

SPAWAR



*Systems Center
San Diego*

TECHNICAL REPORT 1770
April 1998

Link Analysis of Shipboard SATCOM Phased-Array Antennas

R. W. Major
J. W. Rockway
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Distribution authorized to U.S. Government agencies only; administrative or operational use; April 1998. Other requests shall be referred to the Commanding Officer, Space and Naval Warfare Systems Center, San Diego, California 92152-5001.

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ADMINISTRATIVE INFORMATION

The work detailed in this report was performed for Space and Naval Warfare Systems Command, PMW 133, by the Electromagnetics and Advanced Technology Division, Code D85, the RF Networks Branch, Code D824, and the Microwave/MMW Branch, Code D753, Space and Naval Warfare (SPAWAR) Systems Center, San Diego (SSC San Diego).

Under authority of
C. J. Sayre, Head
Electromagnetics &
Advanced Technology Division

EXECUTIVE SUMMARY

SCOPE AND OBJECTIVES

This report is submitted in partial fulfillment of required deliverables in support of the Multi-mission, Multifunction Broadband Antenna (MMBA) project funded by Space and Naval Warfare Systems Command, PMW-133. The objective of the MMBA project is to demonstrate the capability of multibeam, multiband satellite communications (SATCOM) antennas in a low observable shipboard structure with reduced infrared (IR) signature and radar cross section (RCS). Emphasis is on fielding an antenna system that is most appropriate to future SATCOM antenna requirements. This report addresses link analyses for the candidate systems.

APPROACH

The combat effectiveness of current Navy ships is antenna-limited, and the desire for increased data dissemination and connectivity with joint forces is driving the need for new antennas aboard Navy ships. This, and the need for reducing the RCS and IR signatures of next-generation Navy ships, has driven the investigation of multifunction phased-array antennas embedded in the ship superstructure. Mounting the antennas in the superstructure implies reducing their height above the water, which would have a negative effect on line-of-sight systems (reducing their range). Thus, satellite communication systems were chosen for the investigation. The existence of commercial efforts (AIRLINK at L-Band, DBSS at Ku-band) and Air Force efforts (ICAPA and ELCAPA at EHF), and the cost benefits of leveraging off these efforts, has led to the consideration of using the Ball Aerospace and Boeing array technologies.

This report addresses link analyses for the following six SATCOM systems: UHF SATCOM, INMARSAT, SMQ-11, SHF SATCOM (DSCS), EHF SATCOM, and Global Broadcast Service (GBS). Where applicable, parameters from Ball Aerospace array developments are used in the calculations for UHF SATCOM, INMARSAT, and SMQ-11. Likewise, parameters from Boeing array developments are used in the calculations for SHF SATCOM, EHF SATCOM, and GBS.

RESULTS

Each of the individual systems is evaluated. The requirements of a phased-array implementation of each of the systems are derived. Of primary interest is the number of antenna elements. The optimal placement and scan angle requirements for a shipboard implementation of the proposed arrays are also discussed.

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1. INTRODUCTION

This report is submitted in partial fulfillment of required deliverables in support of the Multi-mission, Multifunction Broadband Antenna (MMBA) project funded by Space and Naval Warfare Systems Command, PMW 133. The objective of the MMBA project is to demonstrate the capability of a multibeam, multiband satellite communications (SATCOM) antenna in a low observable shipboard structure with reduced infrared (IR) signature and radar cross section (RCS). The following systems are candidates for the proposed antenna system:

- Ultra-High-Frequency Satellite Communications (UHF SATCOM): 240 to 318 MHz
- International Maritime Satellite (INMARSAT): 1.535 to 1.5425-GHz downlink;
1.6365 to 1.644-GHz uplink
- AN/SMQ-11 shipboard antenna: 1.684-GHz uplink and 2.254-GHz downlink
- Extremely High Frequency SATCOM: 44-GHz, uplink; 20-GHz downlink
- Global Broadcast System (GBS): 20-GHz downlink

Emphasis is on fielding an antenna system that is most appropriate to future SATCOM antenna requirements.

2. SHIPBOARD SATCOM PHASED-ARRAY ANTENNAS

The Space and Naval Warfare (SPAWAR) Systems Center, San Diego (SSC San Diego) Electromagnetics and Advanced Technology Division is conducting research and development efforts for advanced antenna system architectures and technologies for current and future naval surface combatants. The combat effectiveness of current Navy ships is antenna-limited, and the desire for increased data dissemination and connectivity with joint forces is driving the need for new antennas aboard Navy ships. This need and the need for reducing the RCS and IR signatures of next-generation Navy ships has driven the investigation of multifunction phased-array antennas embedded in the ship superstructure. Mounting the antennas in the superstructure implies reducing their height above the water, which would have a negative effect on line-of-sight (LOS) systems (reducing their range). Thus, satellite communication systems were chosen for investigation. The existence of commercial efforts (AIRLINK at L-B, and Direct Broadcast Satellite System (DBSS) at Ku-band) and Air Force efforts (ICAPA and ELCAPA at EHF), and the cost benefits of leveraging off these efforts has lead to consideration of using the Ball Aerospace and Boeing array technologies.

This report addresses link analyses for the following six SATCOM systems:

- UHF SATCOM
- INMARSAT

- AN/SMQ-11
- SHF SATCOM (DSCS)
- EHF SATCOM
- GBS

Where applicable, parameters from Ball Aerospace array developments are used in the calculations for UHF SATCOM, INMARSAT, and SMQ-11. Likewise, parameters from Boeing array developments are used in the calculations for SHF SATCOM, EHF SATCOM, and GBS. Table 1 lists the basic requirements for the identified SATCOM systems. Each of the systems is discussed in the following sections.

Table 1. Basic requirements for SATCOM systems.

Description	Frequency (MHz)	G/T (dB/K)	EIRP (dBw)
UHF SATCOM			
Receive	240 to 270	-18.5	
Transmit	290 to 318		18.8
INMARSAT-B			
Receive	1525 to 1545	-4	
Transmit	1626.5 to 1646.5		25 to 33 in 4-dB steps
SMQ-11 receive	1684 to 1710	1.9	
SMQ-11 receive	2205 to 2254	3.9	
SHF SATCOM			
Receive	7250 to 7750	12.2 (20.0)	
Transmit	7900 to 8400		71.5
GBS receive	20,200 to 21,200	10.6 (18.7)	
EHF SATCOM			
Receive	20,200 to 21,200	5.0 (13.0)	
Transmit	43,500 to 45,500		45.0 (59.0)

3. INTEGRATED UHF/L-BAND/S-BAND ANTENNA

This section addresses the definition of a phased-array system that supports UHF and other L-band and S-band SATCOM communication requirements (e.g., INMARSAT and AN/SMQ-11). The objective is a phased-array system that provides the required communication performance while meeting the projected ship signature requirements. Full-scale demonstration models are under consideration for development to provide cost estimates for future production versions of this antenna system. Presently, it is envisioned that the demonstration antenna systems will be demonstrated within the context of the FY 98 Low Observable, Multifunction Stack (LMS) Advanced Technology Demonstration (ATD). The LMS ATD provides previously unusable locations for use by SATCOM antennas. SATCOM antennas are particularly appropriate for the LMS, since, for the most part, all other antenna types require height and/or an unrestricted view.

For the LMS demonstration, a common aperture for the UHF SATCOM and L-band/S-band receive is under development. A separate, integrated array for INMARSAT-B transmit is currently envisioned. The following subsections discuss each of these individual systems.

3.1 UHF SATCOM

The Navy UHF Satellite Communications (UHF SATCOM) system was designed to be the primary ship-to-shore communications link. The system provides worldwide communications, via satellite, between the latitudes of 70° north and 70° south.

3.1.1 Link Budget Analysis

The derivation of a satellite communication link analysis can be divided into three parts:

- uplink to the satellite from the ground station
- the satellite
- the downlink from the satellite to the receiving ship station

3.1.1.1 Uplink. To describe a transmitter, the variable of interest is the effective isotropic radiating power (EIRP). The transmitter carrier power, C_t , and the equipment losses encountered between the transmitter and the antenna, L_e , define this variable. The transmitter antenna gain, G_t , is also included:

$$\text{EIRP}_u = C_t G_t = C_t G_t / L_e, \quad (1)$$

where

C_t is the carrier power out of transmitter,

L_e is the loss in equipment: diplexers, couplers, and cables,

G_t is the gain of transmit antenna, and

C_{ta} is the carrier power delivered to the antenna.

After the carrier signal leaves the antenna, it experiences a spherical spreading loss, L_{ss} . This loss is directly proportional to the square root of the distance from the transmitter:

$$L_{ss} = 4\pi r^2. \quad (2)$$

The other losses are due to tracking error, polarization error, and fading. These losses are included in a single variable, the uplink losses, L_u . With these different losses and the EIRP_u, the power density, S_{ds} , of the carrier at a given distance, r , from the transmitter can be calculated as

$$S_{ds} = (C_{ta} G_t)/(L_{ss} L_u) = \text{EIRP}_u/(L_u 4\pi r^2). \quad (3)$$

The total signal power collected at the satellite antenna is dependent on the effective area or aperture of the antenna. The antenna aperture is given by

$$A_s = G_{rsa} c^2/(4\pi f_u^2), \quad (4)$$

where

A_s is the satellite antenna aperture,

G_{rsa} is the satellite antenna receive gain,

c is the speed of light, and

f_u is the uplink frequency.

The total signal power, C_u , collected at the satellite receiving antenna, is

$$C_u = S_{ds} A_s = (\text{EIRP}_u/L_u) G_{rsa} (c/(4\pi f_u))^2. \quad (5)$$

If $L_{pu} = (c/(4\pi r f_u))^2$, then the uplink carrier power can be rewritten as

$$C_u = S_{ds} A_s = (\text{EIRP}_u/L_u) (G_{rsa}/L_{pu}). \quad (6)$$

Next, the uplink noise in the system must be determined. Given that thermal white additive Gaussian noise is no longer negligible at the satellite receive antenna as it is at the ground station transmitter, the following equation can be used:

$$N_u = kT_u B, \quad (7)$$

where

N_u is the uplink noise power density,

k is the Boltzman's constant,

T_u is the effective noise temperature of the satellite, and

B is the channel bandwidth.

With the carrier signal power, C_u , and the effective thermal noise power, N_u , the signal-to-noise ratio (SNR) at the satellite receiver can be calculated as

$$C_u/N_u = [EIRP_u/(L_u L_{Pd})] G_{tsa}/(kT_u B). \quad (8)$$

3.1.1.2 Satellite. The hard-limiting of the received signal in the satellite provides a net SNR gain of 1.1 dB for all cases where the received SNR is greater than or equal to 1 dB. This gain is denoted as G_s . Thus, the SNR out of the satellite is

$$C_s/N_s = G_s C_u/N_u, \quad (9)$$

where

C_s is the satellite transmitted carrier power and

N_s is the satellite transmitted noise power.

The noise component of the signal at the output of the satellite transmitter is not negligible and needs to be determined. By rearranging equation (9), the following expression is derived:

$$N_s = (N_u C_s)/(C_u G_s). \quad (10)$$

3.1.1.3 Downlink. The downlink component can be derived in essentially the same manner as the uplink component except that there is an additional noise component. The two noise components can be treated separately because of their statistical independence. The downlink carrier received at the ground or ship receiver is

$$C_r = [(C_s G_{tsa})/(L_d L_{Pd})] G_r. \quad (11)$$

The additional noise component is

$$N_r = G_r (N_s G_{tsa})/(L_d L_{Pd}), \quad (12)$$

where

G_{tsa} is the satellite antenna transmission gain,

G_r is the ground station antenna reception gain,

L_d is the other downlink propagation loss, and

L_{Pd} is the downlink spherical spreading path loss.

If N_s in equation (12) is replaced with equation (10), the following expression results:

$$N_r = [N_u/C_u] [C_s/G_s] [G_{tsa}/(L_d L_{pd})] G_r. \quad (13)$$

Also contributing to the noise component will be the ground station thermal white additive Gaussian noise, which, again, is simply:

$$N_d = kT_d B, \quad (14)$$

where

N_d is the downlink noise power density,

k is the Boltzman's constant,

T_d is the effective noise temperature of the ground station antenna, and

B is the channel bandwidth.

The total noise power is the sum of the two noise powers, N_r and N_d :

$$N = N_r + N_d = [N_u/C_u] [C_s/G_s] [G_{tsa}/(L_d L_{pd})] G_r + kT_d B. \quad (15)$$

Since noise is normally described in terms of noise power density ratio or noise power density per Hz, and because $N_u = kT_u B$, the bandwidth component N_0 is

$$N_0 = [kT_u/C_u] [C_s/G_s] [G_{tsa}/(L_d L_{pd})] G_r + kT_d. \quad (16)$$

At this point, the total carrier-to-noise power density, C_r/N_0 , received by the earth station antenna can be written as

$$C_r/N_0 = \{[(C_s G_{tsa})/(L_d L_{pd})] G_r\} / \{[kT_u/C_u] [C_s/G_s] [G_{tsa}/(L_d L_{pd})] G_r + kT_d\}. \quad (17)$$

To define C_s , the total radiated power from the satellite, P_s , must be determined. This value is equal to the carrier plus the noise:

$$P_s = C_s + N_s = C_s [1 + N_u/(C_u G_s)]. \quad (18)$$

From equation (18), C_s can be determined:

$$C_s = P_s / [1 + N_u/(C_u G_s)]. \quad (19)$$

Substituting equations (19) into equation (17) and assuming EIRP_s is equivalent to P_s times G_{tsa} , the following expressions are derived:

$$C_r/N_0 = [U^1 + D^{-1}]^{-1}, \quad (20)$$

$$U = (G_s C_u)/(k T_u). \quad (21)$$

Thus,

$$D = [\text{EIRP}_s / (1 + N_u / (C_u G_s))] [1 / (L_d L_{pd})] [G_r / T_d] [1/k]. \quad (22)$$

3.1.1.4 Noise Temperatures. There are two items remaining in equation (20) that must be defined, the two noise temperatures, T_d and T_u . Each of these noise temperatures is actually the sum of two temperatures: the source noise temperature or the sky temperature, T_s , and the equivalent system noise temperature, T_{sy} . T_s reflects what is collected by the antenna and is dependent on where the antenna is pointing. T_{sy} is due to internal equipment noise sources reflected back to the receive antenna. Thus, the uplink noise temperature, T_u , is due to the satellite antenna pointed toward a warm earth and the internal temperature generated by the equipment of the satellite receiver. The downlink noise temperature, T_d , is a combination of the ground station receive antenna aimed at the satellite and the internal temperature generated by the ground station receive equipment.

$$\begin{aligned} T_d &= T_s \text{ (ground station receive antenna pointed toward the satellite)} \\ &+ T_{sy} \text{ (ground station internal receive equipment)} \end{aligned} \quad (23)$$

$$\begin{aligned} T_u &= T_s \text{ (satellite receive antenna pointed down to earth)} \\ &+ T_{sy} \text{ (satellite internal receive equipment)} \end{aligned} \quad (24)$$

3.1.1.5 Energy-Per-Bit-To-Noise-Power-Density Ratio (E_b/N_0)

If E_b is defined as the total carrier signal divided by the number of bits transmitted per second, and N_0 is the noise-power density, C_r/N_0 can be converted to E_b/N_0 by the following equation:

$$E_b/N_0 = C_r / (D_r/N_0), \quad (25)$$

Where D_r is the data rate.

3.1.2 Link Budget Calculations

The link budget calculation is presented for the case of a shore-to-ship transmission over LEASAT and ship-to-ship transmission over LEASAT. The ship is configured with four AN/WSC-3 radios and has an elevation angle to the satellite of 10° . The shore station has an AN/WSC-5 configuration and has an elevation of 30° to LEASAT. Both the 25-kHz non-DAMA and 25-kHz DAMA modes are considered. Only the 25-kHz DAMA mode is considered for the ship-to-ship transmission. The non-DAMA mode will be operating at 2400 bps. The DAMA mode will be operating with a 1/2 rate forward error correction (FEC), and a burst rate of 19.2 kbps.

3.1.2.1 25-kHz Non-DAMA Mode (Shore-to-Ship). The first calculations are for the non-DAMA mode. If the uplink term is converted to dB, C_u in equation (21) is replaced by equation (6) and EIRP_u in equation (6) is replaced with equation (1), the following results:

$$U = C_t + G_t - L_e - L_u - L_{pu} + (G_{rsa} / T_u) - k + G_s. \quad (26)$$

From tables 1, 2, and 3 in appendix A of the U.S. Navy Link Margin Calculations,* the following can be found:

$C_t = 20$ dBW, carrier power out of transmitter

$G_t = 15$ dB, gain of transmit antenna

$L_c = -3.5 - 7 - 0.7 = -11.2$ dB, cable loss + combiner loss + diplexer loss

$G_{\text{sat}}/T_u = -18$ dB/K, satellite antenna receive gain divided by effective noise power of the satellite

$L_{\text{Pu}} = 173.7$ dB, uplink spreading loss

$L_u = 3.5$ dB, other uplink losses

$k = -228.6$ dBW/K/Hz, Boltzman's constant

$G_s = 1.1$ dB, satellite gain of hard limiter

Using this data and equation (26), the uplink component value will be $U = 58.3$ dB and $U^1 = -58.3$ dB ($= 1.48 \times 10^{-6}$). Substituting equation (21) into equation (26), and then writing the resulting equation in dB, the following downlink equation is formed:

$$D = \text{EIRP}_s - 10 \log_{10}(1 + BU^1) - L_d - L_{\text{Pd}} + G_r/T_r - k \text{ nm.} \quad (27)$$

where the shipboard antenna receive gain divided by the effective noise of the shipboard receiver is

$$G_r/T_r = G_r - 10 \log_{10}(T_s + T_{\text{sy}}). \quad (28)$$

From tables 1, 2, and 4 in appendix A of the U.S. Navy Link Margin Calculations*, the following can be found:

$\text{EIRP}_s = 26$ dB (channel 6 is used), effective isotropic radiating power from satellite

$B = 25$ kHz, channel bandwidth

$L_d = 5.5$ dB (10° angle from ship to LEASAT), other downlink propagation loss

$G_r = 11$ dB, ground station antenna reception gain

$L_{\text{Pd}} = 172.8$ dB, downlink spherical spreading loss

The value for the ship receiver's sky temperature, T_{sy} , can be found in a Naval Research Laboratory report, "Antennas and Receiving-System Noise-Temperature Calculation." In the

* Navy Report. 15 Aug. 1991. "U.S. Navy Link Margin Calculations." SSC San Diego UHF SATCOM DAMA Library Number U-DA-D-03010-00.

referenced report, T_s is approximately 450K. To obtain the T_{sy} of the ship receiver components, the following relationship for cascading amplifiers is used:

$$T_{sy} = T_o (F_{sy} - 1) = T_o [F_1 - 1 + (F_2 - 1)/G_1 + \dots + (F_n - 1)/(G_1 G_2 \dots G_{n-1})]. \quad (29)$$

The following values are extracted from table 4 in appendix A of the U.S. Navy Link Margin Calculations. The meaning of these values is more apparent with the help of figure 1.

Table 2. Equipment numbers for large ship (four WSC-3 radios).

Equipment	Loss	Noise figure	Gain
Cable 1	1.12	1.12	0.89
Diplexer	1.26	1.26	0.79
LNA		1.78	1000.00
Cable 2	2.00	2.00	0.50
Splitter	3.98	3.98	0.25
AN/WSC-3		19.95	1.00
Cable 3	2.00	2.00	0.50

Using the values in table 2 results in $T_{sy} = 502K$:

$$\begin{aligned} T_{sy} &= 290 [1.12 - 1 + (1.26 - 1)/.89 + (1.78 - 1)/(.79 \times .89) \\ &+ (2 - 1)/(.79 \times .89 \times 1000) + (3.98 - 1)/(.79 \times .89 \times 1000 \times .5) \\ &+ (19.95 - 1)/(.79 \times .89 \times 1000 \times .5 \times .25) = 502K \end{aligned}$$

This results in a downlink component value, $D = 57.34$ dB and $D^{-1} = -57.34$.

If the U and D terms are combined as in equation (20), the resulting carrier-to-noise ratio at the output of the ships receiver is 54.8 dB:

$$C_r/N_o = [(1.48 + 1.82) \times 10^{-6}]^{-1} = .3 \times 10^6 = 54.8 \text{ dB}. \quad (30)$$

From this carrier-to-noise ratio, the energy-per-bit-to-noise ratio is:

$$E_b/N_o = C_r/N_o - D_r = 54.8 - 10 \log_{10}(2400) = 21 \text{ dB} \quad (31)$$

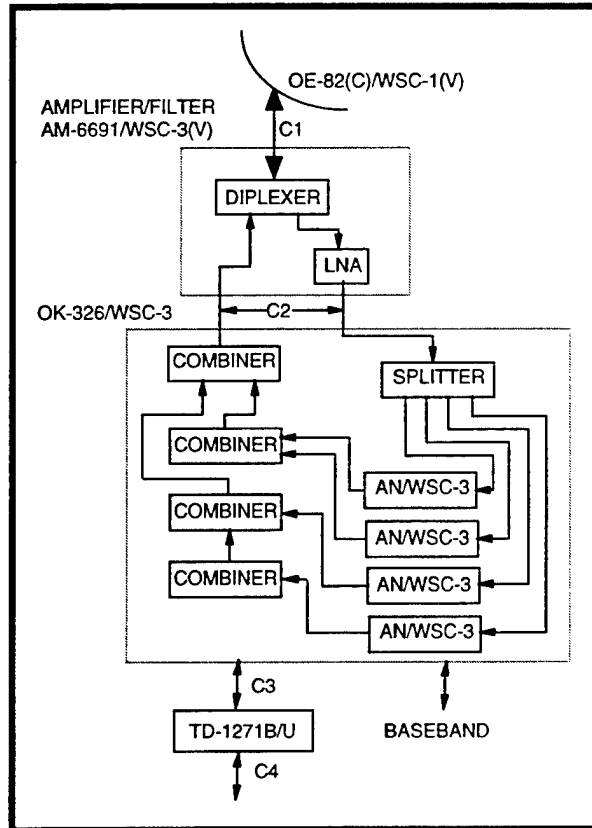


Figure 1. Large ship configuration (four WSC-3 radios)

From table 5 in appendix A in the U.S. Navy Link Margin Calculations report, the required E_b/N_0 for a non-DAMA signal with a BER = 10^{-5} , is 13 dB. This suggests that the link has an 8-dB margin.

3.1.2.2 25-kHz DAMA Mode (Shore-to-Ship). In the case of the 25-kHz DAMA mode, the signal uses a 1/2 rate FEC with a DAMA burst rate, D_r , of 19.2 kbps. Calculations from the transmit site to the ship's AN/WSC-3 radio demodulator are exactly the same as for the 25-kHz non-DAMA mode. However, for the 25-kHz DAMA mode, the signal is now sent via another cable, C_3 , to the 25-kHz DAMA multiplexer instead of passing through the AN/WSC-3 demodulator. This cable will insert additional losses. It was determined from the U.S. Navy Link Margin Calculations report that this cable added an insignificant 2.9° to the systems equivalent temperature, T_{sy} .

To obtain the DAMA modes, E_b/N_0 , the burst rate of the signal and FEC must be taken into account. This yields the following scalar equation:

$$E_b/N_0 = C_r/N_0 [1/(D_r R)], \quad (32)$$

where

$$D_r = 19.2 \text{ kbps,}$$

$$R = 1/2.$$

From equation (32), the resulting SNR is 15 dB. From table 6 in appendix A of the U.S. Navy Link Margin Calculations, for this DAMA system, an E_b/N_0 of 9.2 dB is required to obtain a BER of 10^{-5} . Considering the results in equation (31), a 5.8-dB margin is achieved.

3.1.2.3 25-kHz DAMA Mode (Ship-to-Ship). The only difference between this case and the previous 25 kHz DAMA mode (shore-to-ship) is that the antenna gain on the ship is now 8.65 dB rather than the 11 dB used for shore-to-ship, and both uplink and downlink are via the ship antenna. The resulting calculation results in an excess margin of 0.1 dB. The 25-kHz DAMA mode (ship-to-ship) is the most stressing link.

3.1.2.4 Spread Sheet Summary. Table 3 summarizes the link analysis results for the 25-kHz non-DAMA mode (shore-to-ship), 25-kHz DAMA mode (shore-to-ship), and 25-kHz DAMA mode (ship-to-ship).

Table 3. Summary of link analysis for parabolic dish configurations.

	Non-DAMA shore-to-ship	DAMA shore-to-ship	DAMA ship-to-ship
Shore Tx power (dBW)	20.00	20.00	20.00
Shore antenna gain (dB)	15.00	15.00	8.65
Le (dB)	11.20	11.20	10.20
Lu (dB)	3.50	3.50	5.50
Lpu (dB)	173.70	173.70	173.90

Table 3. Summary of link analysis for parabolic dish configurations. (Continued)

	Non-DAMA shore-to-ship	DAMA shore-to-ship	DAMA ship-to-ship
Satellite signal gain (dB)	1.10	1.10	1.10
Satellite G/T (dB)	-18.00	-18.00	-18.00
Uplink (dB)	58.30	58.30	50.75
Satellite EIRP (dB)	26.00	26.00	26.00
Frequency (MHz)	297.95	297.95	297.95
Slant range (km)	40586.00	40586.00	40546.00
Channel bandwidth (Hz)	25000.00	25000.00	25000.00
Ld (dB)	5.50	5.50	5.50
Lpd (dB)	172.81	172.81	172.81
Ship Receive gain (dB)	11.00	11.00	8.65
Ship sky noise (K)	450.00	450.00	450.00
System noise (K)	502.96	502.96	502.96
Ship G/T (dB/K)	-18.79	-18.79	-21.14
Data rate (bps)	2400.00	19200.00	19200.00
FEC rate	1.00	0.50	0.50
Downlink (dB)	57.34	57.34	54.32
Eb/No (dB)	20.98	14.96	9.34
Required Eb/No (dB)	13.00	9.20	9.20
Excess margin	7.98	5.76	0.14

Table 4 lists system noise temperature for the parabolic dish.

Table 4. System noise temperature of UHF SATCOM parabolic dish configuration.

	Gain (dB)	NF (dB)	Noise
Cable 1	-0.50		35.39
Diplexer	-1.00		84.25
LNA	30.00	2.50	318.81
Cable 2	-3.00		0.41
Splitter	-6.00		2.44
AN/WSC-3	0.00	13.00	<u>61.67</u>
System noise (K)			502.96

3.1.3 Phased-Array Antenna Element Count

3.1.3.1 Method. The number of elements required in a phased-array antenna to duplicate the performance of the existing parabolic satellite antenna can be calculated. The approaches are different for the transmit and receive cases. For the receive case, the first step is to determine the G/T for the receive phased-array antenna. Because of a number of losses unique to the phased-array antenna, this G_r will differ from the gain required of a parabolic antenna. Most of these unique losses can be attributed to the wide scan angle sometimes required of the phased array. Some losses that are more prevalent at the extreme scan angles will include scan angle losses and polarization losses.

Equation (28) can be modified to solve for the receive antenna gain. The modified expression for G_r is

$$G_r = (G_r/T_r)(T_s + T_{sy})L_{pol}L_{scan\ angle}L_{sidelobe}. \quad (33)$$

The scan angle losses can be approximated at 3/2 power of the cosine of the angle to which the beam is scanned off the normal to the array.

$$L_{scan\ angle} = \cos(S)^{3/2}. \quad (34)$$

The phased-array antenna may be circularly polarized at the broadside with an axial ratio near one. As the scan angle is increased, the axial ratio is proportional to the inverse of the cosine of the scan angle. Equation (35) is an approximation of the polarization mismatch.

$$L_{polarization} = [1 + \cos(S)]^2/[2(1 + \cos(S)^2)]. \quad (35)$$

Satellites usually impose side-lobe specifications on antennas. These side-lobe levels are very difficult to meet with a phased-array antenna, given all of the sources of error. This is particularly true at a wide scan angle. Amplitude taper across the array is usually required to mitigate the side-lobes. An amplitude taper implies a loss in antenna gain, here assumed to be a conservative $L_{sidelobe} = 0.5$ dB.

The number of elements required for the receive phased array is

$$N_r = G_r/G_e, \quad (36)$$

where

N_r is the number of receive phased-array elements,

G_r is the gain of the receive phased array, and

G_e is the gain of the individual elements of the receive phased array.

and the elements are assumed to be spaced far enough apart so that the effects of mutual coupling are minimal.

Combining equations (33) and (36) yields the complete expression for the number of elements in a receive phased array:

$$N_r = [(G_r/T_r)(T_s + T_{sy})L_{pol}L_{scan\ angle}L_{sidelobe}]/G_e. \quad (37)$$

To determine the number of elements required for the transmit phased array, the following expression is used:

$$N_t = [EIRPL_{pol}L_{scan\ angle}L_{sidelobe}/C_{cta}/G_e]^{1/2}, \quad (38)$$

where

N_r is the number of transmit phased array elements,

G_r is the gain of the transmit phased array,

L_{pol} is the polarization mismatch loss,

$L_{scan\ angle}$ is the scan angle loss,

$L_{sidelobe}$ is the loss due to amplitude taper to reduce side lobes,

C_{eta} is the carrier power delivered to phased-array antenna element, and

G_e is the gain of the individual elements of the transmit phased array.

3.1.3.2 Element Count Calculation. Using equation (37) for the receive phased array, the number of antenna elements can be calculated for the UHF SATCOM link. A maximum scan angle of 50° is assumed. A 50° maximum scan angle and five strategically placed arrays will provide hemispherical coverage from a shipboard platform. The equivalent system noise temperature, T_{sy} , for the existing ship receiver system will be the same as was calculated in the previous section, or 502K. The T_{sy} for a phased-array antenna system assumes radome losses of -1.5 dB and a phase-shifter loss of 1 dB. An element gain, G_e , of 5 dB is also assumed. Similar to the previous calculation, T_{sy} can be calculated except that the effects of the radome and phase-shifter are added. As shown in table 5, from this calculation, $T_{sy} = 1120K$ and $T_r = 1120 + 450$ or 31.96 dB.

Table 5. System noise temperature of UHF SATCOM passive phased array.

	Gain (dB)	NF (dB)	Noise
Input losses	-1.50		119.64
Phase-shifter	-1.00		106.07
Cable 1 + diplexer	-1.50		212.75
LNA	30.00	2.50	566.94
Cable 2	-3.00		0.72
Splitter	-6.00		4.33
AN/WSC-3	0.00	13.00	<u>109.66</u>
System noise (K)			1120.11

Finally, the polarization (0.2 dB) and scan angle (2.9 dB) losses are calculated for the phased-array antenna using equations (34) and (35). From table 3, when the excess margin is considered, the calculated G/T is -21.4 dB for the 25-kHz DAMA mode (ship-to-ship). Substituting the above values in equation (37) gives

$$N_r = -21.4 + 31.96 + 2.9 + .2 + .5 - 5 = 9.16 \text{ dB or } N_r = 8 \text{ elements.}$$

Table 6 summarizes the results for the 25-kHz non-DAMA mode (shore-to-ship), 25-kHz DAMA mode (shore-to-ship), and 25-kHz DAMA mode (ship-to-ship).

The number of phased-array antenna elements required can be calculated using equation (38). From table 1, the required EIRP for UHF SATCOM is 18.8 dBW. Using equation (38),

$$N_t = (18.8 + 2.9 + .2 + .5 - 5) / 2 = 8.7 \text{ dB or } N_t = 8 \text{ elements.}$$

Table 6. Number of required receive phased-array antenna elements.

	Non-DAMA shore-to-ship	DAMA shore-to-ship	DAMA shore-to-ship
Shore Tx power (dBW)	20.00	20.00	20.00
Shore antenna gain (dB)	15.00	15.00	8.65
Le (dB)	11.20	11.20	10.20
Lu (dB)	3.50	3.50	5.50
Lpu (dB)	173.70	173.70	173.90
Satellite signal gain (dB)	1.10	1.10	1.10
Satellite G/T (dB)	-18.00	-18.00	-18.00
Uplink (dB)	58.30	58.30	50.75
Satellite EIRP (dB)	26.00	26.00	26.00
Frequency (MHz)	297.95	297.95	297.95
Scan angle (deg)	50.00	50.00	50.00
Slant range (km)	40586.00	40586.00	40586.00
Channel bandwidth (Hz)	25000.00	25000.00	25000.00
Ld (dB)	5.50	5.50	5.50
Lpd (dB)	172.81	172.81	172.81
Ship Receive gain (dB)	3.00	5.50	10.50
Ship sky noise (K)	450.00	450.00	450.00
System noise (K)	1120.11	1120.11	1120.11
Ship G/T (dB/K)	-28.96	-26.46	-21.46
Data rate (bps)	2400.00	19200.00	19200.00
FEC rate	1.00	0.50	0.50
Downlink (dB)	47.17	49.67	54.00
Eb/No (dB)	13.05	9.29	9.24
Required Eb/No (dB)	13.00	9.20	9.20
Excess margin	0.05	0.09	0.04
Scan loss (dB)	2.88	2.88	2.88
Polarization loss (dB)	0.20	0.20	0.20
Amplitude taper loss (dB)	0.50	0.50	0.50
Element gain	5.00	5.00	5.00
# of elements	2.00	3.00	8.00

3.2 INMARSAT-B

INMARSAT Service is a telecommunications service that links INMARSAT mobile terminals and telephones, telex, and data terminals via INMARSAT satellites positioned in stationary orbits. The INMARSAT mobile terminal can be broadly divided into terminals installed on ships and portable terminals for use on land. Depending on the functions required by the user, there are four types of mobile terminals:

- INMARSAT-A
- INMARSAT-B
- INMARSAT-M
- INMARSAT-C

INMARSAT-B is of interest in this analysis. INMARSAT-B is and will be fielded on most Navy ships. INMARSAT-B provides 16-kbps voice channel, fax capability up to 9.6 kbps, data up to 9.7 kbps, and a 64-kbps high data rate. INMARSAT services include:

- official phone service/STU III
- sailor debit card phone service
- PC-to-PC data transfer
- Internet access
- SALTS/E-mail/VTC/Fax

Figure 2 shows the INMARSAT-M/B coast earth stations.

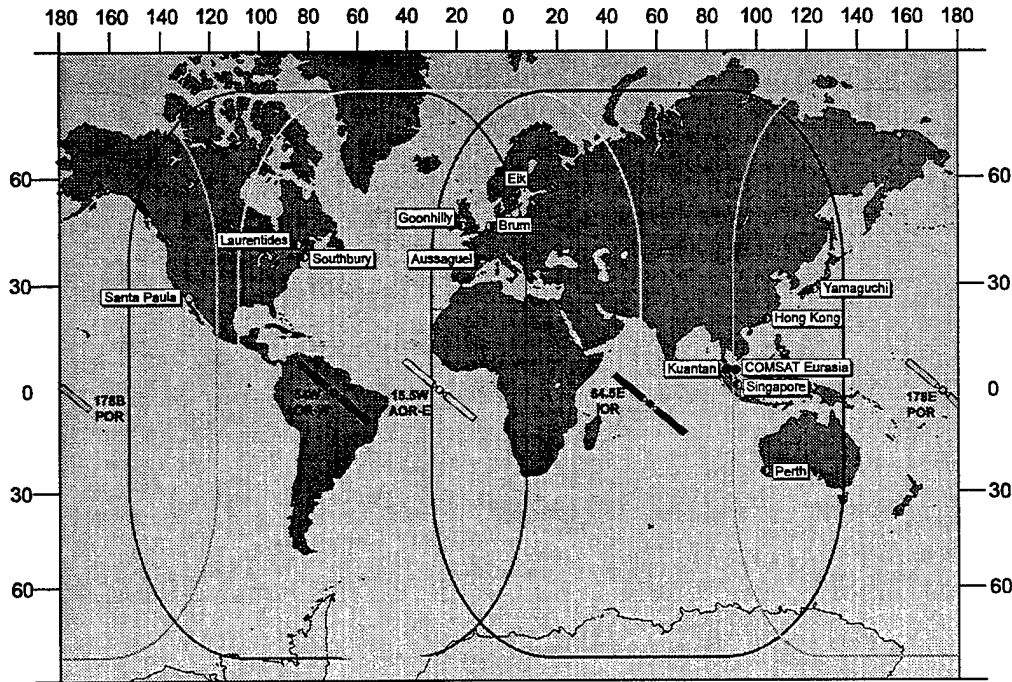


Figure 2. INMARSAT-M/B coast earth stations.

Two different implementations of an INMARSAT phased array are considered. The first implementation is a passive phased array, and the second implementation is an active phased array.

3.2.1 INMARSAT RECEIVE, PASSIVE PHASED ARRAY

Table 7 lists system noise temperature for an INMARSAT passive phased array.

Table 7. System noise temperature of INMARSAT passive phased array.

	Gain (dB)	NF (dB)	Noise
Input losses	-1.50		119.64
Phase-shifter	-1.00		106.07
Diplexer	-1.00		133.53
LNA	30.00	2.00	379.73
Cable 2	-3.00		0.65
Receiver	0.00	13.00	<u>24.55</u>
System noise (K)			764.16

From table 1, the required G/T is -4 dB/K. The sky temperature is assumed to be 70° Kelvin at the receive frequency of 1525 MHz. Using equation (37), table 8 shows the number of elements required for an INMARSAT passive, receive phased array at various scan angles. Again, with an array that can scan 50°, hemispherical coverage is obtained with five arrays placed strategically about the ship. The number of required elements varies from 117 elements for a 30° maximum scan angle to 581 elements required for a 70° scan angle.

Table 8. Number of elements for INMARSAT passive, receive phased array.

Scan angle (deg)	30.00	40.00	50.00	60.00	70.00
Scan loss (dB)	0.94	1.74	2.88	4.52	6.99
Polarization loss (dB)	0.02	0.08	0.20	0.46	0.94
Amplitude taper loss (dB)	0.50	0.50	0.50	0.50	0.50
Element gain	6	6	6	6	6
# of elements	117	143	191	295	581

3.2.2 INMARSAT RECEIVE, ACTIVE PHASED ARRAY

Table 9 lists system noise temperature for an INMARSAT active phased array. The principal difference between the active and passive phased array is that for the active phased array the low noise amplifier (LNA) is placed right after the antenna element. In the passive array, the phase-shifter is next in line from the antenna element. The active phased array configuration results in a considerably lower system noise temperature.

Table 9. System noise temperature of INMARSAT active phased array.

	Gain (dB)	NF (dB)	Noise
Input losses	-1.50		119.64
LNA	30.00	2.00	239.59
Phase-shifter	-1.00		0.11
Cable 2	-3.00		0.51
Receiver	0.00	13.00	<u>19.50</u>
System noise (K)			379.35

From table 1, the required G/T is again -4 dB/K. The sky temperature is again assumed to be 70° Kelvin at the receive frequency of 1525 MHz. Using equation (37), table 10 shows the number of elements required for an INMARSAT active, receive phased array at various scan angles. Again, with an array that can scan 50°, hemispherical coverage is obtained with five arrays placed strategically about the ship. The number of required elements varies from 63 elements for a 30° maximum scan angle to 313 elements required for a 70° scan angle. The fewer required number of elements for the active array configuration is again due to the much lower system noise temperature.

Table 10. Number of elements for INMARSAT active, receive phased array.

Scan angle (deg)	30.00	40.00	50.00	60.00	70.00
Scan loss (dB)	0.94	1.74	2.88	4.52	6.99
Polarization loss (dB)	0.02	0.08	0.20	0.46	0.94
Amplitude taper loss (dB)	0.50	0.50	0.50	0.50	0.50
Element gain	6	6	6	6	6
# of elements	63	77	103	159	313

3.2.3 INMARSAT TRANSMIT PHASED ARRAY

The number of antenna elements required for an INMARSAT transmit phased array can be calculated using equation (38). The required EIRP is 33 dBw. The assumed element gains and power

per element are indicated in the table 11. This table lists the number of antenna elements required for various angles. As seen in this case, the required number of antenna elements for the transmit case are usually much less than the number of antenna elements required for the receive case.

Table 11. Number of elements for INMARSAT transmit phased array.

Scan angle (deg)	30.00	40.00	50.00	60.00	70.00
Power/Element (watts)	3.00	3.00	3.00	3.00	3.00
Scan loss (dB)	0.94	1.74	2.88	4.52	6.99
Polarization loss (dB)	0.02	0.08	0.20	0.46	0.94
Amplitude taper loss (dB)	0.50	0.50	0.50	0.50	0.50
Element gain	6	6	6	6	6
# of elements	16	17	20	25	35

3.3 AN/SMQ-11

The purpose of the AN/SMQ-11 shipboard antenna is to provide high-resolution meteorological/oceanographic satellite imagery support to command and control. The antenna copies both polar orbiter and geostationary satellites. The present shipboard antenna is a dual-tracking slotted planar array. The antenna points using a program that tracks using satellite ephemeris data. The following sections consider phased-array implementations to provide the performance of the present AN/SMQ-11 antenna. Two frequency bands are of interest for this study, 1684 to 1710 MHz (i.e., lower band) and 2205 to 2254 MHz (i.e., upper band).

3.3.1 AN/SMQ-11 RECEIVE, PASSIVE PHASED ARRAY (LOWER BAND)

Table 12 lists system noise temperature for an AN/SMQ-11 passive phased array.

Table 12. System noise temperature of AN/SMQ-11 (lower band) passive, receive phased array.

	Gain (dB)	NF (dB)	Noise
Input losses	-1.50		119.64
Phase-shifter	-1.00		106.07
Diplexer	-1.00		133.53
LNA	30.00	2.00	379.73
Cable 2	-3.00		0.65
Receiver	0.00	13.00	<u>24.55</u>
System noise (K)			764.16

From table 1, the required G/T is 1.9 dB/K. The sky temperature is assumed to be 70° Kelvin at the receive frequency of 1684 MHz. Using equation (37), table 13 shows the number of elements required for an AN/SMQ-11 (lower band) passive, receive phased array at various scan angles. Again, with an array that can scan 50°, hemispherical coverage is obtained with five arrays placed strategically about the ship. The number of required elements varies from 455 elements for a 30° maximum scan angle to 2259 elements required for a 70° scan angle.

Table 13. Number of elements for AN/SMQ-11 (lower band) passive, receive phased array.

Scan angle (deg)	30.00	40.00	50.00	60.00	70.00
Scan loss (dB)	0.94	1.74	2.88	4.52	6.99
Polarization loss (dB)	0.02	0.08	0.20	0.46	0.94
Amplitude taper loss (dB)	0.50	0.50	0.50	0.50	0.50
Element gain	6	6	6	6	6
# of elements	455	553	740	1145	2259

3.3.2 AN/SMQ-11 (LOWER BAND) RECEIVE, ACTIVE PHASED ARRAY

Table 14 lists system noise temperature for an AN/SMQ-11 (lower band) active phased array. The principal difference between the active and passive phased array is that for the active phased array the LNA is placed right after the antenna element. In the passive array, the phase-shifter is next in line from the antenna element. The active phased array configuration results in a considerably lower system noise temperature.

Table 14. System noise temperature of AN/SMQ-11 (lower band) active, receive phased array.

	Gain (dB)	NF (dB)	Noise
Input losses	-1.50		119.64
LNA	30.00	2.00	239.59
Phase shifter	-1.00		0.11
Cable 2	-3.00		0.51
Receiver	0.00	13.00	<u>19.50</u>
System noise (K)			379.35

From table 1, the required G/T is again 1.9 dB/K. The sky temperature is again assumed to be 70° Kelvin at the receive frequency of 1684 MHz. Using equation (37), the following table 15 shows the number of elements required for an AN/SMQ-11 (lower band) active, receive phased array at various scan angles. Again, with an array that can scan 50°, hemispherical coverage is obtained with five arrays placed strategically about the ship. The number of required elements varies from 245 elements for a 30° maximum scan angle to 1217 elements required for a 70° scan angle.

Table 15. Number of elements for AN/SMQ-11 (lower band) active, receive phased array.

Scan angle (deg)	30.00	40.00	50.00	60.00	70.00
Scan loss (dB)	0.94	1.74	2.88	4.52	6.99
Polarization loss (dB)	0.02	0.08	0.20	0.46	0.94
Amplitude taper loss (dB)	0.50	0.50	0.50	0.50	0.50
Element gain	6	6	6	6	6
# of elements	245	298	399	617	1217

3.3.3 AN/SMQ-11 RECEIVE, PASSIVE PHASED ARRAY (UPPER BAND)

Table 16 lists system noise temperature for an AN/SMQ-11 passive phased array.

Table 16. System noise temperature of AN/SMQ-11 (upper band) passive, receive phased array.

	Gain (dB)	NF (dB)	Noise
Input losses	-1.50		119.64
Phase-shifter	-1.00		106.07
Diplexer	-1.00		133.53
LNA	30.00	2.00	379.73
Cable 2	-3.00		0.65
Receiver	0.00	13.00	<u>24.55</u>
System noise (K)			764.16

From table 1, the required G/T is 3.9 dB/K. The sky temperature is assumed to be 70° Kelvin at the receive frequency of 2254 MHz. Using equation (37), table 17 lists the number of elements required for an AN/SMQ-11 (upper band) passive, receive phased array at various scan angles. Again, with an array that can scan 50°, hemispherical coverage is obtained with five arrays placed strategically about the ship. The number of required elements varies from 720 elements for a 30° maximum scan angle to 3579 elements required for a 70° scan angle.

Table 17. Number of elements for AN/SMQ-11 (upper band) passive, receive phased array.

Scan angle (deg)	30.00	40.00	50.00	60.00	70.00
Scan loss (dB)	0.94	1.74	2.88	4.52	6.99
Polarization loss (dB)	0.02	0.08	0.20	0.46	0.94
Amplitude taper loss (dB)	0.50	0.50	0.50	0.50	0.50
Element gain	6	6	6	6	6
# of elements	720	876	1173	1814	3579

3.3.4 AN/SMQ-11 (UPPER BAND) RECEIVE, ACTIVE PHASED ARRAY

Table 18 lists system noise temperature for an AN/SMQ-11 (upper band) active phased array. The principal difference between the active and passive phased array is that for the active phased array, the LNA is placed right after the antenna element. In the passive array, the phase-shifter is next in line from the antenna element. The active phased array configuration results in a considerably lower system noise temperature.

Table 18. System noise temperature of AN/SMQ-11 (upper band) active, receive phased array.

	Gain (dB)	NF (dB)	Noise
Input losses	-1.50		119.64
LNA	30.00	2.00	239.59
Phase-shifter	-1.00		0.11
Cable 2	-3.00		0.51
Receiver	0.00	13.00	<u>19.50</u>
System noise (K)			379.35

From table 1, the required G/T is again 3.9 dB/K. The sky temperature is again assumed to be 70° Kelvin at the receive frequency of 2254 MHz. Using equation (37), table 19 lists the number of elements required for an AN/SMQ-11 (upper band) active, receive phased array at various scan

angles. Again, with an array that can scan 50°, hemispherical coverage is obtained with five arrays placed strategically about the ship. The number of required elements varies from 245 elements for a 30° maximum scan angle to 1217 elements required for a 70° scan angle.

Table 19. Number of elements for AN/SMQ-11 (upper band) active, receive phased array.

Scan angle (deg)	30.00	40.00	50.00	60.00	70.00
Scan loss (dB)	0.94	1.74	2.88	4.52	6.99
Polarization loss (dB)	0.02	0.08	0.20	0.46	0.94
Amplitude taper loss (dB)	0.50	0.50	0.50	0.50	0.50
Element gain	6	6	6	6	6
# of elements	388	472	632	977	1928

4. DEFENSE SATELLITE COMMUNICATIONS SYSTEM (DSCS)

The Defense Satellite Communications System (DSCS) provides secure voice and data communications for the U. S. military. A military satellite constellation is placed in geosynchronous orbit and provides high-volume, secure voice and data communications. Figure 3 shows the current DSCS constellation.

The DSCS satellite receive frequency band is 7.9 to 8.4 GHz. The transmit frequency band is 7.25 to 7.74 GHz. The following discussion compares active phased arrays with the performance of a 4-foot dish and a 7-foot dish.

The specifications for the 4-foot dish are

$$G/T = 12.2 \text{ dB, and EIRP} = 71.5 \text{ dBw.}$$

The specifications for the 7-foot dish are

$$G/T = 20 \text{ dB, and EIRP} = 71.5 \text{ dBw.}$$

The DSCS satellite receive frequency band is 7.9 to 8.4 GHz. The transmit frequency band is 7.25 to 7.74 GHz. The following discussion compares active phased arrays with the performance of a 4-foot dish and a 7-foot dish.

The specifications for the 4-foot dish are

$$G/T = 12.2 \text{ dB, and EIRP} = 71.5 \text{ dBw.}$$

The specifications for the 7-foot dish are

$$G/T = 20 \text{ dB, and EIRP} = 71.5 \text{ dBw.}$$

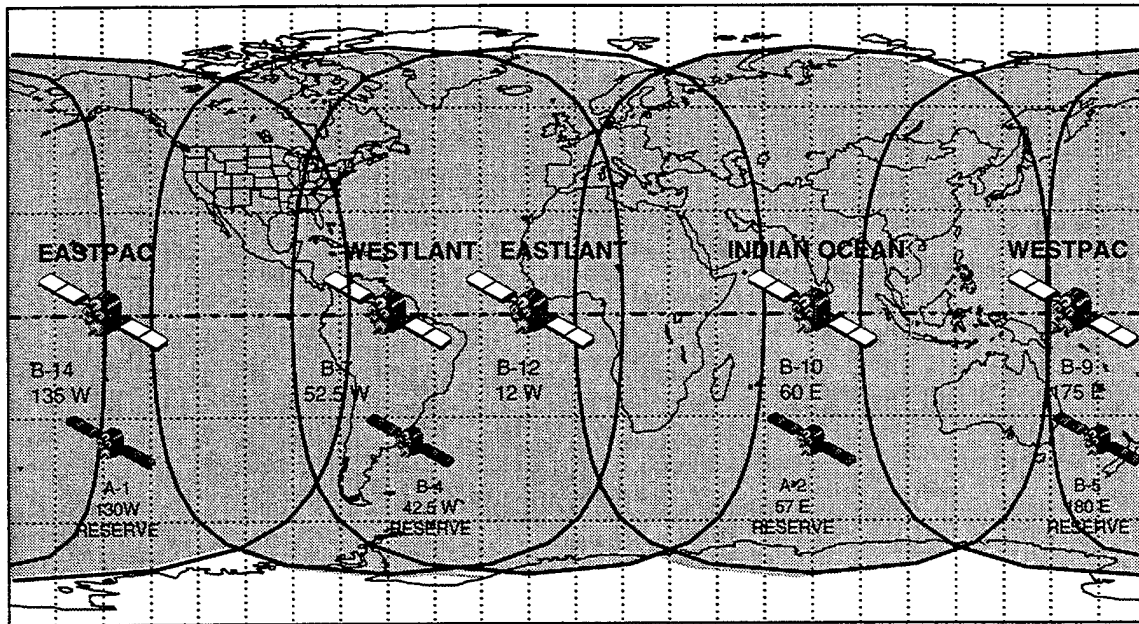


Figure 3. Current DSCS constellation.

4.1 DSCS RECEIVE PHASED ARRAY

Table 20 lists system noise temperature for the DSCS receive phased array.

Table 20. System noise temperature for DSCS receive phased array.

	Gain (dB)	NF (dB)	Noise
Ship sky noise (K)			35.00
Input losses	-1.50		119.64
LNA	30.00	2.50	225.70
Phase-shifter	-11.00		4.75
Cable 2	-3.00		5.13
Receiver	0.00	13.00	<u>195.01</u>
System noise (K)			585.23

Using equation (37), table 21 shows the number of elements required for a DSCS receive phased array at various scan angles. With an array that can scan to 50°, hemispherical coverage is obtained with five arrays placed strategically about the ship. Table 21 presents the number of elements for a G/T of 12.2 dB/K. The 12.2 dB/K is required to provide the same performance as the existing DSCS 4-foot dish. Table 22 presents the number of elements for a G/T of 20 dB/K. The 20 dB/K is required to provide the same performance as the existing DSCS 7-foot dish. The number of elements required to provide the same performance as the 7-foot dish is almost prohibitive. For a maximum 50° scan, the number of required elements increases from 7004 to 42202. This requirement provides the 7.8-dB/K increase in the required G/T.

Table 21. Number of elements for DSCS receive phased array, G/T = 12.2 dB/K.

Scan angle (deg)	30	40	50	60	70
Scan loss (dB)	0.94	1.74	2.88	4.52	6.99
Polarization loss (dB)	0.02	0.08	0.2	0.46	0.94
Amplitude taper loss (dB)	0.5	0.5	0.5	0.5	0.5
Element gain	5	5	5	5	5
# of elements	4299	5240	7004	10848	21396

Table 22. Number of elements for DSCS receive phased array, G/T = 20 dB/K.

Scan angle (deg)	30	40	50	60	70
Scan loss (dB)	0.94	1.74	2.88	4.52	6.99
Polarization loss (dB)	0.02	0.08	0.2	0.46	0.94
Amplitude taper loss (dB)	0.5	0.5	0.5	0.5	0.5
Element gain	5	5	5	5	5
# of elements	25902	31574	42202	65363	128923

4.2 DSCS TRANSMIT PHASED ARRAY

The number of antenna elements required for a DSCS transmit phased array can be calculated using equation (38). The EIRP specification for both the 4- and 7-foot dishes is the same, 71.5 dBw. Table 23 lists the number of antenna elements required for the various scan angles and the required EIRP.

Table 23. Number of elements for EHF transmit phased array, EIRP = 71.5 dBw.

Scan angle (deg)	30.00	40.00	50.00	60.00	70.00
Power/element (watts)	2	2	2	2	2
Scan loss (dB)	0.94	1.74	2.88	4.52	6.99
Polarization mismatch loss (dB)	0.02	0.08	0.2	0.46	0.94
Amplitude taper loss (dB)	0.5	0.5	0.5	0.5	0.5
Element gain	5	5	5	5	5
# of elements =	1769	1953	2257	2809	3945

5. GBS/EHF RECEIVE SATCOM PHASED ARRAY

This section addresses the definition of a phased-array system that supports Global Broadcast Service (GBS) and EHF SATCOM receive. There is also the possibility of supporting regionally available commercial SATCOM systems in the same frequency band. The objective is a phased-array system that provides the required communication performance while meeting the projected ship signature requirements. Full-scale demonstration models are under consideration for development to provide cost estimates for future production versions of this antenna system. Presently, it is envisioned that the demonstration antenna systems will be demonstrated within the context of the FY 98 Low Observable, Multifunction Stack (LMS) Advanced Technology Demonstration (ATD). The LMS ATD provides previously unusable locations for use by SATCOM antennas.

This antenna will electronically switch its polarization sense, thereby permitting it to communicate either with EHF SATCOM or the GBS satellites. Possible designs to provide a dual-beam capability have also been developed. Each SATCOM system is discussed in the following sections.

5.1 GLOBAL BROADCAST SYSTEM (GBS)

The Global Broadcast System (GBS) capitalizes on the popular commercial direct broadcast satellite technology to provide critical information to the warfighter. The GBS system is a space-based, high-data-rate communications link for the asymmetric flow of information from the United States or rear echelon locations to the deployed forces. The GBS will “push” a high volume of intelligence, weather, and other information to widely dispersed, receive terminals. Low-cost, receive only systems are under development for deployment on all ships and submarines. The system will allow the users to request or “pull” specific pieces of information using other existing communication links. Data rates are available for up to 23.6 Mbps. Figure 4 shows the UHF follow-on satellite coverage supporting GBS communications.

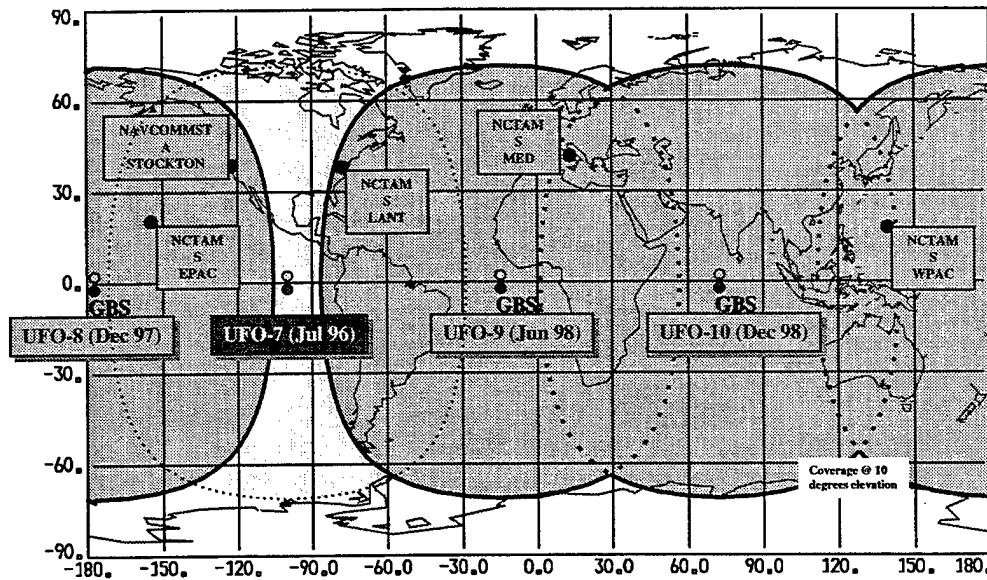


Figure 4. UFO GBS communication coverage.

For the GBS receive phased array, the Air Force above-the-clouds requirement for G/T is 10.6 dB/K. Table 24 lists system noise temperature for the EHF receive phased array.

Table 24. System noise temperature for GBS phased array.

	Gain (dB)	NF (dB)	Noise
Galactic, Terrain & Atmospheric Temperature			100.00
Element Input Losses			
Polarizer and antenna element insertion loss	-0.20		13.67
Radome Loss	-0.10		7.07
Module input loss (transition & microstrip)	-0.60		46.04
MMIC Low Noise Amplifier	25.00	2.00	208.68
Phase shifter loss	-11.50		14.81
Module output loss	-0.60		2.36
WDN loss	-1.00		4.74
Second Stage Low Noise Amplifier	1.00	2.00	13.47
System noise (K)			410.84

Using equation (37), table 25 shows the number of elements required for a GBS phased array at various scan angles. With an array that can scan to 50 degrees, hemispherical coverage is obtained with five arrays placed strategically about the ship. Table 25 presents the number of elements for a G/T of 10.6 dB/K.

Table 25. Number of elements for GBS phased array, G/T = 10.6 dB/K.

Scan angle (deg)	30.00	40.00	50.00	60.00	70.00
Scan loss (dB)	0.94	1.74	2.88	4.52	6.99
Polarization loss	0.02	0.08	0.20	0.46	0.94
Impedance mismatch loss (dB)	0.50	0.50	0.50	0.50	0.50
Element gain	6	6	6	6	6
# of elements	1659	2018	2702	4179	8245

5.2 EHF RECEIVE

Military EHF SATCOM provides support to strategic-level command and control and nuclear forces and provides added communication capability to tactical users. Its capabilities include anti-jam, multichannel, and low probability-of-intercept features. Figure 5 shows the UFO EHF communication coverage.

For EHF receive, the Air Force above-the-clouds requirements for G/T are as follows:

low data rate (LDR) = 5 dB/K,

medium data rate (MDR) = 10 dB/K.

The all-weather requirement for G/T is MDR = 13 dB/K. This assumes 5 dB of weather margin. Table 26 lists system noise temperature for the EHF receive phased array. This is, of course, the same system noise temperature as calculated for the GBS receive phased array. A dual-beam or switched-beam architecture is assumed for the two systems using the same electronics.

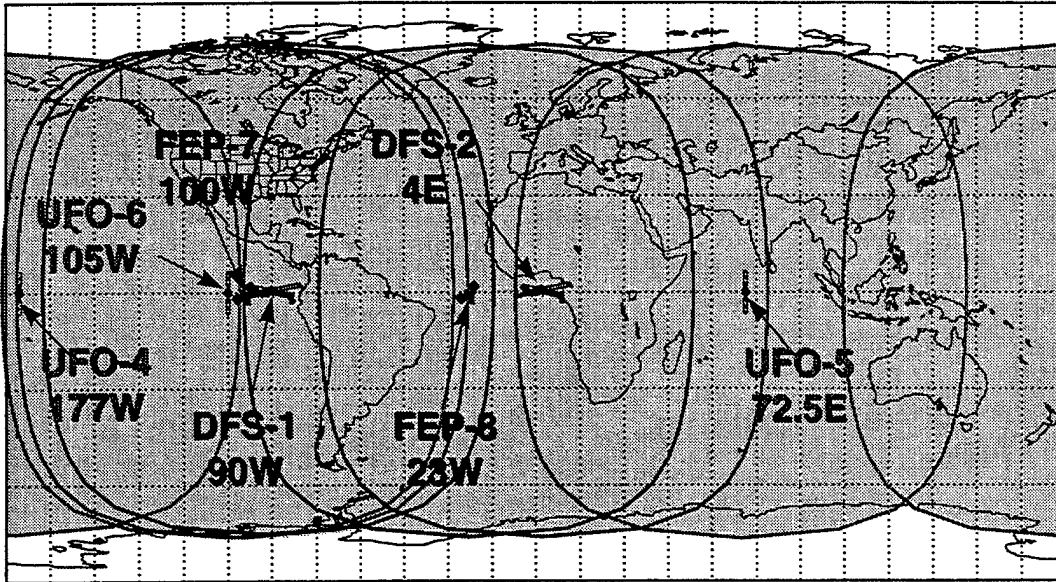


Figure 5. UFO EHF communication coverage.

Table 26. System noise temperature for EHF receive SATCOM phased array.

	Gain (dB)	NF (dB)	Noise
Galactic, Terrain & Atmospheric Temperature			100.00
Element Input Losses			
Polarizer and antenna element insertion loss	-0.20		13.67
Radome Loss	-0.10		7.07
Module input loss (transition & microstrip)	-0.60		46.04
MMIC Low Noise Amplifier	25.00	2.00	208.68
Phase shifter loss	-11.50		14.81
Module output loss	-0.60		2.36
WDN loss	-1.00		4.74
Second Stage Low Noise Amplifier	1.00	2.00	13.47
System noise (K)			410.84

Using equation (37), tables 27 through 29 show the number of elements required for an EHF Receive SATCOM phased array at various scan angles. With an array that can scan to 50°, hemispherical coverage is obtained with five arrays placed strategically about the ship. Table 27 presents the number of elements for a G/T of 5 dB/K, the low-data-rate requirement. Table 28 presents the number of elements for a G/T of 10 dB/K, the medium-data-rate requirement. Finally, table 29 presents the number of elements for a G/T of 13 dB/K, the all-weather medium-data-rate requirement. The impact of rain on the system noise temperature was not included in the calculation.

Table 27. Number of elements for EHF receive SATCOM phased array, G/T = 5 dB/K.

Scan angle (deg)	30.00	40.00	50.00	60.00	70.00
Scan loss (dB)	0.94	1.74	2.88	4.52	6.99
Polarization loss	0.02	0.08	0.20	0.46	0.94
Impedance mismatch loss (dB)	0.50	0.50	0.50	0.50	0.50
Element gain	6	6	6	6	6
# of elements	457	556	745	1151	2271

Table 28. Number of elements for EHF receive SATCOM phased array, G/T = 10 dB/K.

Scan angle (deg)	30.00	40.00	50.00	60.00	70.00
Scan loss (dB)	0.94	1.74	2.88	4.52	6.99
Polarization loss	0.02	0.08	0.20	0.46	0.94
Impedance mismatch loss (dB)	0.50	0.50	0.50	0.50	0.50
Element gain	6	6	6	6	6
# of elements	1445	1758	2354	3639	7181

Table 29. Number of elements for EHF receive SATCOM phased array, G/T = 13 dB/K.

Scan angle (deg)	30.00	40.00	50.00	60.00	70.00
Scan loss (dB)	0.94	1.74	2.88	4.52	6.99
Polarization loss	0.02	0.08	0.20	0.46	0.94
Impedance mismatch loss (dB)	0.50	0.50	0.50	0.50	0.50
Element gain	6	6	6	6	6
# of elements	2882	3507	4695	7261	14327

6. EHF Tx SATCOM PHASED ARRAY

The number of antenna elements required for an EHF Tx SATCOM phased array can be calculated using equation (38). The requirements for the LMS EHF Transmit SATCOM phased array are:

EHF Tx array

EIRP = 45 dBw

The Air Force above-the-clouds requirements for EIRP are LDR = 45 dBw, MDR = 50 dBw. The all-weather requirement for EIRP is MDR = 59 dBw. The assumption is 12 dB of weather margin. Tables 30 through 32 give the number of antenna elements required for the various required EIRP and scan angles.

Table 30. Number of elements for EHF transmit phased array (EIRP = 45 dBw).

Scan angle (deg)	30.00	40.00	50.00	60.00	70.00
Power/element (watts)	0.1	0.1	0.1	0.1	0.1
Scan loss (dB)	0.62	1.16	1.92	3.01	4.66
Polarization mismatch loss (dB)	0.22	0.22	0.22	0.22	0.22
Impedance mismatch loss (dB)	0.58	0.58	0.58	0.58	0.58
Amplitude, phase errors (dB)	0.60	0.60	0.60	0.60	0.60
Radome loss (dB)	0.20	0.20	0.20	0.20	0.20
Element gain	5.00	5.00	5.00	5.00	5.00
# of elements	409	435	475	538	651

Table 31. Number of elements for EHF transmit phased array, EIRP = 50 dBw.

Scan angle (deg)	30.00	400.00	50.00	60.00	70.00
Power/element (watts)	0.1	0.1	0.1	0.1	0.1
Scan loss (dB)	0.62	1.16	1.92	3.01	4.66
Polarization mismatch loss (dB)	0.22	0.22	0.22	0.22	0.22
Impedance mismatch loss (dB)	0.58	0.58	0.58	0.58	0.58
Amplitude, phase errors (dB)	0.60	0.60	0.60	0.60	0.60
Radome loss (dB)	0.20	0.20	0.20	0.20	0.20
Element gain	5.00	5.00	5.00	5.00	5.00
# of elements	727	773	844	957	1157

Table 32. Number of elements for EHF transmit phased array, EIRP = 59 dBw.

Scan angle (deg)	30.00	400.00	50.00	60.00	70.00
Power/element (watts)	0.1	0.1	0.1	0.1	0.1
Scan loss (dB)	0.62	1.16	1.92	3.01	4.66
Polarization mismatch loss (dB)	0.22	0.22	0.22	0.22	0.22
Impedance mismatch loss (dB)	0.58	0.58	0.58	0.58	0.58
Amplitude, phase errors (dB)	0.60	0.60	0.60	0.60	0.60
Radome loss (dB)	0.20	0.20	0.20	0.20	0.20
Element gain	5.00	5.00	5.00	5.00	5.00
# of elements	2048	2178	2377	2695	3259

7. OPTIMAL PLACEMENT AND SCAN ANGLE FOR PHASED ARRAYS

As stated above, with an array that can scan 50°, hemispherical coverage is obtained with five arrays placed strategically about the ship. The next few paragraphs discuss the optimal placement and scan angle for the SATCOM phased arrays.

The first consideration is the number of array faces that will be used to cover the scan volume. The second consideration is the scan volume that must be covered. Reasonable numbers for the number of array faces appears to be four to six. For less than four faces, the maximum scan angle will be too high and the elements will be packed very tightly. This close packing leads to difficulties with mutual coupling between the array elements. For more than six faces, there is little improvement in scan angle or mutual coupling. In addition, there is probably an increase in the number of elements required and, thus, an increase in cost. Initially, it was assumed that the arrays would need to scan down to a 10° elevation and account for a 20° roll. Recently, it has been indicated that scan is typically limited to 20 degrees elevation, but 30° rolls should be considered. Since these assumptions give essentially the same results, the latter case will be used in the following discussion. Since multiple faces must be used to cover the scan volume, there needs to be an overlap in the scan volume of the arrays to facilitate handover. The typical overlap is 5°. A 5° handover is assumed in the following discussion.

The optimal tilt angle is calculated for four-, five- and six-faced arrays. With five- and six-faced arrays, it is assumed that one of the faces is looking toward the zenith. For four faces, the optimal tilt angle is

$$\theta = 90^\circ - \sin^{-1} \{ [-\cos^2\phi + (1 - \cos^2\phi - \cos^4\phi)^{1/2}] / \sin^2\phi \}. \quad (39)$$

The resulting optimal tilt angle is 35.3° . For five- and six-faced arrays, the optimal tilt angle is

$$\theta = \sin^{-1} \{ [1 - (1 - \cos^2 \varphi - \cos^4 \varphi)^{1/2}] / \sin^2 \varphi \} \quad (40)$$

Here, 2φ is equal to the spacing of the faces, not including the top array. As an example, for five faces, $2\varphi = 360^\circ/4 = 90^\circ$, with one face on top. If there is no face on top, $2\varphi = 360^\circ/5 = 72^\circ$. The resulting optimal tilt angles are 15.5° for five faces and 20.4° for six faces. The maximum scan angles for the three configurations, allowing for adequate overlap at a 20° elevation angle and a 30° roll, was determined by the Communication Link Evaluation Framework (CLEW) program recently developed by the Applied Electromagnetic Branch, Code D851 at SSC San Diego. The resulting maximum scan requirements are 59° , 50° , and 44° , respectively. Figures 6 through 9 demonstrate the scan coverage provided by the four- and five-faced configurations. In each case, the highest elevation angle of beam crossover is 15° , thus allowing adequate overlap at 20° elevation.

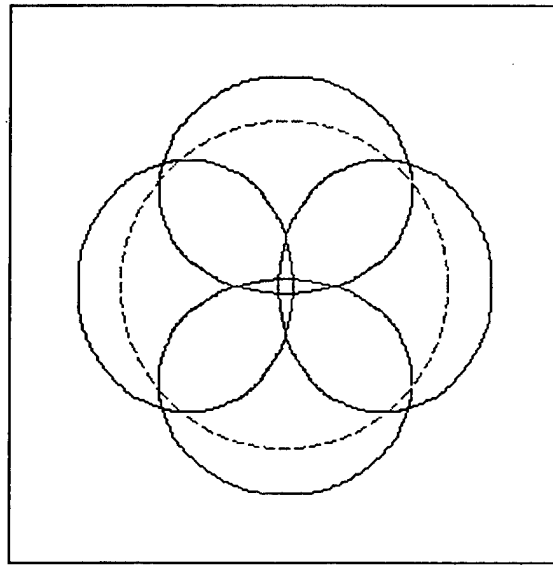


Figure 6. Four-face array, scan = 59° , tilt = 35.3° , roll = 0° .

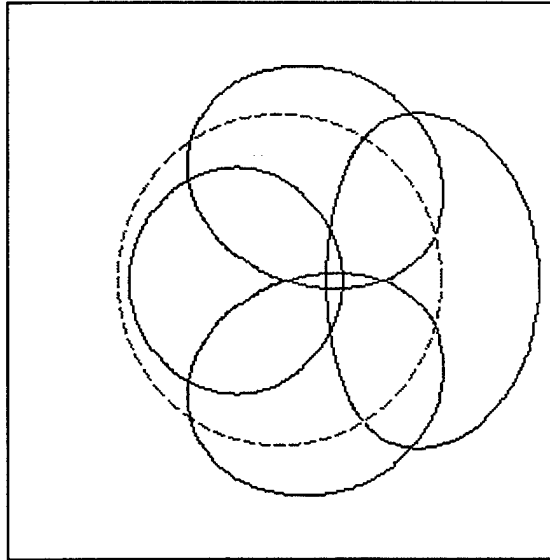


Figure 7. Four-face array, scan = 59° , tilt = 35.3° , roll = 30° .

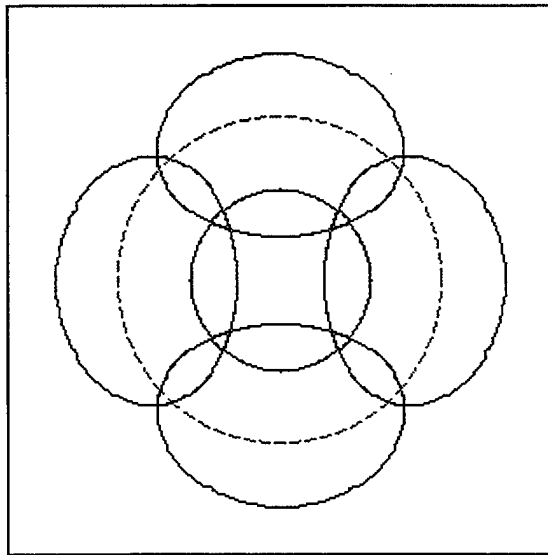


Figure 8. Five-face array, scan = 50° , tilt = 15.5° , roll = 0° .

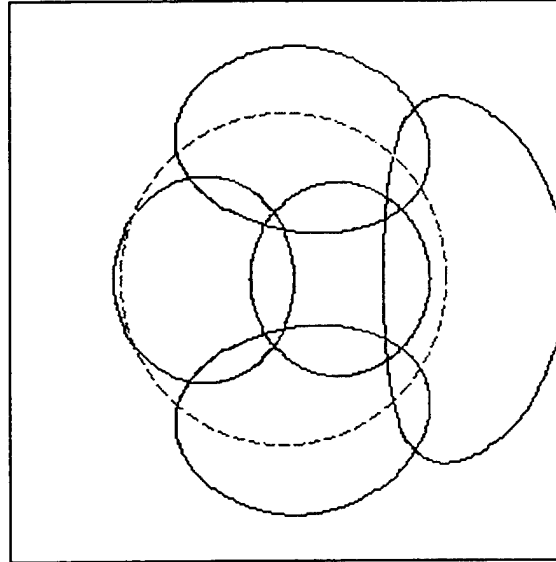


Figure 9. Five-face array, scan = 50°, tilt = 15.5°, roll = 30°.

The optimum configuration is not obvious, although it seems that a six-face arrangement would be less desirable. Thus, a comparison of relative size was conducted. Basically, the gain of an array is assumed to roll off with the cosine of the scan angle and, thus, the size, in number of elements, is inversely proportional to this value. In actuality, the gain rolls off more than this, due to mutual coupling. A slightly conservative and typically used estimate is that the gain rolls off proportional to cosine to the 1.5 power. Using this rule of thumb, the relative sizes of the arrays are as follows:

Four-face	$4[\cos(50)/\cos(59)]^{1.5} = 5.58$
Five-face	$5[\cos(50)/\cos(50)]^{1.5} = 5.00$
Six-face	$6[\cos(50)/\cos(44)]^{1.5} = 5.07$

From this calculation it is seen that the five-face configuration is over 11% smaller than the four-face configuration, and over 1% smaller than the six-face configuration. Thus the five-face array was chosen as the baseline. The optimal tilt angle or slope for an operational installation is, thus, 15.5°, and the maximum scan angle is 50°.

8. REFERENCE

Naval Research Laboratory. 1961. "Antennas and Receiving-System Noise-Temperature Calculation," NRL Report 5668 (Sep 19). Ruth H. Hooker Research Library and Technical Information Center, Washington, DC.

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