30.48m of RG - 214		3.6	5.1
AN/SRA-33 multicoupler	not applicable	less than 3.0	
AN/SRA-60(V) multicoupler	less than 2.4	not applicable	
CU-1559/SRC multicoupler	not applicable	less than 1.3	

MEAN TOTAL NOISE POWER (N_T). This is the total average noise power contributed by man-made noise, atmospheric noise, galactic noise, receiver noise, and antenna thermal noise. This summation is performed by equations (9) and (10)

$$N_T = 10 \log_{10} \left(N_A + N_G + N_M + N_R \right) + 10 \log_{10} B \qquad (9)$$

$$N_R = 10^{(\log_{10} KT + N_F/10)} = 10^{(-20.4 + N_F/10)} \qquad (10)$$

where:

N_A = Atmospheric noise in W/Hz

N_G = Galactic noise in W/Hz

N_M = Man-made noise in W/Hz

N_F = Noise figure of receiver

K = Boltzmann constant = 1.38×10^{-23} joule/K

B = Noise bandwidth of the system in Hz

T = Absolute temperature of the antenna (generally assumed to to be 288K so that KT = -204dBW)

N_R = Receiver noise in W/Hz

N_A and N_G may be found by using figure 7 and converting to W/Hz. In general, N_A and N_G are small with respect to the other noise powers. Figure 7 also indicates the large variation in N_A at the lower frequencies. B and N_F can be found from the receiver specifications.

In general, one of the powers from the various noise sources dominates the total, and the other sources may be considered negligible. For vhf/uhf receivers in Navy use, this dominant source is generally assumed to be N_R. However, with the ever increasing number of communication circuits on ship, it is speculated that man-made noise in these bands may be increasing above receiver noise. In this case, N_M cannot be considered negligible and must be included in the summation. One should see the appendix for the impact of items which were considered in a sample multicircuit situation and use judgment to determine how these items will impact on N_M in the design under consideration. Doing this, one can see that N_M may be the dominant term.

PROTECTION BIAS B(TA). Protection Bias takes into account antenna pattern nulls, variations in basic transmission loss, and variations in noise power. In vhf/uhf communications, each of these random variables may be considered to be normally distributed with zero mean. In the design case, one can say that these variations are uncorrelated, since the random

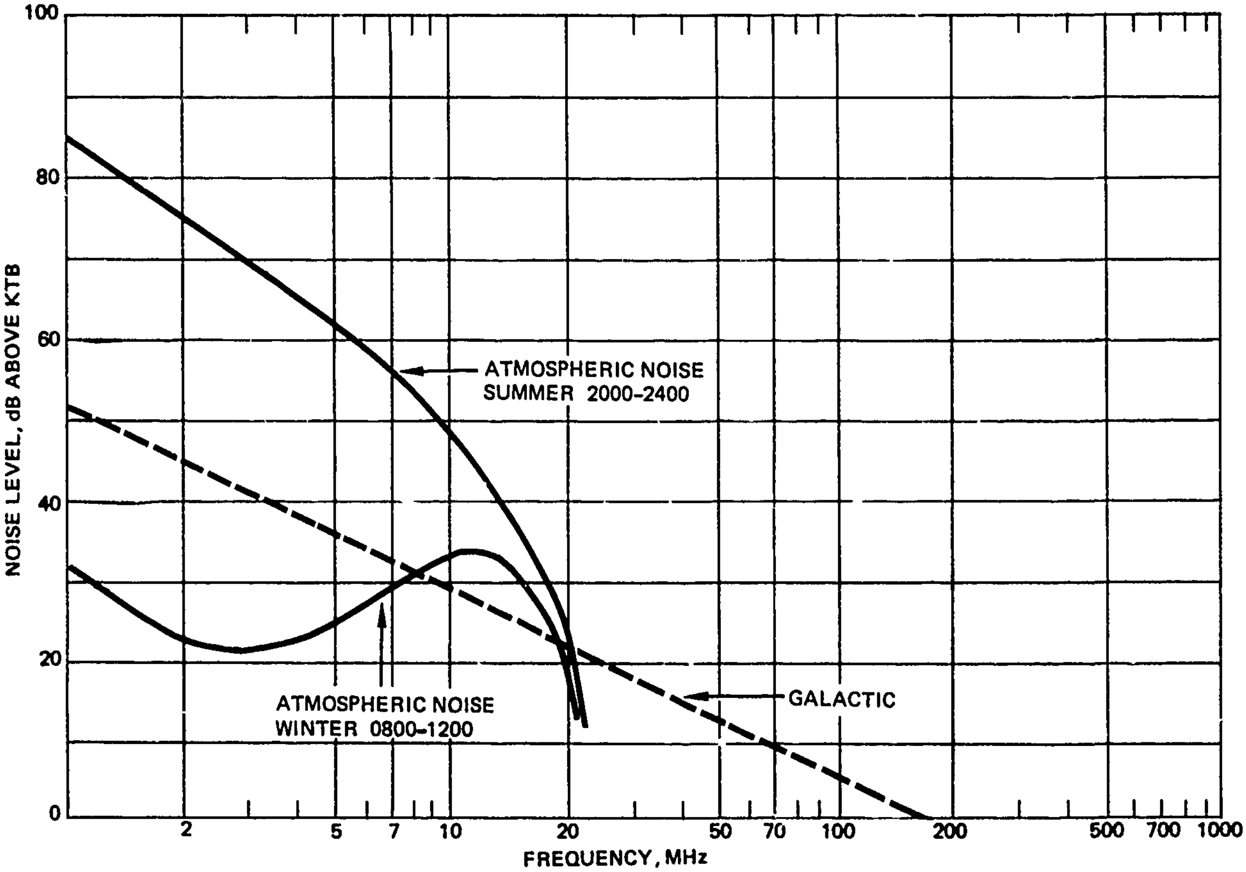


Figure 7. Expected noise levels of atmospheric and galactic sources, dB above KTB.

variables are completely independent. This is the same as saying that there is low probability that the following circumstances will occur simultaneously: the gains of each antenna are minimum, the transmission loss is maximum, and the noise level is maximum. Since each random item has been assumed to be normally distributed, the random variations of the whole circuit are randomly distributed, with a standard deviation, σ_B, which is the square root of the sum of the squares of the standard deviations of the individual distributions. If the distributions are correlated, the same result holds, except that some provision must be made to include the correlation function in the calculation of the standard deviation.

To calculate B(TA), one must find the standard normal deviate for the desired time availability and multiply it by σ_B as calculated by equation (4). Some representative values of the standard normal deviate are given in table 2. B(TA) can be found from equations (3) and (4) or from equation (4) and figure 8. As pointed out previously, representative values of σ_N and σ_L are 4 and 3dB, respectively. These values are representative, and, although not always true, may be used if no other information is available. σ_{TA} and σ_{RA} are unknowns and must be determined to establish design and location criteria. Depending upon the desired time availability and the variability of statistical items, the magnitude of B(TA) can take on very large positive or negative values, and it is always zero for 50% time availability.

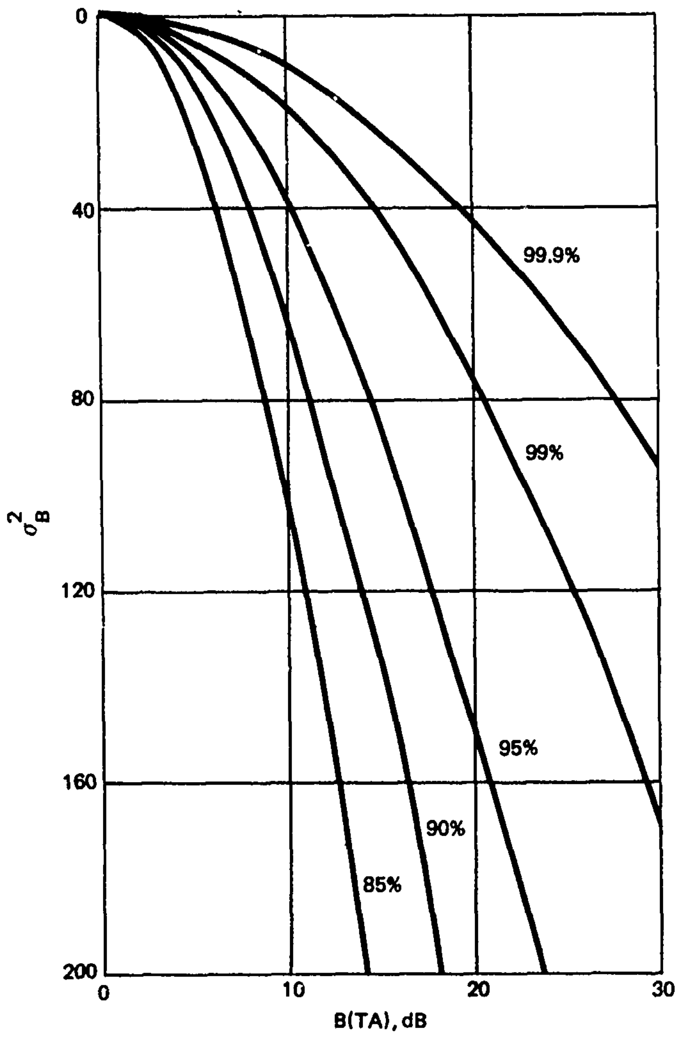


Figure 8. Protection bias as a function of time availability and σ_B^2.

TABLE 2 TIME AVAILABILITY AND STANDARD NORMAL DEVIATE.

Time Availability (%)	Standard Normal Deviate
1.00	-2.327
15.87	-1.000
50.00	0.000
60.00	0.253
70.00	0.524
80.00	0.842
84.13	1.000
95.00	1.645
99.00	2.327
99.90	3.09

EXAMPLE. Previous to this point, the method for establishing the value of each term in equation (2) has been covered except for finding the average gain of the antenna, antenna height, and the standard deviation of the antenna gain. An example illustrates the technique and trade-offs involved in finding these values [instruction manuals].

The hypothetical problem is to design an antenna system for a communications link that has a range requirement of 55.6km (30nmi), a 10dB SNR grade of service, an AN/SRC-31 transceiver, a CU-1559/SRC multicoupler, and a 99% time availability requirement.

It is necessary initially to establish the values of the parameters in equation (2) from the requirements and the equipment specifications. P_T is 30dBW, because the AN/SRC-31 has a 1000W capability. The insertion loss of the CU-1559/SRC is 1.3dB. P_{TL} = 1.3dB plus cable losses = P_{RL}. Since nothing is known about the length of cable, assume the cable losses on both ends are 2dB. This is a conservative estimate. Thus, $P_{TL} = P_{RL} = 3.3$. Assume the system is internally noise-limited, which, from specifications, indicates -147dBW. From the requirements, GS = 10dB SNR. The standard normal deviate is 2.3, so equation (2) yields equation (11).

$$30 - 3.3 + G_{AT} - L_B + G_{AR} + 147 - 3.3 - 2.3\,(\sigma^2_{AT} + \sigma^2_{AR} + 25)^{1/2} = 10. \qquad (11)$$

The range requirement and frequency range establish some bounds for L_B. Figure 3 indicates the loss is 142dB for 30m antenna heights and 400MHz. For any other height, the loss must be corrected by the height correction value, HF, from figure 4F. Under these conditions, equation (11) becomes equation (12). Now the values of the unknowns must be chosen so that equation (12) is satisfied.

$$HF + 18.4 + G_{AT} + G_{AR} - 2.3\,(\sqrt{25 + \sigma^2_{AT} + \sigma^2_{AR}}\,) = 0. \qquad (12)$$

Assuming the antennas can be well designed and located, let us choose $\sigma_{AT} = \sigma_{AR}$ = 3dB. Then equation (12) yields equation (13).

$$HF + 18.4 + G_{AT} + G_{AR} - 15.1 = 0. \qquad (13)$$

One can make trade-offs and further choices, if the heights are left at 30 meters. Then HF = 0, and $G_{AT} = G_{AR}$ = -1.6dB is a solution. Another solution is $HF = 0 = G_{AT} = G_{AR}$, which leads to $\sigma^2_{AT} + \sigma^2_{AR} = 39.0$.

TRADE-OFFS. As can be seen from the previous two examples, there are many trade-offs that must and can be made. Some of the important ones and their ramifications are covered in the following paragraphs:

1. Antenna height has little effect upon basic transmission loss at the low vhf frequencies. This is seen from figure 4A. In fact, the basic transmission loss is less at the lower heights.

2. Antenna height has a large effect upon loss at frequencies above 100MHz. However, at uhf frequencies, much greater benefit is gained by raising the antennas from 0 to 30m than from 30 to 60m.

3. Also, at the higher antenna heights, the increased cable loss due to greater length tends to reduce even further the small benefits gained from larger heights.

4. For antenna heights greater than 20m above the sea surface and the ranges of interest, loss increases with increasing frequency from 30 to 76MHz and is substantially constant from 76 to 400MHz.

5. The trade-offs for time availability, etc., can be seen from figure 8, which shows the bias needed to give the indicated time availability for various values of σ_B^2 . To understand how this plot is of use, consider the previous example, except that the time availability and grade of service have not been specified, and the antennas have an average gain of 0dB. Thus, the only unspecified items are those having to do with the random variables – the amount that can be taken up by grade of service and bias for time availability. In this case, there is 28.4dB of margin available. If 14.4dB is allocated to grade of service, then 14dB is left for bias. In figure 8, this is represented by a vertical line at 14dB. For 85% time availability, σ_B^2 can be 196, but for 99% time availability, it can be only 37, a considerably more stringent requirement. If desired grade of service requirement is relaxed to 8.4dB, then σ_B^2 is 400 for 85% and 76 for 99%. Thus, for 85% time availability, reducing σ_B by 6dB results in a grade of service improvement of 6dB, but for 99% reducing σ_B from $\sqrt{76}$ to $\sqrt{37}$, or by 2.6dB, also improves GS by 6dB. This indicates that small variations in σ_B (and thus small variations in any of the terms comprising σ_B) are very much more important for the high time availabilities (>85%) than for the medium time availabilities (50 to 85%).

There is also a trade-off in relative importance in the terms comprising σ_B^2. Suppose, for instance, that σ_N is large due to some type of man-made interference, say 12dB, $\sigma_L = 3$, $\sigma_{AR} = \sigma_{AT} = 6$, and TA = 85%, and we would like to know the effects of decreasing each antenna standard deviation from 6 to 2. Doing this results in a system gain $(12^2 + 3^2 + 6^2 + 6^2)^{1/2} - (12^2 + 3^2 + 2^2 + 2^2)^{1/2} = 2.3$dB. Now if the same calculation is done with $\sigma_N = 5$, the result is $(5^2 + 3^2 + 6^2 + 6^2)^{1/2} - (5^2 + 3^2 + 2^2 + 2^2)^{1/2} = 4.1$dB, a greater system benefit than when $\sigma_N = 12$dB. This shows that the relative importance of reducing the value of certain terms in equation (3) is highly dependent upon the value of the other terms in general. For any considerable effect, the term being reduced must be greater than or equal to the next largest value.

SHIP TO AIR

Design and location criteria for shipboard antennas for ship-to-air circuits can be found by following essentially the same approach as that taken in the previous section. However, in this case the range requirements are much greater, and one of the antenna heights has a much larger variation.

Since this study is directed primarily at shipboard antennas, it is assumed that the characteristics of the airborne communications system are fixed and easily obtainable. For the purposes of this discussion on design criteria, the following assumptions are made about the system:

1. The airborne receiving system is similar in electrical characteristics to the shipboard system

2. The random variable can be represented by the same type of probability distributions as in the ship-to-ship case

3. The airborne antenna system is assumed to have a 0dB mean gain and a 4dB standard deviation

4. Noise has a 4dB standard deviation

5. The basic transmission loss has a 5dB standard deviation because of the greater distances involved.

These values are chosen for the discussion because it is felt they are representative. However, they may be different, and it is felt that after the following discussion the results may be adjusted to reflect any differences that may occur.

The same approach is followed as in the ship-to-ship case, and the value of as many terms as possible in equation (2) is determined from the specified equipment and the circuit requirements. If this is done, the only terms generally remaining to be specified are (1) the standard deviation of the shipboard antenna, σ_{SA}, (2) the mean gain of the shipboard antenna, G_{SA}, and (3) the basic transmission loss, L_B.

Again, when equation (2) is solved, the remaining terms represent more unknowns than equations. There are fewer unknowns than in the case of ship-to-ship circuits, but one of these has a much larger variability. This unknown is L_B. Its great variability results from two factors – the effect of the addition of the direct and reflected waves, and the large height and range requirements. For these reasons it is felt that the methods of determining basic transmission loss for ship-to-air circuits should be discussed in some detail.

BASIC TRANSMISSION LOSS. L_B can be calculated by standard two-ray optic theory. Fortunately, much of the work of calculation has been done and is presented so that it facilitates trade-offs. The calculations by standard two-ray theory are reported by Goodbody [1972], who tasked L. V. Blake, of the Naval Research Laboratory [Blake, 1970], to calculate and plot detection contours for typical ship-to-air circuits for free-space ranges of 250 and 500 nautical miles. These curves may also be interpreted as constant basic transmission loss curves, or isoloss contours.

The relation between free-space range, R, and basic transmission loss is given by equation (14). Solving this equation for L_B yields equation (15).

$$R = \frac{\lambda}{4\pi}\left(10^{L_B/10}\right)^{1/2} \text{ m.} \tag{14}$$

$$L_B = 20 \log_{10}\left(\frac{4\pi R}{\lambda}\right). \tag{15}$$

Since Blake's curves are plotted for constant take-off angles, the contours for other values of loss are similar, but with the locus shifted with respect to the origin. The scale factor between the new locus and the one given is effectively the free-space range corresponding to the desired loss divided by the reference free-space range. Thus, to find the loss contour for + 140dB, 300MHz, and 59m antenna height, using equation (14), we find that 796km is the free-space range for 300MHz and 140dB. Thus, the range grid (fig. 9) would have

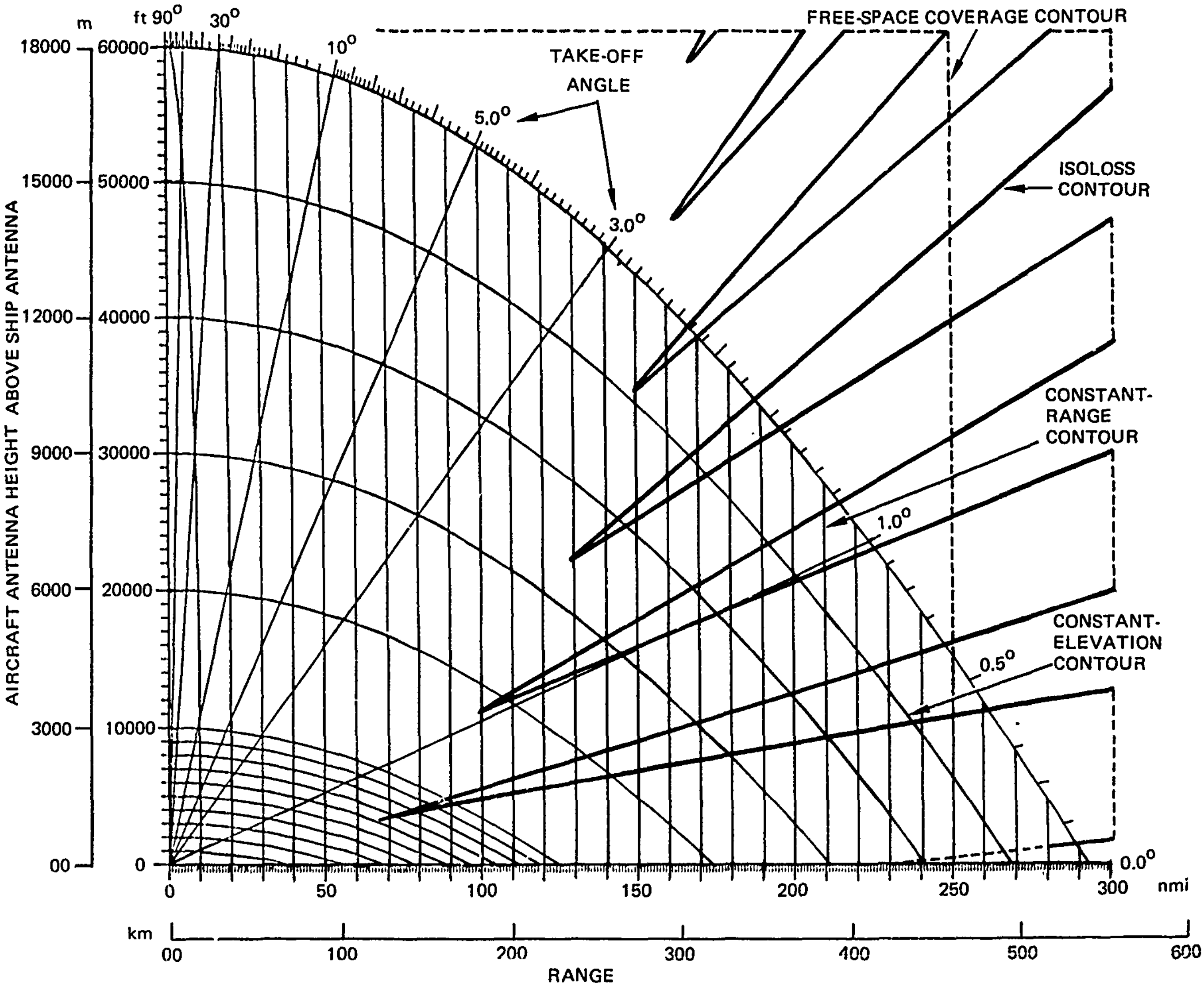


Figure 9. Detection contour for ship-to-air circuit. Radio frequency 300MHz, free-space range 464km (250nmi), ship antenna height 59m (180ft).

to be expanded so that the present 464km range (250 nautical miles) becomes 796km, or the range scale is multiplied by 1.73. A similar multiplication is necessary for the height scale. Another way to look at this is to say: the isoloss contour for 140dB would occur in figure 9 if the present locus were printed at 1.73 distance and height. Thus, Blake's curves coupled with equations (14) and (15) can be used to calculate detection contours for any particular system.

The Goodbody report gives an idea of the dependence of frequency and antenna height on the threshold of detection contour. One sees from it that the minimum detection contour occurs at the shortest distance for the higher frequencies and the higher antenna heights. It is also apparent that increasing the free-space range capability also increases the altitude at which the minimum distance of detection occurs. This is significant because the altitude capabilities of the aircraft are significant in determining the range requirements. For instance, for the aircraft to have need for a 556km communication range, it must fly at over 18 000m altitude.

It is of interest to calculate the maximum basic transmission loss a system needs to overcome to provide complete airborne coverage for ranges less than 556km. The highest frequency presently used for ship-to-air communications is 300MHz. Since 59m (180ft) is approaching the maximum possible shipboard antenna height, one can get an indication from figure 9 of the maximum mean basic transmission loss which may occur for ship-to-air circuits. By the calculation done previously, the results of Goodbody indicate that all nulls in the detection contour can be removed by increasing the free-space range capability to 2050km. This corresponds to a maximum loss of 148.2dB. Thus, any system which will overcome this value of L_B will provide acceptable service in the complete airspace. Bear in mind that this calculation was done for a smooth sea surface. A rough sea surface will reduce the value of 148.2dB.

EXAMPLE. As an example, assume the design of a shipboard antenna system which will provide null-free service in the complete airspace from zero to 556km. Assume the transmitters and multicouplers have characteristics similar to those of the AN/SRC-31 and CU-1559, and the system is internally noise-limited. Under these conditions, and the assumptions about the airborne system given previously: $P_T = 30$dB; $P_{TL} = P_{RL} = 3.3$dB; mean aircraft antenna gain, G_{AA}, = 0; standard deviation of the aircraft antenna gain, σ_{AA}, = 4dB; $\sigma_L = 5$dB; $N_T = 147$dBW; GS = 10; $\sigma_N = 4$dB; and $L_B = 148.2$dB. Inserting these values in equation (2) yields equation (16). One solution to this –

$$G_{SA} - 2.3\sqrt{54 + \sigma_{SA}^2} = -14.8 \qquad (16)$$

– is G_{SA}, the ship antenna gain, equal to 4.5dB and σ_{SA}, the standard deviation of the ship antenna gain, equal to 4dB. There are other solutions, but it should be noted that reducing σ_{SA} to zero only reduces the requirements on G_{SA} to 2.2dB.

TRADE-OFFS. Again there are many trade-offs that can be made. Some of them and their consequences are listed here.

1. High antennas and the highest frequencies produce detection contours with large amounts of lobing and the shortest distances of satisfactory performance.

2. Low antenna heights lead to less lobing, but performance falls off at the lower-elevation, long-range paths.

3. High antennas lead to the best long-range performance, but have poor performance near the transmitter because of lobing.

4. Maximum airspace coverage can be obtained by increasing the transmitter power and the average gains in the circuit, but may be difficult to achieve on the airborne end because of weight.

5. Better airspace coverage can be obtained by connecting two antennas in vertical-pattern diversity. Blake's [Goodbody, 1972] results indicate that a vertical spacing of about 30 meters is needed to do this.

6. Because of the large variability of basic transmission loss for uhf circuits with ranges to 556km, little is gained by reducing the variability of the free-space antenna gains to zero.

7. The altitude and range limitations of the aircraft have great influence on antenna and aircraft requirements.

ANALYSIS FINDINGS

When analyzing an existing system, one is studying a communications system after installation. Under these conditions, many of the statistical items are fixed, and a somewhat different approach is required. For accuracy, knowledge of the system parameters after installation is required. It is assumed in the following discussion that these past installation parameters are available, or there exists a means of measuring them.

In analysis problems there are two potential questions. First, does the system as installed meet the specified requirements from a statistical point of view? Second, does the system meet the requirements in specific situations? In either case, equation (2) is used, but now it is solved only for the grade of service.

Method. Again the procedure of the two previous sections is used. The value of each term in equation (2) is identified. P_T is found by measuring the transmitter power, P_{TL} and P_{RL} are the measured line losses of the system, and N_T can be found from the average value of measured noise data, if available, or can be calculated by use of the procedure given in the design section.

σ_N and σ_L are difficult to find unless elaborate test equipment is used to measure them. If this equipment is available, the measured values of σ_N and σ_L can be used; if not, the values used in the design section provide reasonable substitutions.

L_B can be determined from the design section. For ship-to-ship analysis, L_B can be determined from figures 3 and 4. For ship-to-air circuits, L_B can be determined from the work of Blake [Goodbody, 1972] and equation (15). To do this, one must determine a factor for expanding the detection contour for that height and frequency so that it falls on the desired range and elevation. This factor times the reference free-space range determines the new free-space range for that point. The new free-space range used in equation (15) yields the basic transmission loss between the ship and the aircraft.

Before proceeding further with the identification of terms in equation (2), one must ask whether one wants to do a statistical analysis of the existing system as a particular point-to-point solution. The answer to this question determines how the antenna terms in equation (2) will be characterized.

STATISTICAL ANALYSIS

To determine whether an existing system can meet the statistical circuit requirements, one must determine the actual low-take-off angle free-space patterns as a function of azimuth. Examples of this type of pattern are shown in figure 10. From these patterns, the mean gain of each antenna, G_T and G_R, can be identified. With the gain distributions of the antennas about their means and the assumed or actual distributions of the noise and transmission loss known, the approximate probability distribution function for the sum of the random variables for the whole circuit can be found by the use of convolution methods [Meyer, 1965]. According to the central limit theorem, this distribution should tend to approximate a normal distribution. This probability density function may be integrated and the result solved to get the bias, B(TA), required for the desired time availability.

This value, and values of other terms, may then be inserted in equation (2), and the grade of service can be calculated. If the result is greater than or equal to the desired grade of service, satisfactory service is achieved. If not, each term in equation (2) must be investigated to see where the problem lies.

If there is a preferred direction of communication, the problem is approached as above, except that the antenna patterns are considered to exist only in that direction. For instance, if the antenna is known to be used only for starboard reception and transmission, then only the starboard 180° of the antenna gain need be included in the calculations.

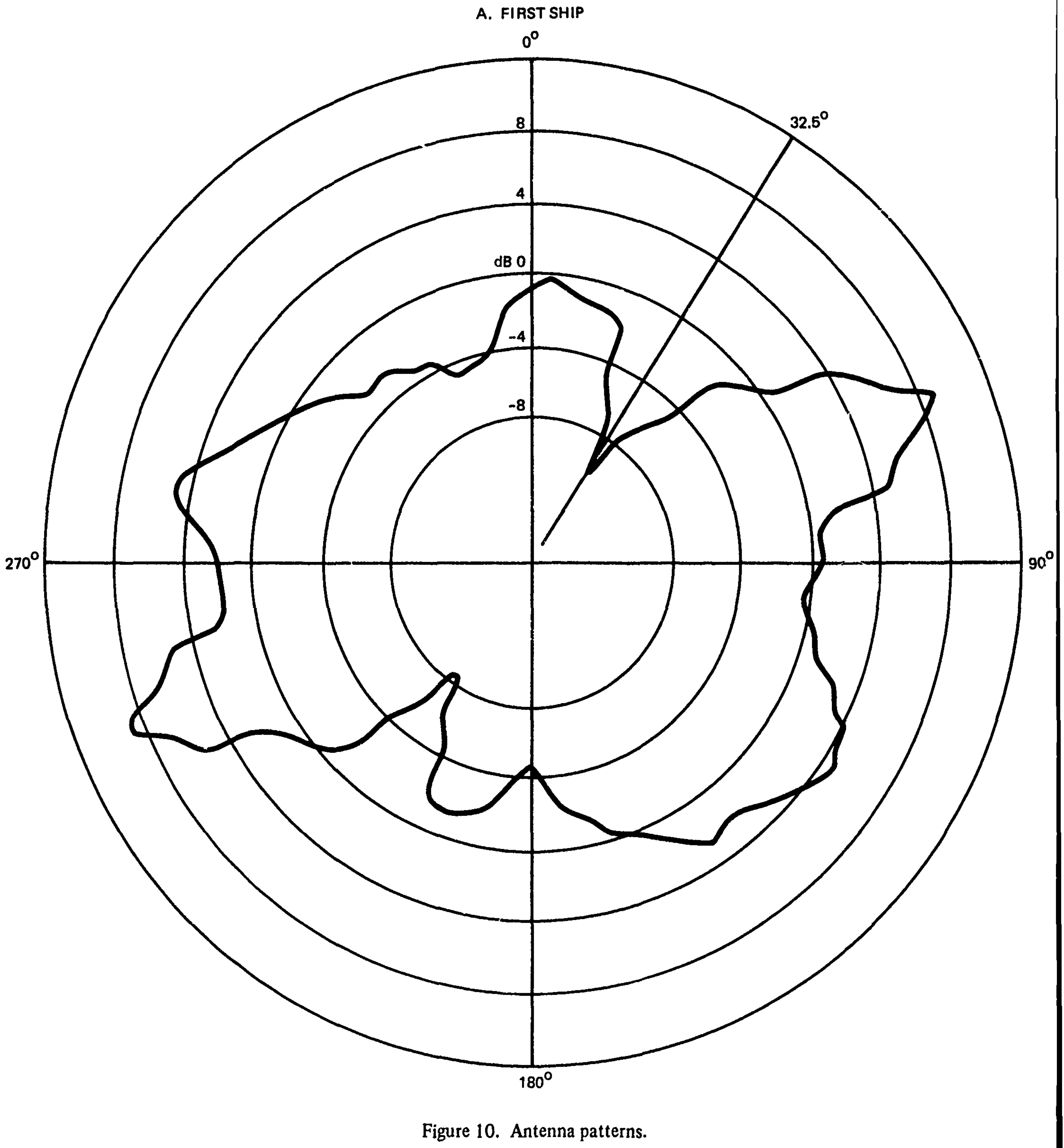


Figure 10. Antenna patterns.

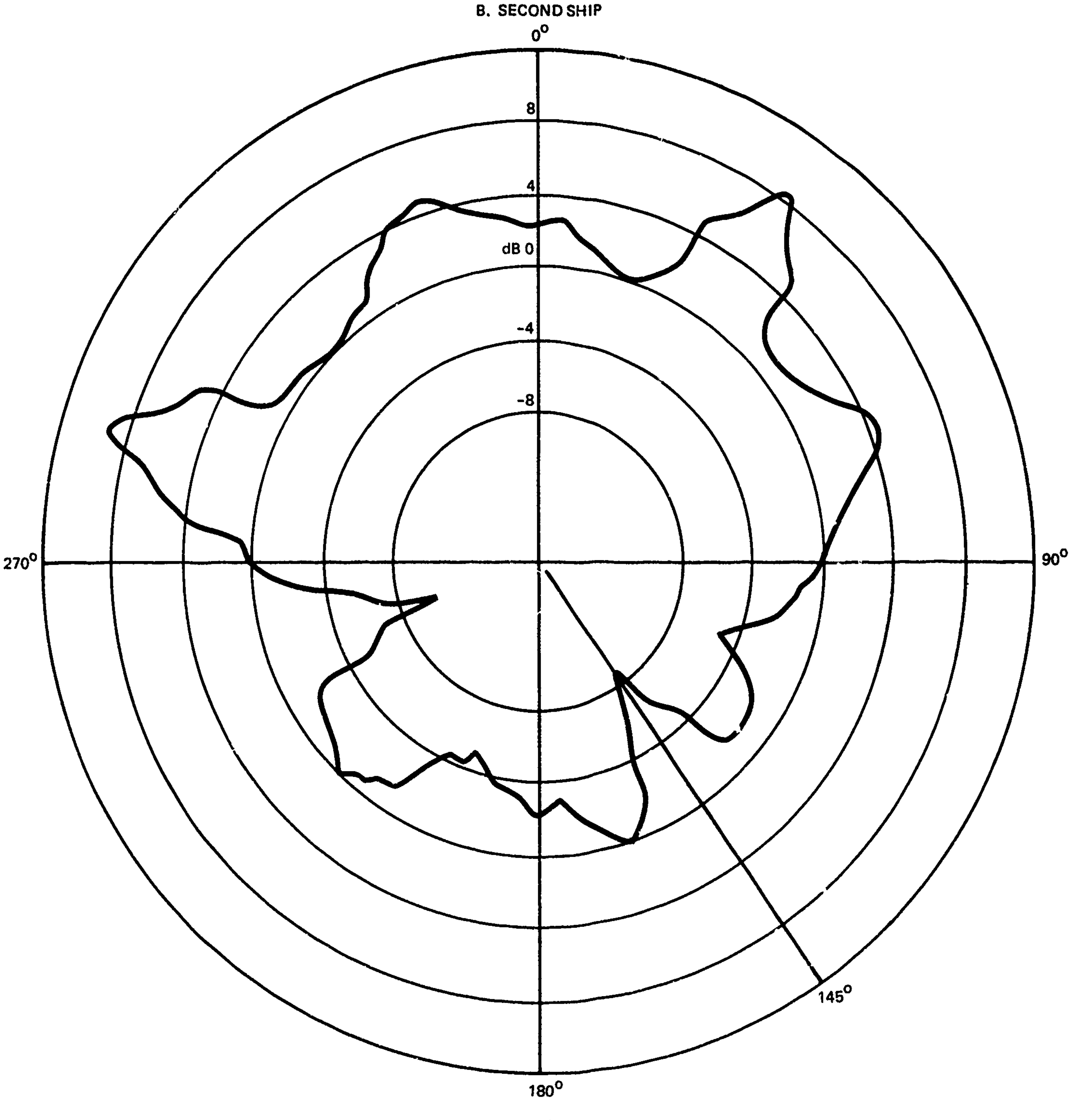


Figure 10. (Continued)

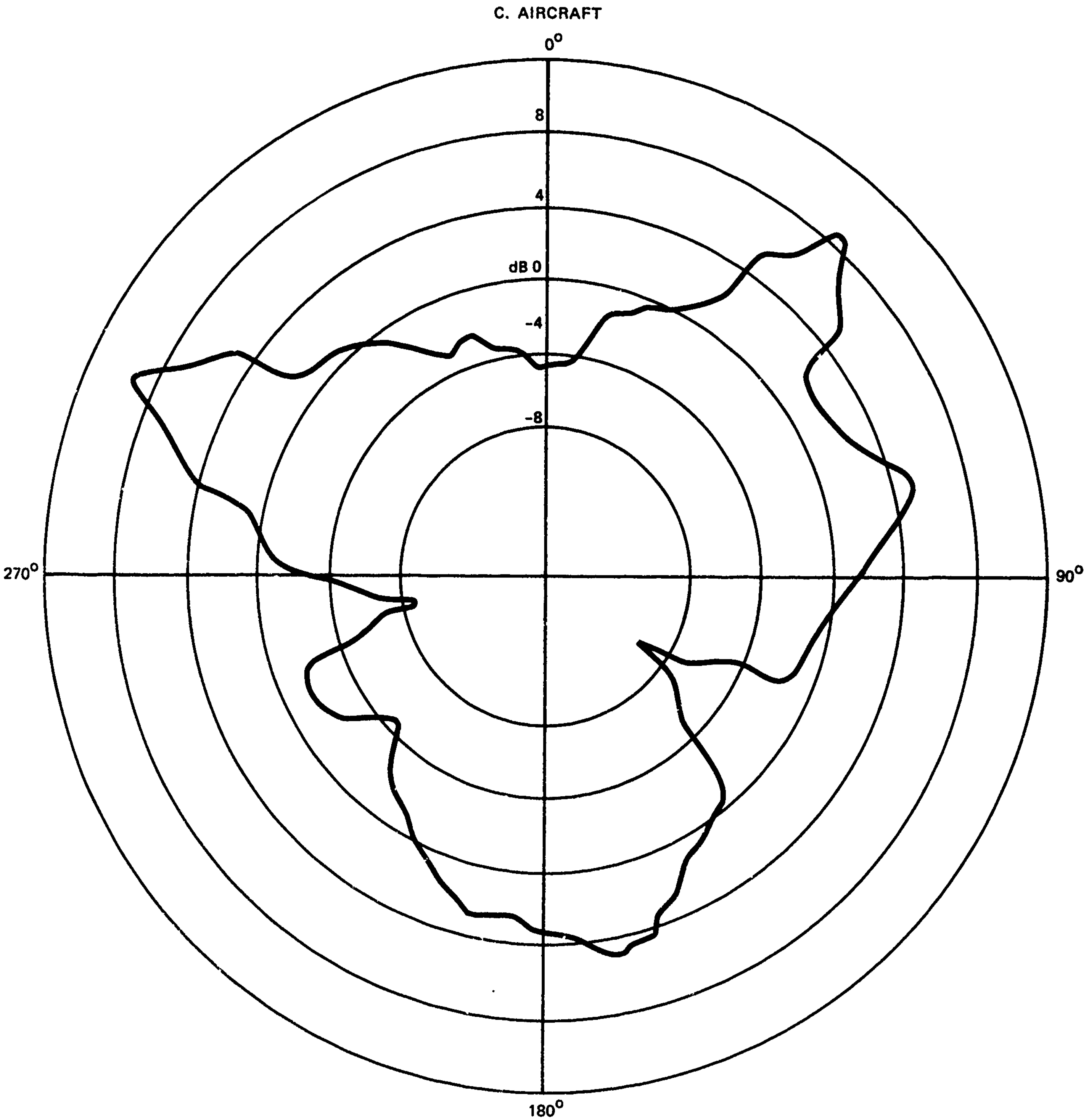


Figure 10. (Continued)

SPECIFIC POINT-TO-POINT ANALYSIS

For the analysis of a specific point-to-point problem, the standard deviations of the antennas are removed from equation (4). Under these conditions, G_{AT} and G_{AR} become the specified antenna gains in that particular direction. Again, as in the statistical analysis case, actual measured values can be used for σ_L and σ_N if they are available. If they are not, the same approach used in the design section can be taken, and representative values assumed and used.

One must be careful while doing this type of analysis not to draw unfounded conclusions about the antennas. For instance, if this calculation is done for a system in which the direction of communication falls in deep nulls in the antenna pattern, there may be a tendency to state that the antenna is not meeting its requirements. Before one can accurately state this, one must ask how probable the occurrence of this is. Under conditions in which the nulls are narrow and extend many dB from the mean, and the direction of communication is random, it is highly probable that satisfactory communications will occur. However, if communication in the direction in which these nulls occur is preferred or highly probable, then it is probable that the antennas will not meet their requirements.

EXAMPLE

As a first example, consider a ship-to-ship case. Assume that both ships are equipped with AN/SRC-31 and CU-1559 systems. The antenna of the first ship has the pattern shown in figure 10A and the antenna on the second ship has the pattern shown in figure 10B. One antenna is 50m high and the second is 20m. The receivers on each ship are connected to modems that have bit error characteristics similar to those shown in figure 11. The problem is to discover whether this system meets the requirements stated in the requirement section.

We begin by assigning values to terms in equation (2). Measurements on ship indicate P_T = 30dB, P_{TL} = 3dB, and P_{RL} = 3dB. All the patterns in figure 10 are statistically the same. Each is normally distributed with a mean of 0dB and a standard deviation of 4dB. Thus, G_{AT} and G_{AR} both equal zero, and σ_{AT} and σ_{AR} both equal 4dB. Since nothing has been indicated about the noise or the path loss variability, apply the value used in the design section in which the system was assumed to be internally noise limited with N_T = -147dBW, σ_N = 4dB, and σ_L = 3dB. Since both heights are above the critical heights for these frequencies, figure 3 indicates that 400MHz will have maximum loss. Figure 3 indicates the loss for 30m heights is 146dB and figure 4F indicates there is a correction factor of -1.7dB for antenna heights of 50m and 20m, so the total loss is 144.3dB. For 99% time availability, the standard normal deviate is 2.3, which, coupled with the above standard deviations, leads to B(TA) = 17.3dB. Solving equation (2) yields the fact that received

SNR will be greater than 9.4dB 99% of the time. Figure 11 indicates this SNR applied to the modem will yield a bit error rate of less than 8 X 10^{-6} for 99% of the time, or, in other words, acceptable service.

Suppose we would like to ascertain whether the requirements can be met for the previous situation, except that communication is to be along a line through 32.5° on pattern 10A and145° on pattern 10B. In this case, G_{AT} = -10dB and G_{AR} = -9dB, and the only items contributing to the variability of the circuit are the noise and path loss. Making assumptions the same as before, we have σ_L = 3dB and σ_N = 4dB so that B(TA) = 11.5dB. Inserting these values into equation (2) yields -1.8dB for the received SNR. Hence, the received SNR will be greater than -1.8dB 99% of the time. It is almost certain that this will provide unacceptable service if this direction of communication is used a lot. However, as illustrated by the previous example, this system meets circuit requirements 99% of the time if a random direction of communication is assumed.

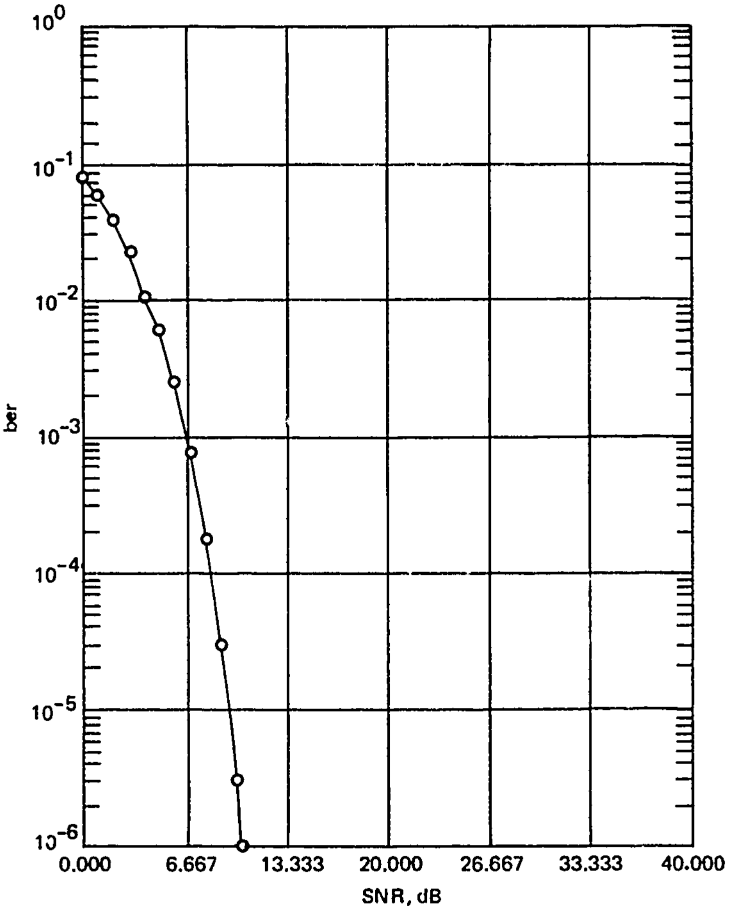


Figure 11. Modem ber as a function of SNR.

Now let us consider the statistical analysis of a ship-to-air circuit. The shipboard antenna has a 59m height and an antenna pattern the same as figure 10B with a mean gain of 0dB and a standard deviation of 4dB. The same equipment is on the ship as in the previous ship-to-ship example. Similar equipment is on the aircraft, and its antenna pattern is shown in figure 10C. The problems are to find the point at which the minimum SNR can most probably be expected as the aircraft flies along at 15 000m directly toward the ship, and, at this point, to calculate the expected SNR for 99% time availability and a frequency of 300MHz.

From figure 9, we find that the most probable point of minimum SNR will occur at 0.5° take-off angle, or at 426km, since this is the take-off angle which has the minimum distance to the detection contour. It is even more probable that the minimum SNR will occur when communication is attempted along the nulls in the antenna patterns shown in figures 10B and 10C.

To calculate the basic transmission loss for this point, we note the factor by which the detection contour must be expanded to place the contour on 15 000m and 426km. This factor is 426/126 = 3.38. This is multiplied by 464km to yield the free-space range of an isoloss contour through the point of interest. This results in 1570km. Using equation (15), we find that L_B is 146dB. The only other item that is different than before is σ_L, and, as before, we use the value of 5dB from the design section. Solving equation (2) with these values yields 7.3dB. It should be noted in this situation, in which σ_L is greater than σ_{TA} and σ_{RA}, that if the antennas are improved so that σ_{TA} and σ_{RA} equal zero, the grade of service only improves to 10.9dB.

SUMMARY AND CONCLUSIONS

Shipboard antenna design and location criteria can be found by use of equation (2). The sequence of steps is as follows: Assign values to P_T, P_{LT}, P_{LR}, and GS from the equipment specifications and circuit requirements. Determine whether the system is externally or internally noise limited and the mean value of the noise. Find, if possible, or assign reasonable values to, the noise power standard deviation and the standard deviation of the basic transmission loss. For ship-to-ship circuits assign heights to the receiving and transmitting antennas and use figures 3 and 4 to determine L_B. For ship-to-air circuits, L_B can be determined from Blake's work [Goodbody, 1972] and equations (14) and (15). Now, the only items unknown are the mean gains and standard deviations of the antennas. Choose the values of these items so they are physically realizable and satisfy equation (2). Trade-offs may be made by noting the change in grade of service as calculated by equation (2) as the parameter under question changes.

Analysis of present antenna systems can be done by using actual data on system parameters and solving equation (2) for the received grade of service. For analysis work, L_B can be determined from figures 3 and 4 and the work of Goodbody [1972].

The study reported here indicated the following conclusions about shipboard antenna design and location.

SHIP TO SHIP

1. Ship antenna height has little effect on circuit performance at low vhf frequencies.

2. At frequencies above 100MHz, antenna height has a large influence on system performance.

3. At uhf frequencies, more benefit is gained by raising the antennas from 0 to 30m than from 30 to 60m.

4. For antenna heights greater than 20m above the sea, system performance decreases with increasing frequency from 30 to 76MHz, but is essentially independent of frequency from 76 to 400MHz.

SHIP TO AIR

1. High ship antennas and the highest frequencies produce detection contours with large amounts of lobing and the shortest distances of satisfactory performance.

2. Low ship antenna heights lead to less lobing, but performance falls off at the lower-elevation, long-range paths.

3. High ship antennas lead to the best long-range performance, but have poor performance near the transmitter because of lobing.

4. Maximum airspace coverage can be obtained by increasing the transmitter power and the average gains in the circuit, but may be difficult to achieve on the airborne end because of weight.

5. Because of the large variability of basic transmission loss for uhf circuits with ranges to 556km, little is gained by reducing the variability of the free-space antenna gains to zero.

GENERAL

1. High time availabilities require large protection biases to achieve the desired performances.

2. For situations in which antenna variability is the significant contributor to system variability, and a high time availability is desired, it is important to minimize antenna standard deviations. However, if antenna variability is not a significant contributor to system variability, it is more important to increase the mean gain of the antenna to improve system performance.

3. On the basis of system gain per dollar, it is important to consider all parts of the total system, rather than just antennas, in an improvement program. More gain may be had by reducing such factors as man-made noise and multicoupler and coaxial cable losses.

In conclusion, the results of the previous analysis have been applied to two typical Navy systems. These are representative of the systems in the present Navy and have the following characteristics:

1. Transmitter powers of 100 watts and 16 watts; P_T = 20dB, 12dB

2. Line and multicoupler losses of 4dB; $P_{LT} = P_{LR}$ = 4dB

3. Mean free-space antenna gains of 1.5dB above isotropic; $G_{AT} = G_{AR}$ = 1.5dB

4. 3μV sensitivity for 10dB SNR. (Studies have shown that 10dB SNR is adequate to provide 95% sentence intelligibility for trained operators using limited vocabulary. This is also the level required for 10^{-5} error probability for a data link using a modem which achieves its theoretical limit for synchronous, coherent, phase shift keying modulation. N_T = -137.5dBW; GS = 10dB.

5. There are four independent, normally distributed, random variables influencing the system. These variables and their standard deviations are as follows:

   a. Path loss variations = σ_L = 4dB

   b. Receiver input noise variation = σ_N = 4dB

   c. Standard deviation of the receiver antenna free-space gain = σ_{AR} = 4dB

   d. Standard deviation of the transmitter antenna free-space gain = σ_{AT} = 4dB

Thus, for 99% time availability, B(TA) = B (99%) = 18.4dB, and for 95% time availability, B(TA) = B (95%) = 13.2dB. Using the above and solving equation (2) for L_B, we have the following maximum values for L_B:

1. 16W, 95%; 121.5dB
2. 16W, 99%; 116.3dB
3. 100W, 95%; 129.5dB
4. 100W, 99%; 124.3dB

Figures 3 and 4 were used to convert these values to range of communications for ship-to-ship circuits. The results for three different height pairs (30m, 40m, 60m) and the upper and lower frequency in each band of interest are shown in figure 12.

The detection contours for ship-to-air circuits with the same electrical characteristics as above are shown in figure 13 for the worst possible case of 300MHz, smooth sea, and ship antenna height of 61m.

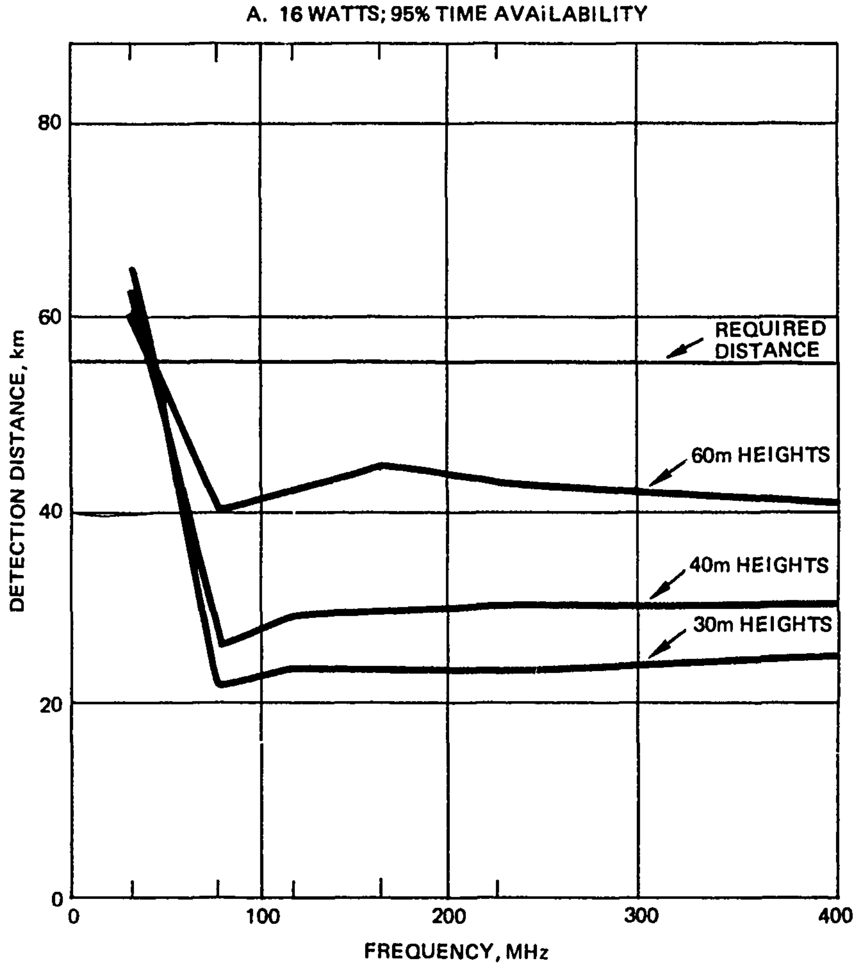


Figure 12. Ship-to-ship detection range.

B. 16 WATTS; 99% TIME AVAILABILITY

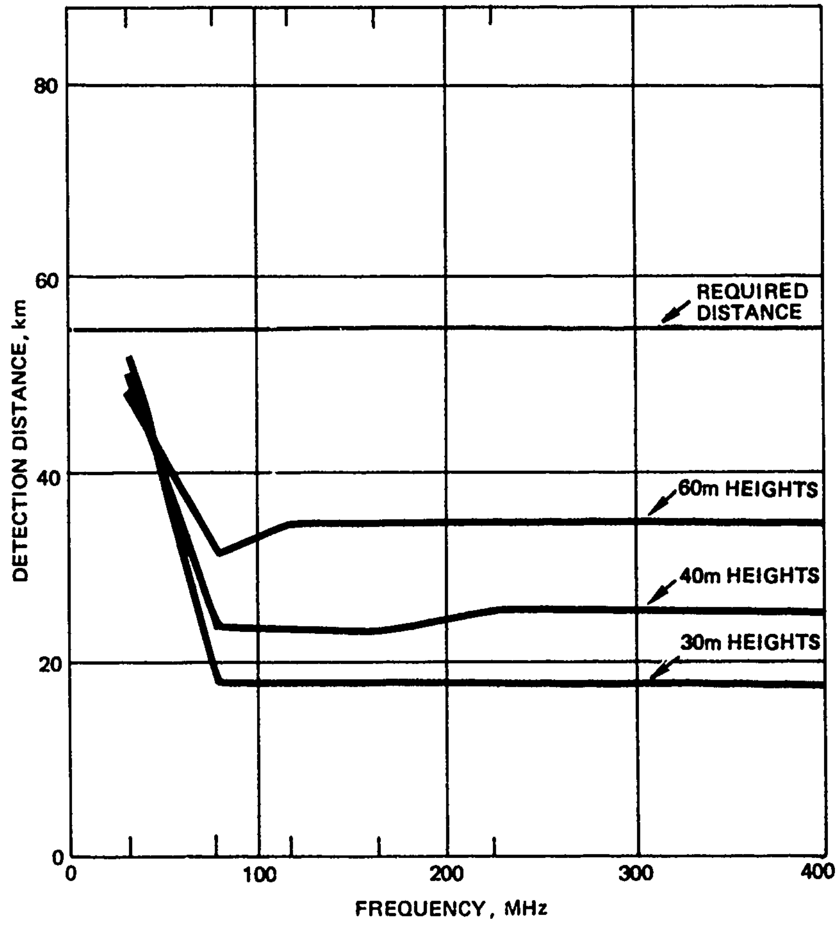


Figure 12. (Continued)

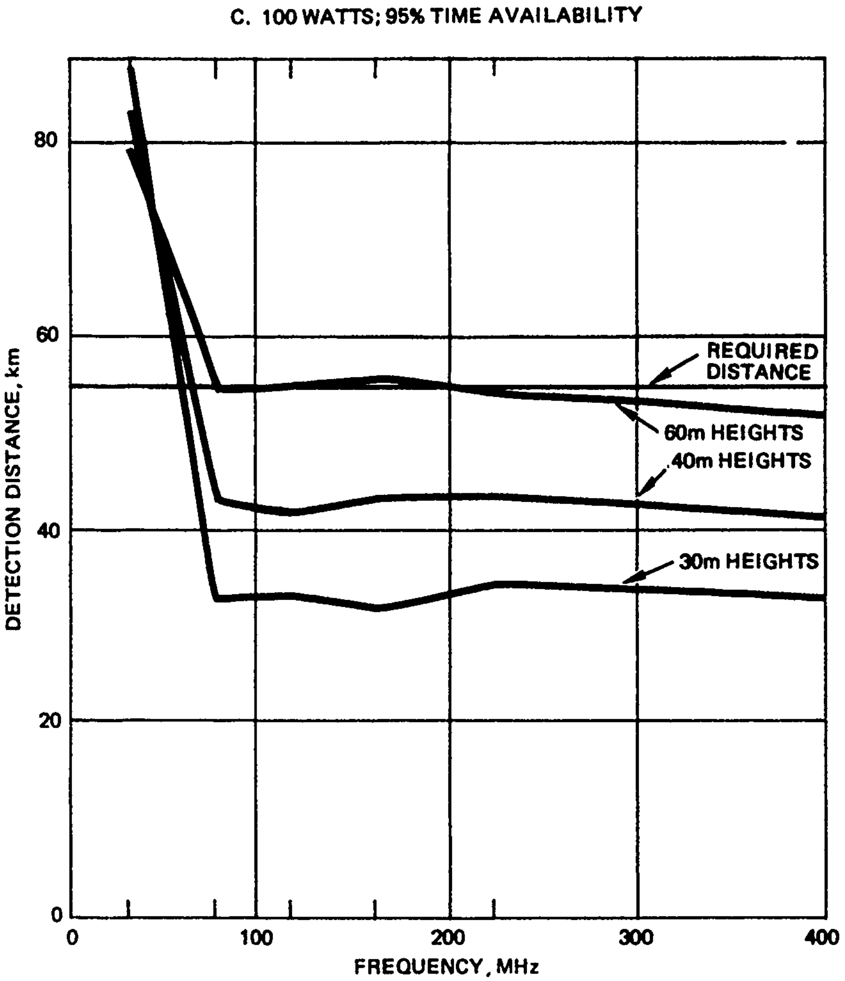


Figure 12. (Continued)

D. 100 WATTS; 99% TIME AVAILABILITY

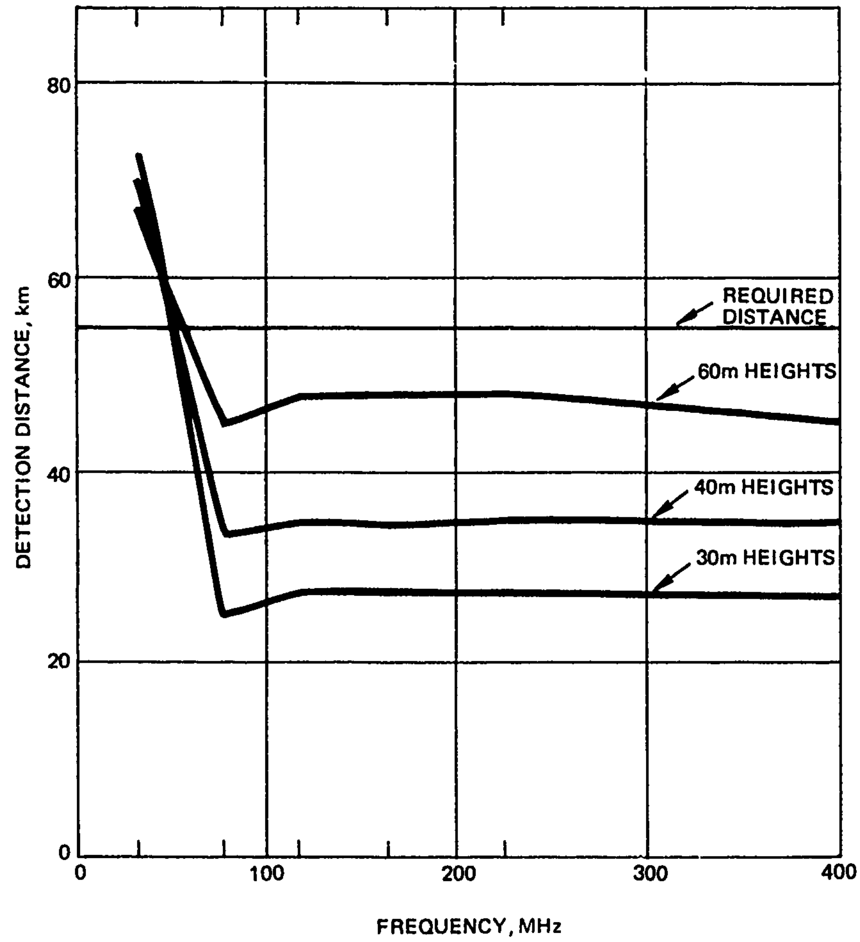


Figure 12. (Continued)

In all cases except at 30MHz and 100W, there is a problem in satisfying the requirements. Thus, to improve the range of communication, some combination of the following must be undertaken to satisfy the requirements:

1. Increase transmitter power as much as economically feasible.
2. Decrease electronic cable losses.
3. Increase average antenna gains.
4. Decrease standard deviation of the antenna gains (little is accomplished, since they are at 4dB already).
5. Increase receiver sensitivity.

The results of making modifications or use of different system parameters can be found by following the procedure outlined above.

Thus, the above theoretical calculations indicate that there is a problem in reaching CNO reliability and range requirements with the representative systems discussed here.

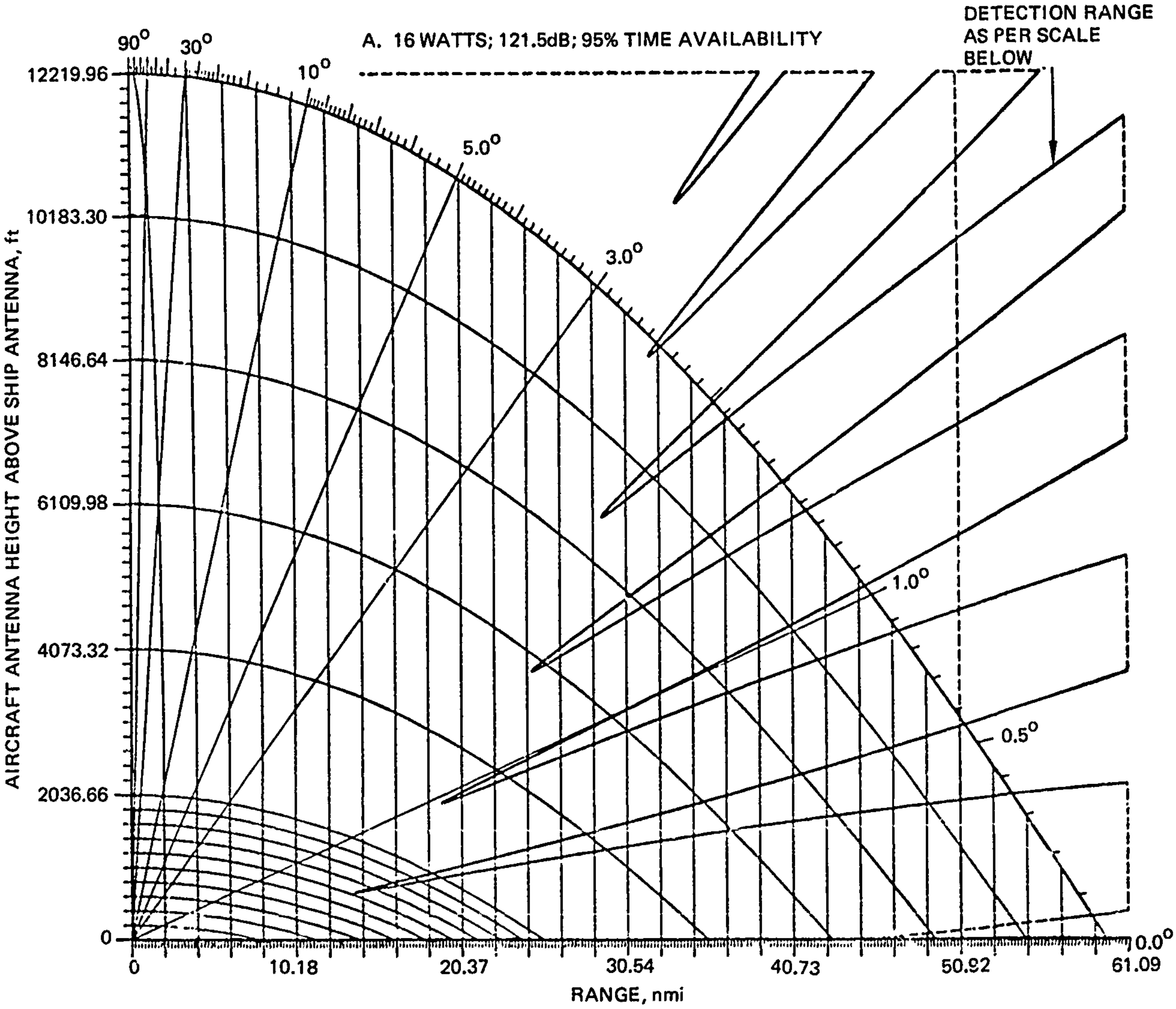
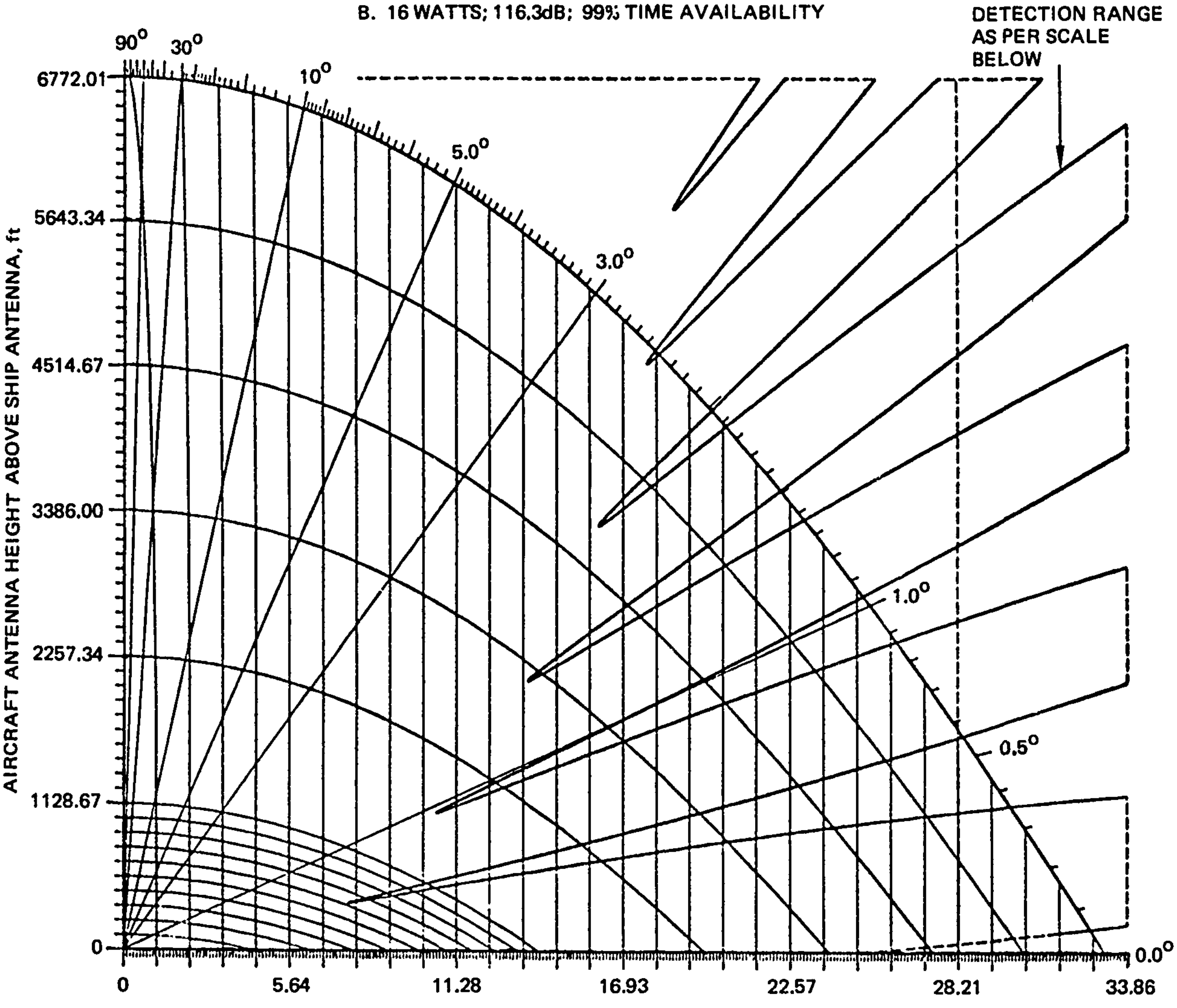
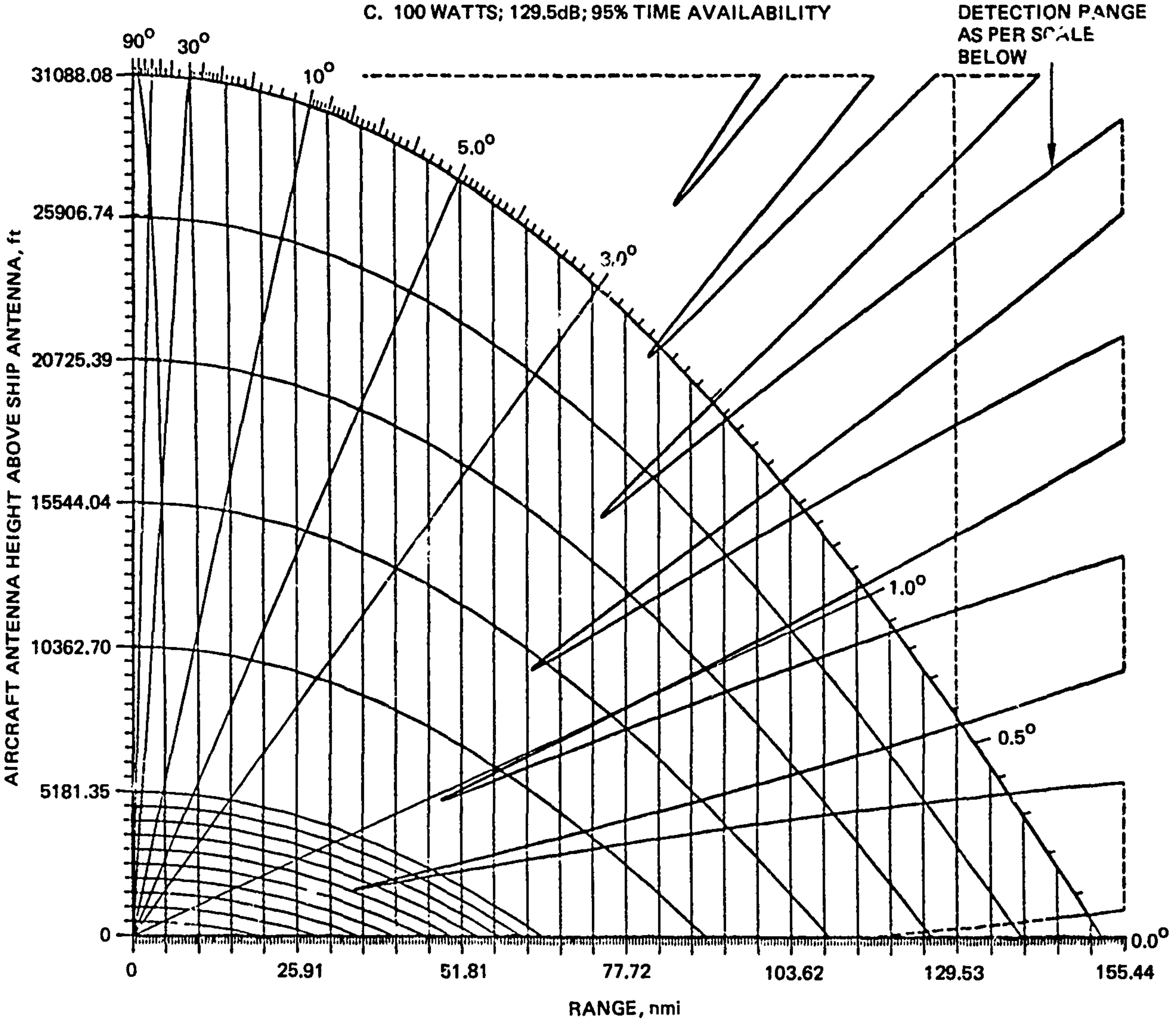


Figure 13. Ship-to-air detection range. Radio frequency 300MHz, ship antenna height 200 ft.



B. 16 WATTS; 116.3dB; 99% TIME AVAILABILITY

Figure 13. (Continued)



C. 100 WATTS; 129.5dB; 95% TIME AVAILABILITY

Figure 13. (Continued)

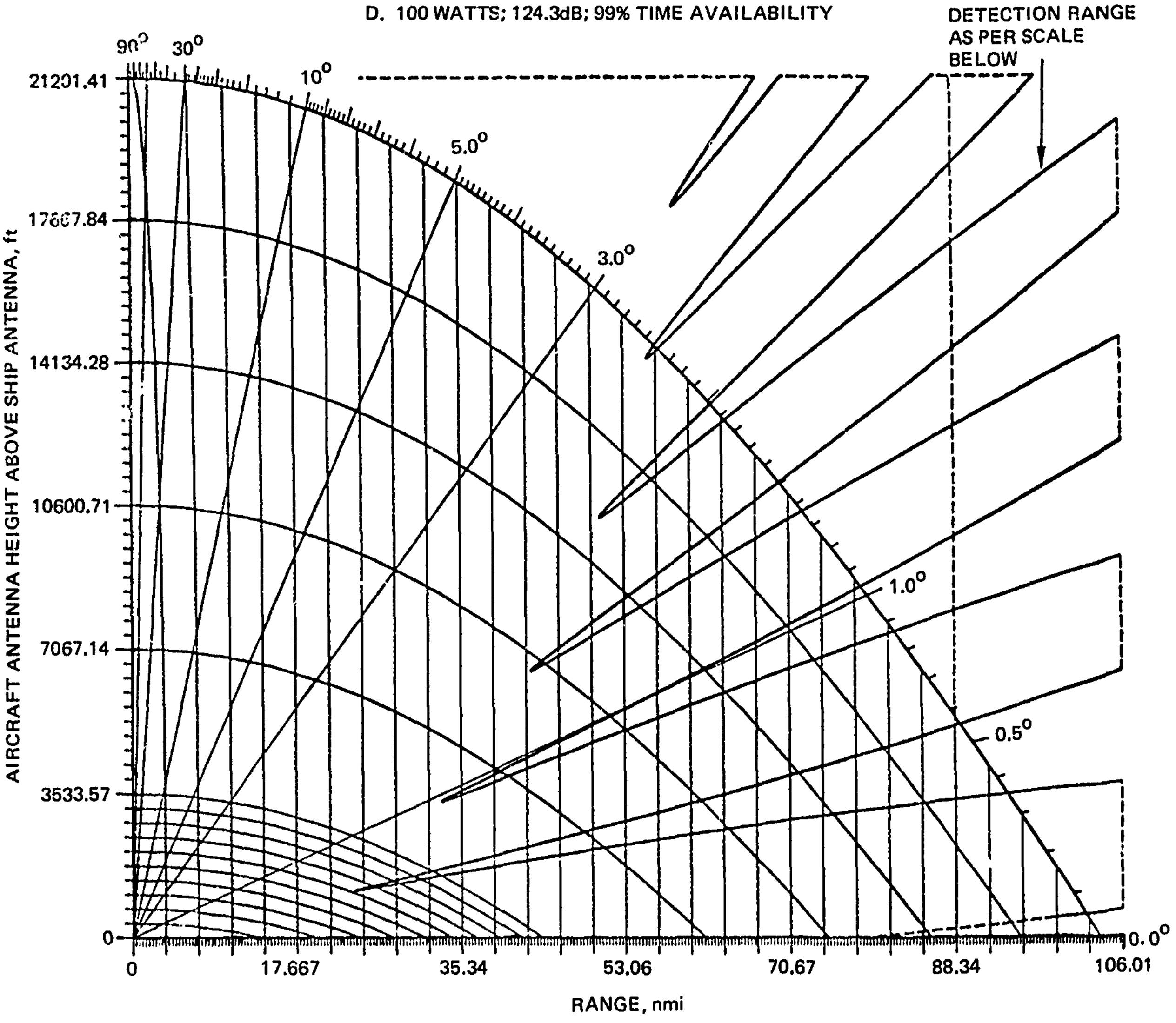


Figure 13. (Continued)

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APPENDIX: SHIPBOARD UHF SYSTEM PERFORMANCE CRITERIA

by

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INTRODUCTION

The most fundamental limitation to successful reception of a signal in the uhf military frequency spectrum (225–400MHz) is the natural noise derived from a combination of solar and galactic sources. In an idealized system – one transmitter and one receiver on a simplex circuit – the major concern of receiving system design would be the relationship between this natural noise and the receiver's internal noise. But in considering the probable system performance in the situation to be discussed in this report, there are many interdependent items which force departure from the ideal.

Uhf communication aboard ship is adversely affected by limited isolation between transmitted-signal sources and the input terminals of the receivers. If there were no limit to physical separation between transmit and receive antennas, the obligation of needed isolation could be met by antenna separation alone. But, as a practical matter, in the crowded surroundings aboard ship, the distance between antennas provides only part of the total isolation requirement; the remainder must be found in the rejection characteristics of selective circuits placed between antennas and equipments. In the event that an antenna is shared by transmit and receive equipments, the responsibility for sufficient isolation is solely that of the selective circuits. Any provision of isolation by a protective filtering circuit is obtained at the cost of insertion loss, which makes the receiving system that much less sensitive or the radiated power from the transmitting system lower than the available power. Thus there are definite practical bounds to the amount of selectivity which can be provided artificially by circuits in black boxes. This fact, in turn, settles the minimum frequency separation between receive and transmit channels if the degree of isolation required is to be had. Other less obvious types of interference contribute further difficulties to system performance and must be weighed in the evolution of an accurate determination of the comparative worth of several available options.

This report describes an example of a system analysis procedure which must be followed if adequate consideration is to be given each of the many items having some effect on uhf communications in a less than ideal environment. An attempt is made to show clearly the relative importance of each item. Certain quantitative assumptions are made and used in the process of working out conclusions for the example. Some of these values will be different when the evaluation procedure is applied to an actual, specific situation.

To keep the analysis as simple as possible, only a limited equipment arrangement has been considered and at only one frequency, the midband frequency of 300MHz. Interferences to and from equipments outside the uhf communication band of 225–400MHz have not been covered.

REPRESENTATIVE EQUIPMENTS AND PARAMETERS

Throughout the description of the system analysis process, the following specific inputs are used. Only where necessary are other frequencies, equipments, etc., discussed. Since the uhf spectrum involves a frequency change of less than two to one, the midband of 300MHz is emphasized. A practical value for isolation between uhf antennas in a shipboard installation is 35dB. Although other transmission line types and lengths may be found in actual installations, 100 feet of RG-218/U coax is typical; the attenuation from a transmission line run is thus fixed at 2dB. The AT-150 broadband dipole is an example of an uhf antenna with low VSWR. It will be served by the four-channel multicoupler AN/SRA-33 where protective selectivity and antenna sharing are necessary. The on-channel insertion loss for this device with its twin, tunable cavities in cascade is about 2dB. Figure A1 shows its selectivity at 300MHz. Receiving and transmitting will be provided by the respective modes of the AN/SRC-20 transceiver. Transmit mode output power is 100 watts. Receive mode sensitivity (6dB (S+N)/N, 1kHz 30%-modulation, 6kHz bandwidth) is -107dBm carrier power. The ratio between SRC-20 transmitter output power and its receiver threshold power is 157dB. Evaluation tests show transmitter harmonics and other spurious signals to be more than 80dB below the fundamental power, but these spurious signals are 77dB or less above receiver threshold.

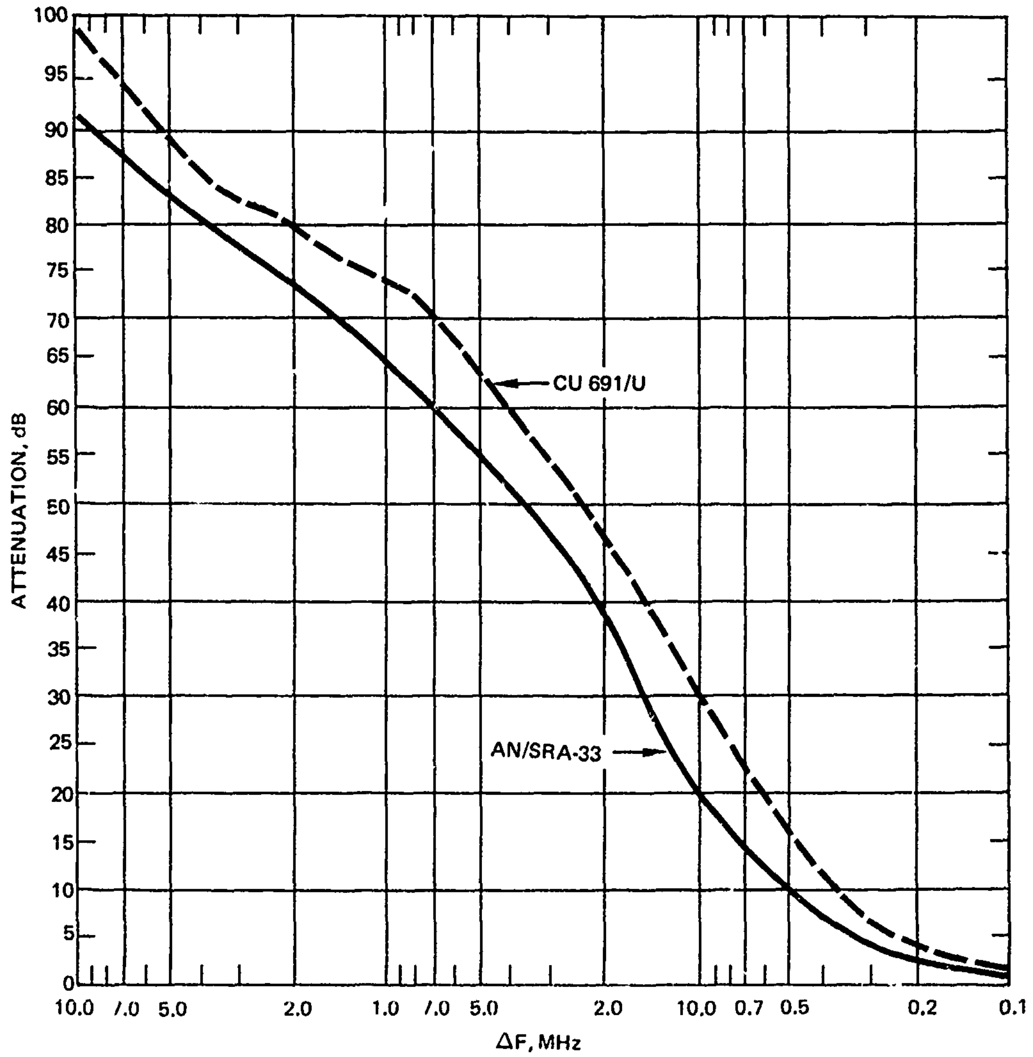

Figure A1. Uhf multicoupler insertion loss at 300MHz.

RELEVANT RECEIVING SYSTEM DETAILS

SENSITIVITY

At uhf the level of external noise from natural sources is 5dB above thermal noise. The SRC-20 receiver sensitivity can be expressed as a noise figure of 11dB above thermal. Hence, the inherent receiver noise, even before system sources of attenuation are taken into account, is the major factor limiting receivability of any desired signal. (A 6dB (S+N)/N ratio with natural noise alone becomes a 2.4dB (S+N)/N ratio with receiver noise.) With the inclusion of transmission line loss, system sensitivity drops to a noise figure of 13dB; addition of multicoupler insertion loss degrades the system to a total of 15dB above thermal noise. The important conclusion from this information is that any further decrease in system sensitivity – from poor equipment maintenance or damaged transmission line, for example – has a direct impact on reception capabilities.

EQUIPMENT-GENERATED INTERFERENCES, GENERAL

An overall consideration of signals generated in a communications system which impair receiving performance can describe them all as being indirectly or directly the result of strong local transmissions. (The only exception to this statement is the "birdie" interference generated on specific fixed frequencies in a receiver without the influence of any external signal.) Interference generated in the transmitters and radiated to cause reception errors is in the indirect category and includes transmitter spurious, intermodulation, and broadband noise. Direct interference is that generated in a receiver by the effect of one or more strong transmitter fundamental signals at the receiver terminals. Difficulties of this type come from receiver spurious, desensitization, cross modulation, and intermodulation.

Indirect interference can be controlled only by providing protective selectivity between transmitter outputs and antennas. The effect of this filtering is twofold: (1) production of intermodulation between two or more transmitter frequencies is lowered; (2) transmitter intermodulation cross products, transmitter spurious signals, and transmitter noise are all greatly weakened before being radiated by the transmitting antenna. Direct interference, too, can be restrained by selectivity between receiving antennas and receiver inputs.

ADJACENT CHANNEL INTERFERENCE, DIRECT

In the example of an uhf communications system being investigated by the application of this system analysis procedure, there are three possible situations regarding antennas. The first, though impractical for serious consideration aboard ship, gives an antenna to each SRC-20 receiver. With the assumed antenna isolation figure of 35dB between antennas, the power induced by 100W (50dBm) of transmit power in a separate antenna serving a receiver would be 15dBm. This induced signal is sufficient to cause unacceptable direct interference by desensitization and cross modulation ("adjacent channel" interference) to a received signal unless the separation between transmit and receive frequencies is greater than 15MHz. The second arrangement allows four transceivers to share a single antenna with an SRA-33 multicoupler, but now the available power at the transmitter frequency which is a potential threat to the receivers on the same antenna is 45dBm. Even though the interfering signal is now 30dB greater than in the separate-antenna case, the rejection characteristic of the SRA-33 is sufficient to avoid direct interference if the transmit and receive frequency separation is more than 4.5MHz. The last arrangement is again two separate antennas but with an SRA-33 multicoupler serving each antenna. The combination of selectivity and isolation now decreases the threat from desensitization or cross modulation until frequency separation is less than 1.1MHz. Figure A2 presents curves showing the combined effect of receiver desensitization and cross modulation, which occur at approximately equal signal levels.

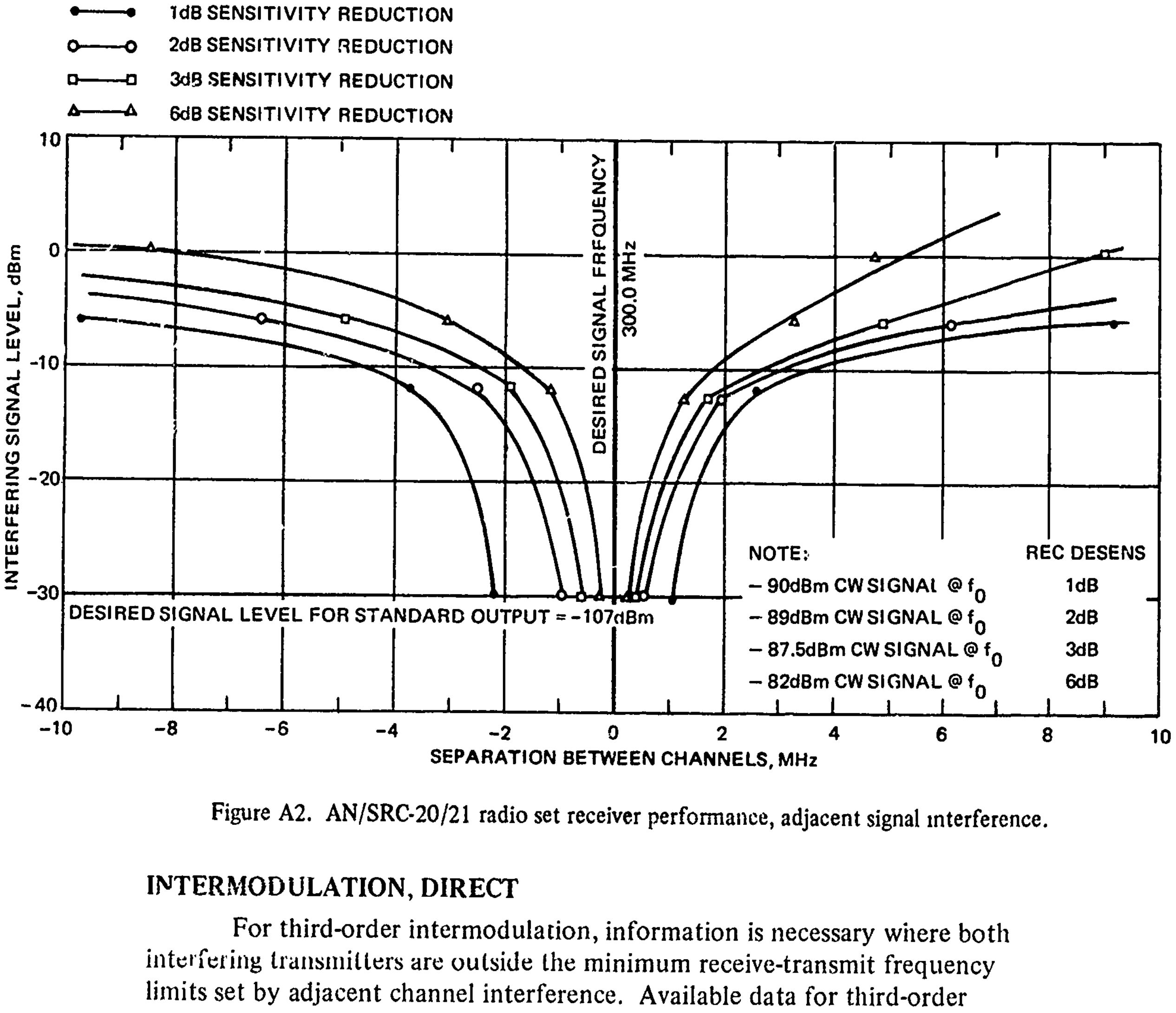

Figure A2. AN/SRC-20/21 radio set receiver performance, adjacent signal interference.

INTERMODULATION, DIRECT

For third-order intermodulation, information is necessary where both interfering transmitters are outside the minimum receive-transmit frequency limits set by adjacent channel interference. Available data for third-order receiver intermodulation do not include frequency separations greater than 9MHz below and 7MHz above the 300MHz receiver frequency. It is necessary to extend the very limited curves described by these data to estimate the frequency separation demanded by the 15dBm induced power in the receiving antenna by two 100W transmitters, when the SRC-20s are on separate antennas without multicouplers and adjacent channel limits are plus and minus 15MHz. From these extrapolated curves a frequency difference of only 11MHz or greater for transmitters above 300MHz will be enough to avoid third-order IM generation in the receiver. But the slope of the similar curve below 300MHz is much less steep, and a frequency difference of at least 29MHz is apparent. If four transceivers share a common antenna/SRA-33 combination, the extrapolated curves are referred to as before, and the variation of interfering signal powers at the receiver with change in frequency difference is calculated. When interfering powers equal the third-order intermodulation curve data at the same frequency difference, then that is the limit beyond which IM interference is insignificant. These comparisons prove that 6MHz above 300MHz and 9MHz below are the limits set by receiver intermodulation; adjacent channel interference limits were only 4.5MHz. It is only necessary to use this same comparative exercise, with an additional constant 35dB from antenna isolation added to the variable SRA-33 rejection, to show that with transceivers on separate antennas plus multicouplers, the receiver-generated third-order intermodulation interference is not a problem outside adjacent channel interference limits of 1.1MHz.

RECEIVER RADIATION, DIRECT

The local oscillator and other oscillators in a receiver can radiate small amounts of power, acting the same as a very low power transmitter and, under certain circumstances, producing interference to a close-by receiver. While this is seldom a source of severe interference, it should be checked to confirm that it is negligible.

The radiations occur at the local oscillator frequency or at harmonics of the local oscillator frequency. They may also occur at multiples of the crystal oscillator frequency where frequency multiplication is used to realize the local oscillator frequency. These frequencies are related to the frequency to which the receiver is tuned, and change as the receiver tuning is changed.

Receiver radiations must be eliminated at the source or by selectivity inserted in the path between the radiating receiver input terminals and the antenna connected to this receiver. Once radiated, the receiver radiation is indistinguishable from weak signals being received by other receivers and cannot be discriminated against.

The AN/SRC-20/21 receiver has three crystal oscillators, so there is a possibility of radiation at any multiple of these oscillators. When the receiver is tuned to 300MHz, these crystal oscillators are at 31.111MHz, 17MHz, and 3.5MHz. Two inband radiations were measured, one at 280MHz at -72dBm level and one at 342MHz at -89dBm level. In addition there were several out-of-band radiations.

The receiver radiation at 280MHz at -72dBm level will just produce a standard response (requires a level of -107dBm) in a receiver tuned to that frequency on a separate antenna with 35dB space isolation. The 342MHz at -89dBm level will be below receiver noise level and hence will cause no interference to a receiver tuned to 342MHz. When antenna couplers are included, the coupler selectivity is sufficient to eliminate any interference from this source.

A receiver tuned to 300MHz will be interfered with by the spurious radiation of a receiver tuned to 268MHz and of a receiver tuned to 320MHz in a manner analogous to that outlined above, provided that the available data for 300MHz can be extrapolated to cover these frequencies.

SPURIOUS, DIRECT

When SRC-20 transceivers are on separate antennas without receiver mode protection from multicoupler selectivity, antenna isolation alone is not great enough to avoid generation of significant receiver spurious signals at three frequencies below and one frequency above the 15MHz adjacent channel limitation. Two frequencies below the 4.5MHz adjacent channel minimum cause spurious signal interference when transmitter and receiver share an antenna and multicoupler. When the receiver is protected from the transmitter by both SRA-33 and 35dB antenna isolation, there are only one spurious frequency below and one above the 1.1MHz adjacent channel minimum. (These two frequencies are found from table A1 in the rows in which the values in the last column exceed 35dB – namely, 298.486 and 301.665MHz.)

TABLE A1. SPURIOUS RESPONSES OF AN/SRC-20 RECEIVER, TUNED TO 300MHz.

Frequency of Response	Level to Produce Standard Output	Atten Required to Reduce 51dBm to this Level	Coupler Attenuation	Added Atten Required*
260.056MHz	-40.2dBm	91dB	79dB	18dB
270.004	- 1.6	53	76	–
283.056	- 1.9	53	71	–
286.678	- 6.2	57	68	–
290.018	-20.8	72	65	13
292.388	>+ 7	<44	61	–
293.962	>+ 7	<44	58	-
296.556	>+ 7	<44	50	–
297.400	>+ 7	<44	45	5
298.486	- 9.9	61	31	36
(Responses 299 to 301 excluded)				
301.005	-22.4	73	20	59
301.503	- 4.9	56	30	32
301.665	-22.9	74	34	46
302.477	>+ 7	<44	37	<13
303.084	- 1.9	53	48	11
303.637	- 2.2	53	51	8
305.009	+ 2.4	49	55	
306.010	+ 4.2	47	58	–
317.040	- 4.2	55	71	–

*Includes 6dB required to reduce interference to 6dB below standard response level of 6dB (S+N)/N ratio.

NOISE, INDIRECT

Under each of the three possible antenna and/or multicoupler combinations for the SRC-20 transceivers there have been established bands of exclusion centered on the receive frequency by adjacent channel (desensitization and cross-modulation) interference. No information was located concerning broadband transmitter noise. This lack requires the calculation of transmitter noise power limits for each of the three antenna conditions. The most stringent of these limits should become a standard specification requirement.

The calculations will be based on that level of noise which increases receive system noise figure by 1dB. If transmitters and receivers are on separate antennas without SRA-33 multicouplers, the system noise figure at the receiving antennas is 13dB above thermal (–123dBm in a 6kHz bandwidth). An increase of 1dB will result from induced transmitter noise of –129dBm. Permissible radiated noise at the transmitter antenna to produce this level will be –94dBm. Transmitter system coax attenuation is 2dB; the limit of noise power delivered to a 50Ω load at transmitter terminals at 15MHz from its frequency is –92dBm.

When transmitters and receivers share a common antenna and multicoupler, there is no isolation between antennas. Only the 54dB multicoupler rejection, 4.5MHz from transmit frequency, attenuates transmitter noise. Receive system noise in 6kHz at the multicoupler antenna terminal is –121dBm. Induced transmitter noise must not exceed –127dBm to keep sensitivity decrease to 1dB. Now the limit on transmitter noise delivered to a 50Ω load at the transmitter output is –73dBm in a 6kHz band 4.5MHz from the transmit frequency.

Under conditions of separate antennas and multicouplers, both antenna isolation and multicoupler selectivity control transmitter noise impact on the receive system. Receive system noise figure and acceptable induced transmitter noise levels are the same as above. The total attenuation of 57dB puts the transmitter noise limit at –70dBm in a 6kHz band 1.1MHz from the transmit frequency. Table A2 summarizes these results.

TABLE A2. PERMISSIBLE TRANSMITTER BROADBAND NOISE LEVELS FOR 1dB IMPAIRMENT OF RECEIVER SENSITIVITY (6kHz bandwidth).

	Level at Transmitter Output	Level Below 100W Transmitter Rating
With separate antennas	–92dBm	142dB
Common antenna with couplers	–73	123
Separate antennas with couplers	–70	120

(Based on minimum channel separations of 15, 4.5, and 1.1MHz, respectively. Does not include any selectivity of transmitter output circuit because of lack of available data)

SPURIOUS, INDIRECT

Review of transmitter mode spurious signals finds only four frequencies as potential threats to receiver performance: transmitter at 300MHz; interference at 280 (–49dBm), 297 (–42dBm), 303 (–32dBm), and 320MHz (–55dBm). In a separate-antenna case with no multicouplers only receiver frequencies of 280 and 320MHz must be considered, because they fall outside the plus and minus 15MHz band around the receiver frequency already set by direct interference. The average level of these two spurious signals at the transmitter is –52dBm. Taking coax attenuation and antenna isolation into account, the transmitter spurious interference level is -91dBm at receiver terminals. This is 16dB greater than the level of the carrier used in sensitivity measurements.

When transceivers are served by a common antenna/multicoupler combination, the exclusion band is plus and minus 4.5MHz; the same two receiver frequencies are subject to transmitter spurious interference. But now the SRA-33 rejection to transmitter signals at 20MHz from midband is 72dB. This is enough to decrease the spurious signal to -124dBm at the receiver, removing the possibility of interference.

All four spurious frequencies must be checked when transceivers are on separate antennas with multicouplers. Signals at the two outer frequencies are attenuated by the total of 111dB, and the two inner signals become 87dB weaker. Therefore, at the receiver terminals, none of the interfering signals – at -163dBm and -124dBm respectively – are really spurious interference problems.

INTERMODULATION, INDIRECT

Only incomplete data on third- and fifth-order transmitter-generated intermodulation signals are available. With one SRC-20 transmitter at 300MHz (F1) and another (F2) at frequencies 1, 5, and 10% above 300MHz, investigations were made with 20, 40, and 60dB decoupling between transmitter terminals. At 1% (3MHz) separation only one value of IM signal level is published: -23dBm fifth order (3F1 - 2F2) with 20dB decoupling. A -51dBm third-order intermodulation signal was measured at 2F1 -F2 with 40dB decoupling for 5% (15MHz) separation. 20dB decoupling and 10% (30MHz) separation yielded a third-order intermodulation (2F1 - F2) at -40dBm. It is difficult to demonstrate the effect of this kind of interference with the analysis procedure without more data, but the single instance of third-order IM with 15MHz separation and 40dB decoupling can be applied to the usual three cases of antenna and multicoupler combinations. With separate antennas for both transmitters and the victim receiver on a third antenna tuned to the intermodulation frequency, the 40dB transmitter decoupling can be approximated closely by the summation of antenna isolation and coax losses. The -51dBm intermodulation signal generated in each transmitter is brought down to a level of -90dBm at the receiver by application of the 39dB attenuation sum from antenna isolation and coax losses. This signal, at a level 17dB above the carrier used during sensitivity measurements, will be a combination of single frequency (from carrier mixing) and an interference band caused by the information modulating the transmitters. When the two transmitters and victim receiver share a common antenna through a multicoupler, the 70dB decoupling between transmitters derived from multicoupler rejection at 15MHz is reason enough for removing the danger of this intermodulation interference. Of course, when this multicoupler rejection is increased by another 35dB from antenna isolation, under conditions of separate antennas with multicouplers, even less concern is justified.

TOPSIDE INTERMODULATION

Investigations of uhf intermodulation product levels known to be generated outside receive or transmit system have been made on several typical ships. There is considerable scatter in the measurement data, as is to be expected from ships varying considerably in configuration and topside arrangement. The average third-order intermodulation signal power level when the receiver is on an antenna separate from the transmitters is 28dB above thermal noise (18dB min, 51dB max); when the receiver shares an antenna with the transmitters, the average level increases to 51dB (24dB min, 66dB max). These figures are for transmitter powers of 20W, however. The increase of transmitter power to 100W (a 7dB change) should raise the average intermodulation levels to about 42 and 65dB above thermal, respectively. (In general, intermodulation signal levels vary as the square of the change in the transmitted signals causing them.) Receive system noise is only 15dB above thermal. The average intermodulation interference will then be 27 and 50dB above receive system sensitivity. (The more than 20dB difference between the levels for separate and shared antennas obviously implies that a receiver's coupling to IM sources in the transmitter antenna system and immediate vicinity is much greater when it shares an antenna than when it is on a separate antenna.) Converting interference signal levels for comparison with system interference yields -80 and -57dBm. None of the equipment-generated interference signal levels is greater than -90dBm. Thus, the topside third-order intermodulation sources provide interference 10 and 38dB more severe than those from system sources, on the average. Table A3 summarizes intermodulation levels.

TABLE A3. COMPARISON OF THIRD-ORDER INTERMODULATION LEVELS.

	Separate Antennas	Common Antennas with Couplers
Generated at transmitter, level at receiver	-90dBm	no problem
Generated in receivers	no problem	no problem
Generated in antenna environment, level at receiver	-80dBm	-57dBm

(These figures apply to situations outside the adjacent channel limits of 15, 4.5, and 1.1MHz previously established.)

SUMMARY OF RESULTS

Under the limitations previously listed and for an operating frequency of 300MHz, the following conclusions hold:

I – With transmitter and receiver on separate antennas and no couplers.

(a) Rejection of transmitter fundamental interference demands an excluded band greater than 15MHz each side of receiving frequency to avoid desensitization and cross modulation.

(b) Spurious responses of the receiver will occur for three specific transmitter frequencies below and one frequency above the excluded band of 15MHz.

(c) Third-order intermodulation interference will occur in a receiver for interfering signals from two 100W transmitters even for frequency separation well beyond the 15MHz excluded band.

(d) Transmitter broadband noise in a 6kHz band must be less than -92dBm at a frequency 15MHz away from the carrier frequency if decreased system sensitivity is to be prevented.

(e) Transmitter spurious radiations will be strong enough to cause interference at two frequencies, one 20MHz above and one 20MHz below the operating frequency. Two other interferences fall within the excluded band.

(f) Transmitter intermodulation will produce a third-order interfering signal of approximately -90dBm level at frequency separations of approximately 15MHz.

(g) Intermodulation products of the third order generated in the antenna system and antenna environment will be a problem. The average level is 27dB above the receiving system sensitivity. This is 10dB more severe than for any equipment-generated intermodulation, and will fall on the same frequencies.

II – <u>With transmitters and receivers on the same antenna isolated by couplers.</u>

(a) Rejection of transmitter fundamental interference demands an excluded band of 4.5MHz each side of receiving frequency to avoid receiver desensitization and cross modulation.

(b) Spurious responses in the receiver will occur for only two specific transmitter frequencies below the excluded band of 4.5MHz.

(c) Third-order intermodulation interference will occur in receivers for interfering signals from two 100W transmitters for a frequency separation of 9.5MHz or less from the receiving frequency.

(d) Transmitter broadband noise in a 6kHz band must be less than -73dBm at a frequency 4.5 MHz away from the carrier frequency if decreased system sensitivity is to be prevented.

(e) Transmitter spurious radiations will produce potential interference at two frequencies, one 20MHz above and one 20MHz below the operating frequency, but the levels are approximately equal to the noise level of the receiving system and should cause little interference.

(f) Transmitter intermodulation will not be a problem, as it is of lower level than the receiving system noise.

(g) Intermodulation products of the third order generated in the antenna system and antenna environment will be a problem. The average level is 50dB above the receiving system sensitivity. This is 33dB more severe than for any equipment-generated intermodulation, and will fall on the same frequencies.

III – With transmitters on one antenna and receivers on a separate antenna, using couplers.

(a) Rejection of transmitter fundamental interference demands an excluded band of 1.1MHz each side of receiving frequency to avoid receiver desensitization and cross modulation.

(b) Spurious responses of the receiver will occur for one specific transmitter frequency below and above the excluded band of 1.1MHz each side of the receiving frequency.

(c) Third-order intermodulation in receivers is not a problem for interfering signals from two 100W transmitters outside the excluded band of 1.1MHz each side of the receiving frequency.

(d) Transmitter broadband noise in a 6kHz band must be less than -70dBm at a frequency 1.1MHz away from the carrier frequency if decreased system sensitivity is to be prevented.

(e) Transmitter spurious radiations will not be a problem, as they are attenuated below the receiving system noise.

(f) Transmitter intermodulation is not a problem, as it is below the receiving system noise level.

(g) Intermodulation products of the third order generated in the antenna system and antenna environment will be a problem. The average level is 27dB above the receiving system sensitivity. This is 10dB more severe than for any equipment-generated intermodulation, and will fall on the same frequencies.

CONCLUSIONS

A technique has been developed for the analysis of the interference situation in a uhf communication system and illustrated by application at one specific midband frequency of 300MHz. With minor modifications this technique can be applied over the uhf band and to other equipments and arrangements wherever adequate basic measurement data are available or can be reliably estimated.

The following specific conclusions are reached:

(a) The use of antenna multicouplers (or filters) is essential in shipboard uhf communication systems, even in situations in which there is no overriding requirement to reduce the number of antennas. The selectivity of multicouplers greatly reduces the number of interferences experienced.

(b) In general, increased selectivity is much more effective in reducing interferences than is any practical increase of isolation due to an increase in antenna separation.

(c) In situations in which the added expense and extra cables can be justified, a system having minimum interference can be achieved by using multicouplers and by grouping transmitters on one antenna and receivers on a separate antenna. This may not be convenient with transceiver-type equipments without modification.

(d) Much can be done to alleviate interference by careful consideration of frequency assignments.

(e) A certain minimum frequency separation must be maintained between channels having transmitters and receivers operating simultaneously. This minimum requirement varies with equipment type, multicoupler application, antenna separation, and the portion of the frequency band under consideration. For the three antenna system and equipment arrangements assumed in this report, these minimum frequency separations are approximately 15MHz, 4.5MHz, and 1.1MHz.

(f) Certain specific frequencies outside these minimum frequency separations must be left unassigned if interference from intermodulation products, receiver spurious responses, etc., are to be avoided. In general, these frequencies change as the operating frequencies of transmitters and receivers change.

(g) Only interferences arising from sources within the uhf 225–400MHz band have been considered and those only for one particular equipment, the AN/SRC-20, and only at one particular operating frequency, 300MHz.

RECOMMENDATIONS

(a) The work and this report should be extended to consider the interference situation at other representative frequencies, or possibly at all frequencies, within the uhf communication band from 225 to 400MHz.

(b) This report should be extended to include consideration of interference to and from other types of uhf communication equipments operating in or proposed for this band.

(c) This report should be extended to include out-of-band interferences to hf, vhf, uhf, and shf communication equipments and out-of-band interferences from hf, vhf, uhf, and shf communication equipments.

(d) This technique should be extended to include interferences to and from radar equipments, ECM equipments, and other related equipments. This may require a measurement program in cases in which reliable data are currently nonexistent.

(e) Because some information required for system performance analysis is either lacking (as in transmitter broadband noise) from present transmitter and receiver performance tests or not directly applicable (as in receiver intermodulation and receiver spurious response data), a detailed evaluation should be conducted to modify equipment test methods so that better support of system analyses will be provided by future equipment test data.

(f) This report should be extended to include techniques for the devising of frequency assignment plans that are as nearly interference-free as possible considering the performance limitations of current equipments. Some suggestions for assignments of those channels carrying heavy or urgent traffic should be included.

REFERENCES AND ACKNOWLEDGMENTS

The data contained in this report have been obtained from several sources. Among these are:

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DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY *(Corporate author)*

Naval Electronics Laboratory Center
San Diego, California 92152

2a. REPORT SECURITY CLASSIFICATION

UNCLASSIFIED

2b. GROUP

3 REPORT TITLE

SHIPBOARD VHF/UHF ANTENNA DESIGN AND UTILIZATION CRITERIA

4 DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Research and Development July 1971 through August 1972

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

M. S. Kvigne

6 REPORT DATE

5 January 1973

7a. TOTAL NO OF PAGES

66

7b. NO. OF REFS

14

8a. CONTRACT OR GRANT NO

b. PROJECT NO. SF14.222.004
Tasks 15347B, C

c. (NELC B164)

d.

9a. ORIGINATOR'S REPORT NUMBER(S)

TR 1853

9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10 DISTRIBUTION STATEMENT

Distribution limited to U.S. Government agencies only; Test and Evaluation; 5 January 1973. Other requests for this document must be referred to NELC.

11 SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY

Naval Ship Systems Command

13 ABSTRACT

Presents a technique which enables the antenna design engineer to establish his own design and location criteria and the associated trade-offs and to analyze existing circuits.

Conclusions are drawn about shipboard antenna design and location for the ship-to-ship case (example: Ship antenna height has little effect on circuit performance at low vhf frequencies), the ship-to-air case (High ship antennas and the highest frequencies produce detection contours with large amounts of lobing and the shortest distances of satisfactory performance); and the general case (High time availabilities require large protection biases to achieve the desired performances).

An appendix indicates the effect of a complex shipboard environment upon a sample receiving system.

DD FORM 1 NOV 65 1473 (PAGE 1)
0102-014-6600

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Shipboard antenna systems Vhf/uhf communications Mathematical modeling Statistical communications						