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SELECTION AND PRELIMINARY DESIGN OF LIGHT-WEIGHT, LOW-COST X-BAND AIRCRAFT ANTENNAS FOR DEFENSE SATELLITE COMMUNICATIONS

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ABSTRACT

As satellite communications requirements increase and more functions are combined in the same frequency band in accordance with the ICNI concept, special requirements are being imposed on the aircraft antenna system.

Depending on data rates to be transmitted via a satellite link, various bandwidths are required for the earth terminals. For high data rates, large relative bandwidths are necessary; and available frequency allocations generally indicate operation at X-band, with K_u-band as a possible additional choice.

Mobile users require full hemispherical coverage of the antenna system. Aircraft users have the additional constraint that the antenna aperture has to be flush with the skin of the aircraft and to conform to the structure.

In this paper, earth terminals utilizing an integrated military satellite communication (ICNI) system are tabulated, and typical parameters are summarized. A number of potential aircraft antenna configurations are analyzed, and a selection process leading to a minimum-cost, minimum-weight, aircraft-antenna system for X-band operation is discussed. The chosen antenna system, a phased array using a combination of digital phase steering and traveling wave phase velocity steering, is described in detail. A comparison is presented between this antenna and several other systems.

1. INTRODUCTION

Future defense communication satellite systems will have to accommodate both small (tactical) and large (strategic) users. Also, for maximum utilization of the expensive user equipment, other functions may have to be included, such as navigation and identification.

Possible frequency bands for such a system are located in L-band, S-band, X-band and K_u-band. Allocations at L-band and S-band should be difficult to obtain, and are incompatible with the high data rate requirements of some of the strategic users of a combined defense satellite system. In general, considerations of reduced weight and complexity, low doppler shift in moving users, and low path loss favor low frequencies, whereas considerations of privacy (sidelobes, beamwidth), attenuation in an ionized atmosphere, high data rates, and protection against multipath favor higher frequencies. The final choice appears to be X-band, except for cases where the requirement for absolute minimum user weight and cost dictates minimum user complexity at the expense of jamming protection and data rate.

It is stipulated, at the present time, that the satellite (from synchronous altitude) will provide both full earth coverage and narrow steerable beams pointing only at a specific theater of operation. The following fixed and mobile surface users can then utilize this satellite system: teampacks, jeeps, trucks, tanks, large ships, small ships, submarines, and divisional headquarters.

Among the airborne users we can differentiate helicopters, fighters, bombers, tankers, transports, airborne command posts, and space shuttles.

2. SUMMARY OF TYPICAL USER ANTENNA TECHNICAL OBJECTIVES

2.1 General

Since the users can have any orientation and service is required up to high latitudes, hemispherical coverage is required of all user antennas down to elevation angles of about 10 degrees above the horizon.

For most of the ground-based (surface) users, this coverage is most conveniently accomplished with mechanical steering. For fast-moving vehicles, however, the steering may have to be accomplished electrically. Also, if an interference problem exists due to noise, electrical coupling, or mechanical shadowing (such as on a ship or a helicopter), a displaced arrangement may be more optimum than a "conformal" installation. Two typical user configurations are described in the following paragraphs.

2.2 Shipboard Phased Arrays

Since the area in the center of the ship is normally crowded, it may not be possible and/or economical to mount a mechanically steered dish in this location. Shadowing and reflections from the superstructure can be avoided by locating a number of phased arrays at the stern and bow, as shown in Figure 1.

Four arrays can be "distributed" over the maximum dimension of the ship, eliminating the interference from within the ship. Typical performance objectives are summarized in Table 1. The arrays will have to be protected against the environment and may have to be hardened to withstand attacks with conventional weapons. Similar hardened arrays can be used for Army Division Headquarters.

Table 1. Shipboard Antenna Performance Objectives

Installation:	Four arrays per ship, low-silhouette, salt spray protected
Angular coverage:	
Azimuth:	360° (±45° for each of four arrays)
Elevation:	60° (±30° centered at 40° elevation)
Beam steering speed:	10°/ sec
Power handling:	5 kW average
Gain:	37 dB

2.3 Aircraft SHF Antennas

Some of the salient considerations are listed in Table 2. To overcome propagation losses, aircraft SHF antennas must have relatively high gains. If no space is available in the radome at the nose of the aircraft, then a flush-mounted array is required.

Table 2. Aircraft Antenna Operational Considerations

- Operation at Microwave Frequencies Requires Narrow Beams
- Medium and Small Aircraft Require Phased Arrays (Several Separate Arrays Required for Coverage)
- Large Aircraft Can Use Steered Reflectors, if Space is Available in Nose
- Beam Steering Approach:
    - Reference — Inertial Platform Coordinates
    - Pilot Sets Initial Direction
    - Inertial Navigator Compensates for Maneuvers
- Pointing Error Beamwidth Limitation: ±1.5°

Only the largest aircraft, such as the C-5A, can afford the luxury of having a dish both in the nose radome and in a tail radome. Even then, full coverage is probably not possible because of the limited view from the tail end. Also, vibrations in the vertical stabilizer may be severe. If electrical steering is used for distributed (or "conformal") arrays on the aircraft surface, then one can choose either adaptive or command steering. Command steering should be adequate in most applications, utilizing the aircraft's inertial navigator, perhaps with occasional additional correction from a satellite (or some other) electronic navigation system.

The pointing error limitation dictated by the use of an inertial system puts a lower bound on the feasible beamwidth of approximately 3 degrees. Autotrack techniques can be employed, of course, to assure beam lock, e.g., under banking, but this is at the expense of additional weight, cost, and complexity.

3. AIRCRAFT ANTENNA SELECTION

3.1 Summary of Aircraft Antenna Technical Objectives (Table 3)

If the aircraft will be operational only at latitudes up to perhaps 70 degrees, then an angular coverage of 360 degrees azimuth by 160 degrees elevation is sufficient.

During ordinary maneuvers, no greater rate of change in beam direction is visualized than about 25 degrees per second, with banking angles not exceeding 10 degrees.

As in all satellite communications systems, circular polarization is preferred, but linear polarization is acceptable if the residual gain is sufficient (i.e., the antenna gain has to be 3 dB greater for the linearly polarized case).

For most applications in a tactical environment, a power-handling capability of 500 watts will be required for the aircraft antenna, but this is not necessarily an upper limit.

Finally, gains of up to 35 dB are required to satisfy the data rates of some of the aircraft users.

Table 3. Aircraft Antenna Technical Objectives

Installation:	Flush-mounted
Angular coverage (level flight):	Approximately hemispherical
Azimuth:	360°
Elevation:	160° (80° from zenith)
Beam steering speed:	25°/ sec
Polarization:	Circular preferred linear acceptable
Power handling:	500 W
Desired gains:	35 dB, 25 dB, 10 dB
Weight and cost:	Minimum

3.2 Possible Antenna Approaches

Table 4 summarizes the technical approaches which have been investigated.

3.2.1 Switched Elements

The first approach considered consisted of a number of cavity-backed dielectric-loaded slot antennas, distributed over the surface of the aircraft and selected by switches. Besides the fact that such antennas are narrowband, each of them supplies only a small amount of gain in the desired direction. To increase the gain, a number of them will have to be grouped together, thus leading to a phased array concept. (See the following paragraphs.) Each individual element beam is, of course, not steerable.

Table 4. Summary of Possible Approaches

Type	Advantage	Disadvantage
Individual Slot	Simple	Limited Gain; Not Steerable
Surface-Wave Array	Relatively Simple	Limited Gain; Not Steerable
Flush-Radome Dish	High-Aperture Efficiency	Limited View; Excessive Space
Passive Lens	High-Aperture Efficiency	Limited View; Excessive Space
Active Lens	Simple Feed, Electronic Steering	Excessive Space
Linear Array	Electronic Steering in One Plane	Beamwidth Too Narrow in Steered Plane
Planar-Phased Array	Electronic or Electromechanical Steering	Feed Network Losses, Complexity

3.2.2 Switched Surface-Wave Arrays

The next category of antennas is the family of surface wave antennas or arrays. Dielectric or other surface wave structures are used to excite a beam along the surface of the aircraft. Again, the gain is limited maximally to about 20 dB, and now a very large number of antennas are required to achieve a tolerable beam overlap.

3.2.3 Flush-Mounted Dish

To get more gain, one could consider mounting a dish in the surface of the aircraft, covering it with a high-temperature (ceramic) slab as a radome. If a spherical reflector is used, considerable beam steering is possible, but it is still limited to about a 100-degree cone. If three of these antennas are mounted around the circumference, one would get good coverage in this plane, but for front-and-aft coverage two more reflectors are required. The biggest drawback, however, is the excessive installation depth that cuts severely into the rib structure supporting the aircraft skin. A further disadvantage of the spherical reflector is the limited steering speed of the mechanically moved feed. Finally, the sidelobes are high.

3.2.4 Passive Lens

Approximately the same considerations apply to passive metal (artificial-dielectric) lenses, the angular coverage being limited to a few beamwidths off broadside, similar to a parabolic reflector. On the other hand, for Luneburg lenses, the weight becomes excessive for gains above 20 dB.

3.2.5 Active Lens

The "active lens" concept, also called "space-fed array," also requires excessive installation depth and has poor aperture efficiency. Essentially, beam-steering range is traded for absolute gain.

3.2.6 Phased Arrays

This leaves the large category of linear or planar arrays of elements. To get gains above 10 dB, the linear array dimensions must be fairly large and the beam in the steered plane must be so narrow that it becomes difficult to provide effective beam lock. Therefore, only planar arrays are considered further, excluding "reflectarrays," which also require an excessive installation depth.

4. DISCUSSION OF PLANAR PHASED-ARRAY CONFIGURATIONS

4.1 Summary of Phased-Array Techniques

In Table 5, some basic phased array configurations are compared: the Butler matrix-fed array, the retrodirective array, the adaptive (or self-steering) array, the corporate feed array, and the array with traveling-wave excitation. Since only planar arrays are considered, all these techniques are now discussed in the planar configuration. The term "Butler/Butler" then means that a Butler matrix is used for both rows and columns.

Table 5. Summary of Phased-Array Configurations

Type	Advantage	Disadvantage
Butler/Butler	Multiple Beams	High-Beam Crossover Loss; Beams at Fixed Angles, Heavy.
Retro-Directive Transdirective	Automatic Steering	Extreme Cost and Complexity; Vulnerability to Interference; Heavy.
Adaptive, Self-Steering	Automatic Beam Steering, High Gain	Receive Only; Extreme Complexity; High Cost; Vulnerability to Interference.
Corporate/ Corporate	High Flexibility; Wide Bandwidth	Large Weight; High Complexity; High Cost
Corporate Feed/ Traveling Wave	Near-Optimum Compromise Between Gain and Weight	Reduced Steering Range; Separate Receive and Transmit Antennas.
Traveling Wave/ Traveling Wave	Minimum Weight; High Efficiency	Limited Beam-Steering Range, Slow Steering Speed. Separate Receive and Transmit Antennas.
Solid State	Fast Steering	Low Efficiency, Extreme Cost.

4.2 The Hybrid (Butler) Matrix Array

A number of simultaneous beams can be formed by using some kind of hybrid matrix technique. The Butler matrix has the disadvantage of high-beam crossover loss (4 dB for the linear array, 8 dB for the planar array), but this can be overcome by special combining techniques of the beams, which are simultaneously formed at fixed angles.(1) Even for the optimum hybrid matrix array, the achievable efficiencies are in the neighborhood of 10 percent, much below the theoretical "lossless" beam forming property. At X-band, in particular, the losses and circuit tolerances will make it very difficult to construct a working matrix system in stripline configuration, so that the weight of a waveguide feed matrix necessary for operation will be excessive.

4.3 The Retrodirective Array

The concept of the retrodirective array is based on the ability to reflect electromagnetic energy back into the direction from which it came, and amplify the signal at the same time. A variation of this array then allows a change in the direction in a predetermined manner; i.e., regardless of where the energy came from, it will always be directed at a certain fixed angle. This "transdirective" concept is thus not applicable at all for tactical satellite communications, because the whole purpose of the system is to communicate through the satellite. The straightforward retrodirective array must be addressable by the satellite from any direction. This makes the aircraft vulnerable to jamming. Also, a hemispherical array is required with elements either located on a protruding bubble, which is bad aerodynamically, or located around the body of the aircraft, which requires a large amount of interconnecting circuitry with high losses and large weight. Finally, when the aircraft wants to address the satellite, the retrodirective mechanism has to be controlled somehow or locked into the right direction through a pilot frequency from the satellite. If a pilot is available anyway, there is no need to go to the phase-conjugation system of the retrodirective array. The whole concept is thus not really applicable to the problem at hand.

4.4 Adaptive and Self-Steering Arrays

In the adaptive array, phase-adjusting devices are located in each element feed line and controlled through a servo loop so that the outputs from each feed line are in phase. For transmitting without simultaneous receiving, a pilot frequency is provided to lock on to. In self-steering arrays, the received signals are compared with a fixed-reference phase signal. Both systems are vulnerable to interference and jamming and are complex and expensive.

4.5 "Corporate" Feed Arrays

4.5.1 Passive.

Figure 2A illustrates an array beam-forming and beam-steering circuit using a dual corporate feed network. Hence, this network is briefly called corporate/corporate feed, indicating that a "corporate" feed network is used both to combine elements in each row and to combine rows. Corporate/corporate arrays have a high degree of operational flexibility and, of all array feed systems, have the greatest bandwidth potential. However, they are fairly complex in control circuitry, expensive, and heavy if ferrite phase shifters are used. Ferrite phase shifters are more or less mandatory to get the required power-handling capability and low loss.

4.5.2 Solid State Array

To overcome feed network losses, amplifiers can be used directly at the array elements, For minimum weight, solid-state amplifiers have to be used. Unfortunately, efficiencies and power capabilities at X-band are presently too low to result in a competitive system (Figures 3 and 4).

4.6 Corporate Feed/Traveling Wave Array

In Figure 2B, a combination feed circuit diagram is shown; this consists of arrays with traveling-wave excitation fed by a corporate feed network. It has the advantage of reducing the weight of the ferrite phase shifter steering system drastically. Only eight phase shifters are required in a 64-element array, or $\sqrt{N}$ phase shifters in an N-element array. This results in a near optimum compromise between weight and gain. The total beam-steering range is reduced somewhat due to the limited steerability of a traveling-wave array, and the reduced bandwidth generally requires separate arrays for receiving and transmitting.

4.7 Traveling Wave/Traveling Wave Array

Using a traveling-wave excitation in both planes further reduces the weight for a certain gain, but now the beam-steering range and speed are fairly limited. Nevertheless, applications exist where great steering speed is not required.

5. PHASED ARRAY DESIGN CONSIDERATIONS AND PERFORMANCE ANALYSIS

5.1 Basic Phased-Array Performance Limitations

In Figure 5 certain basic performance considerations are illustrated. The top curve shows the maximum element spacing that can be tolerated for a certain beam-steering angle off broadside (see bottom horizontal scale). This spacing is dictated by grating lobe considerations. The center curve shows gain reduction versus beam-steering angle due to reduction in available aperture. (Only the projection of the physical aperture is available for capturing electromagnetic energy at a certain angle.) The bottom curve, finally, illustrates the reduction in gain due to mutual element coupling, which is relatively small. In addition to the minimum beam-steering losses shown in the bottom two curves, there can be a gain reduction due to a narrowing of the phased array element pattern due to mutual coupling.

These performance reductions must be considered in the actual phased array application. In other words, the available gain at the extremes of array-beam steering is the gain which is used in communication link calculations.

5.2 Beam Steering of Traveling-Wave Slot Arrays

Figure 6 shows a technique for steering the beam of a traveling-wave excited slot array. The waveguide slots are cut in the narrow walls, so that the waveguides can be spaced as close as possible for maximum beam steering in the direction perpendicular to the length of the arrays. The beam can then be steered in the plane of the waveguides (along the length of the waveguides) by variation of the phase velocity. In practice this is accomplished by varying the width of the waveguide (2) (Figure 6) or by positioning a dielectric slab inside the waveguide (3) (Figure 7). (See the Appendix for a discussion of both cases.) The individual waveguides are then phased together as indicated in Figure 8. Since phase velocity steering only allows to steer the beam efficiently from broadside to one extreme angle ($\theta = 0$ to $\theta \approx 30$ degrees), the other steering range has to be selected by feeding the waveguides from the other side. This is readily accomplished by means of transfer switches. This approach allows beem steering with a minimum of cost, weight, and complexity.

This array system is equally useful for both receiving and transmitting but, due to the limited bandwidth (≈200 MHz maximum at X-band for broad-beam arrays), a different array will have to be used for receiving and transmitting. The performance of this array is now analyzed and compared with corporate/corporate arrays and arrays with traveling-wave excitation in both planes.

5.3 Performance Analysis of Medium-Gain Aircraft Array with Combination Steering

Table 6 summarizes the characteristics of a medium-gain X-band array for possible installation in medium-size to large aircraft. Also shown is a gain budget for the feed system (corporate/traveling wave) and for the selected maximum beam steering range. The net gain is approximately 26 dB. A possible installation on a medium-size aircraft is shown in Figure 9. Four array pairs are located in the front section of the aircraft, each pair consisting of a receive and a transmit array oriented in the same direction conveniently close to the cockpit. The transmitter may be in a central location between the arrays to minimize loss in the waveguide runs. Angular coverage around the fuselage is illustrated in the top sketch of Figure 9.

The slotted waveguide sections of the array systems are oriented circumferentially, so that a total of 180 degrees is covered with some overlap where the traveling wave steering capability is ±30 degrees. This, then, allows operation during 10-degree banking. Fore and aft steering is 50 degrees, leaving a 40 degree solid angle toward the rear which is not illuminated.

Table 6. Advanced Tacsat Communications Aircraft Medium Gain X-Band Antennas (Traveling Wave/Corporate Feed)

Center Frequency Range	7.25 to 8.4 gHz
Size	20.5 x 20.5 In. at 7.25 gHz
Weight	~50 lb (One Array - ten required)
Maximum Bandwidth	100 MHz
Polarization	Linear
Beam Steering Range	±30° in Traveling Wave Plane ±50° in Corporate Feed Plane
Aperture Gain ($4\pi A/\lambda^2$)	33 dB
Element Efficiency	-0.5 dB
Feed Network Loss	-0.5 dB
Traveling Wave Loss (One Level)	-1.0 dB (Power into Termination)
Phase Shifter Loss (One Level)	-0.6 dB (Dielectric or Choke Loss)
Phase Shifter Loss (One Level)	-0.9 dB (Analog Ferrite Phase Shifters)
Switch Loss:	0.2 dB
Net Absolute Gain at Beam	29.3 dB
Maximum; No Steering Beam Crossover Level	N/A
Element Pattern Loss	-1.5 dB (for Traveling Wave Steering Plane)
Effective Aperture Reduction	-1.0 dB (for Phase Steering Plane)
Mutual Coupling Loss	-0.3 dB
Net Absolute Gain at Extreme Beam Positions:	26.5 dB
Cost:	≈$50K

To get operation in this direction also, either a number of fixed-beam traveling-wave arrays could be mounted in the vertical stabilizer, or a fifth steerable array pair could be located in the tip of the tail.

5.4 Other Phased-Array Antennas

If minimum available gains in excess of 26 dB are required, then an array of traveling-wave slot arrays can be used, where the excitation is also accomplished through a light-weight traveling-wave feed. A similar gain budget shows a minimum gain of 34 dB for an array size of 46 x 46 inches.

On the other hand, for maximum beam-steering speed and maximum bandwidths, a regular broadside array with corporate/corporate excitation can be designed at an increased weight. It is for this type of array that advances in component technology, particularly in the areas of phase shifters and solid-state amplifiers, will prove most beneficial.

5.5 Phased-Array Performance Summary

A performance summary of all these types is shown in Table 7. It appears from this analysis that arrays with combination corporate/traveling wave excitation are near optimum for medium-size to large aircraft.

For smaller high-performance aircraft, preliminary link calculations have shown that an array with 10-dB minimum available gain (13 dB gain for a linearly polarized antenna) is acceptable.

Table 7. Aircraft Antennas Performance Summary

	Traveling Wave/ Traveling Wave	Traveling Wave/ Corporate Feed	Corporate Feed/ Corporate Feed
Maximum Array Size (In.)	46 x 46	20.5 x 20.5	14.5 x 14.5
Number of Arrays (Total)	10	10	5
Total Weight (lb)	700	500	650
Maximum Bandwidth	100 MHz	100 MHz	15%
Polarization	Linear	Linear	Circular
Net Gain At Extreme Beam Positions (dB)	34.0	26.5	19.7
Beamwidth (deg)	2.5 x 2.5	5 x 5	8 x 8
Number of Arrays Per Direction	2	2	1

Table 8 compares the three X-band array types discussed above for this fixed-gain situation. Unless some major breakthroughs are achieved in reducing the weight of ferrite phase shifters, the total array systems weight for an installation using five pairs of combination traveling wave/corporate feed arrays is superior to the array using corporate/corporate excitation.

Table 8. Small Phased Arrays For Aircraft Performance Summary Frequency = 8 GHz

Type Characteristic	Traveling Wave/ Traveling Wave	Traveling Wave/ Corporate Feed	Corporate Feed/ Corporate Feed
Minimum Gain	13 dB	13 dB	13 dB
Power Handling Capability	500 W	500 W	500 W
Array Size (in.)	6.0 x 6.0	14.5 x 3.5	7.0 x 7.0
Maximum Bandwidth	100 MHz	100 MHz	15%
Weight of Each Array	14 lb(1)	10 lb	35 lb
No. of Arrays	10(2)	10(2)	5(3)
Total Weight	140 lb	100 lb	175 lb
Beamwidth (deg)	14 x 14	8 x 24	12 x 12
Minimum ERP(4)	40 dBW	40 dBW	40 dBW

(1) Includes weight of 6 dummy loads required to absorb residual traveling wave power of 30 W each.
(2) Five for transmitting and five for receiving.
(3) Common arrays for transmitting and receiving.
(4) As measured with circularly polarized receiver antenna.

6. CONCLUSION

A near-optimum SHF aircraft antenna design for net gains of 10 dB to approximately 26 dB is a combination traveling wave/corporate feed array. Ten of these arrays must be distributed around the aircraft in pairs (one receive array and one transmit array) to get full coverage during up to 10-degree banking. The total installed weight is presently estimated at 100 pounds for a 10-dB configuration, and 500 pounds for a 26-dB configuration. The 26-dB configuration, in particular, is considerably lighter than the best standard planar array (using individual phase shifters for each element) which can presently be visualized.

APPENDIX

BEAM STEERING BY PHASE VELOCITY VARIATION IN TRAVELING-WAVE EXCITED WAVEGUIDE SLOT ARRAYS

INTRODUCTION

The angle of maximum radiation in a traveling-wave excited waveguide slot array is given by Reference 2.

$$\sin\theta = \left(\frac{\lambda}{\lambda_g}\right) - \left(\frac{\lambda}{2d}\right) \qquad (1)$$

where

λg = guide wavelength

d = spacing between slots

θ = angle from broadside

The guide wavelength is given (for TE waves in vacuum) by:

$$\lambda_{gv} = \frac{\lambda}{\sqrt{1 - \left(\frac{f_{cv}}{f}\right)^2}} \qquad (2)$$

where

f_{cv} = cutoff frequency in vacuum.

Also, the maximum width of the waveguide cannot exceed a wavelength, or higher order modes will occur:

$$a \le \lambda \qquad (3)$$

If we assume operation at 8 GHz, then the wavelength in vacuum is $\lambda_v = 1.475$ in. The ratio of free space wavelength to guide wavelength is given by:

$$\frac{\lambda}{\lambda_g} = \sqrt{1 - \left(\frac{\lambda}{2a}\right)^2} \qquad (4)$$

For the limiting (maximum) width,

$$\frac{\lambda}{\lambda_g} = \sqrt{1 - \left(\frac{1}{2}\right)^2} \doteq 0.866$$

The slot spacing for the beam at broadside is then determined by (assuming $\lambda/\lambda_g = 0.865$):

$$\sin\theta = 0 = 0.865 - \frac{\lambda}{2d}$$

and

$$d = \frac{\lambda}{2\frac{\lambda}{\lambda_g}} = \frac{1.475}{2 \times 0.865}$$

$$d = 0.852 \text{ in.}$$

BEAM STEERING BY WAVEGUIDE WIDTH VARIATION

We now can rewrite equation (1) to read

$$a = \left[\frac{0.543}{1 - (\sin\theta + 0.865)^2}\right]^{1/2} \qquad (5)$$

This will give the waveguide dimension as a function of steering angle θ. Evaluating this formula for angles from broadside to 30 degrees gives the following waveguide widths:

θ (Deg)	a (In.)
- 30	0.79
- 25	0.804
- 20	0.864
- 15	0.926
- 10	1.02
- 5	1.32
0	1.475

The minus sign indicates that the beam is pointing in the backfire direction. To point the beam in the other direction, the waveguide has to be fed from the opposite end.

BEAM STEERING BY VARIABLE DIELECTRIC SLAB

Assuming a waveguide filled completely with dielectric, equation (4) changes to

$$\frac{\lambda}{\lambda_g} = \sqrt{\epsilon_r - \left(\frac{\lambda}{2a}\right)^2} \qquad (6)$$

If only a portion of the waveguide cross-section is filled, then the effective dielectric constant will be somewhere between 1 and ϵ_r. The effective dielectric constant cannot exceed a value where higher order modes occur. Generally,

$$(\epsilon_r)_{eff} < 4 \qquad (7)$$

By varying the position of a thin dielectric slab of high permittivity from the center of the guide all the way to one narrow wall, the maximum amount of variation in effective dielectric constant is achieved. For this case, the phase velocity variation is also a maximum and, consequently, is the beam steering range. With the slab all the way at the narrow wall, the effective dielectric constant is essentially unity. We then have the same condition as previously, and can design the slot spacing for a broadside beam. Theoretical (computed) variations are shown in Figure 10 (3), where β is the propagation constant. As one would expect, the variation is greatest close to the waveguide wall, and becomes very small toward the center of the waveguide ($\alpha = 0.5$ in.). It is also obvious that the dielectric slab has to be very thin to get maximum variation (Case No. 3). This will cause a mechanical problem with regard to supporting the slab. Nevertheless, total beamshift for Case No. 3 is about 30 degrees. Due to the complexity of the field distribution, some experimental work will be required to determine optimum slab support configurations.

ACKNOWLEDGEMENT

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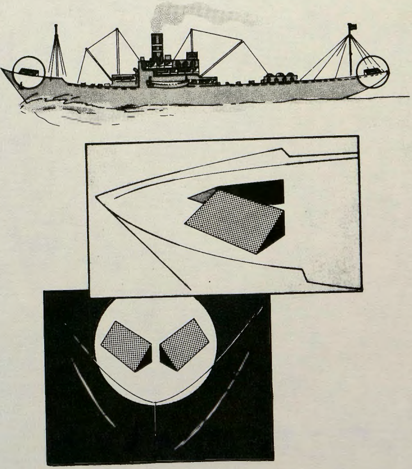
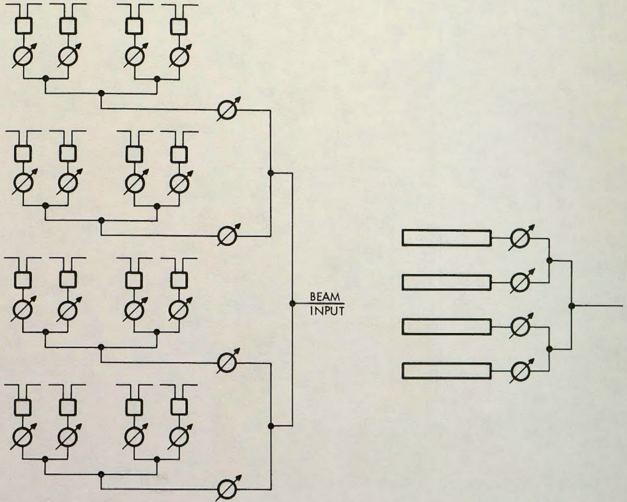


FIG. 1 SHIPBOARD PHASED ARRAY



A) CORPORATE FEED/CORPORATE FEED BEAM FORMING NETWORK

B) TRAVELING WAVE/CORPORATE FEED BEAM FORMING NETWORK

FIG. 2

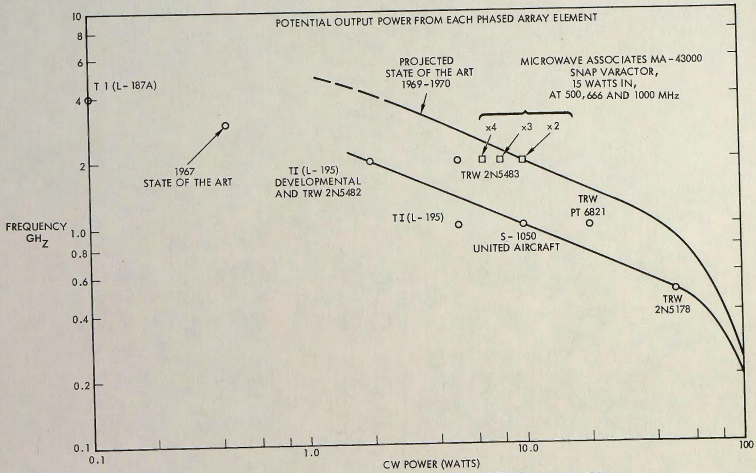


FIG. 3 MICROWAVE POWER GENERATION FROM SINGLE TRANSISTORS AND VARACTORS

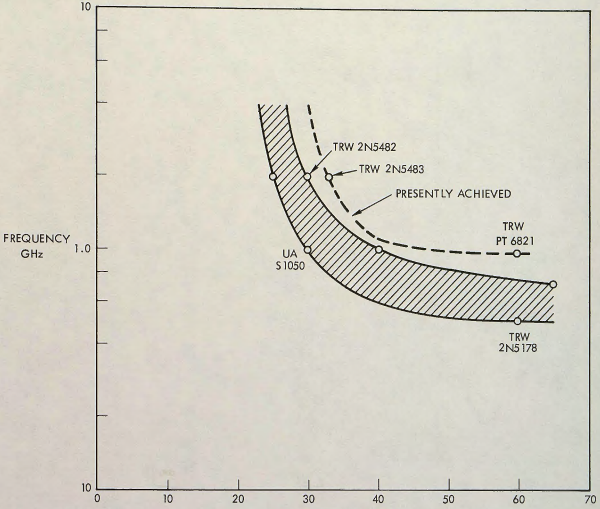


FIG. 4 MICROWAVE POWER GENERATION FROM SINGLE TRANSISTORS AND CORRESPONDING EFFICIENCY

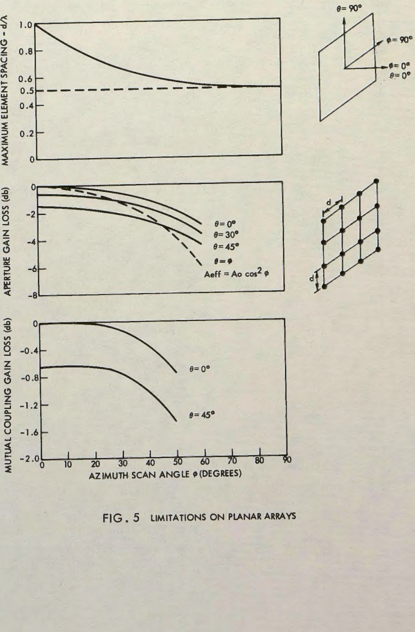


FIG. 5 LIMITATIONS ON PLANAR ARRAYS

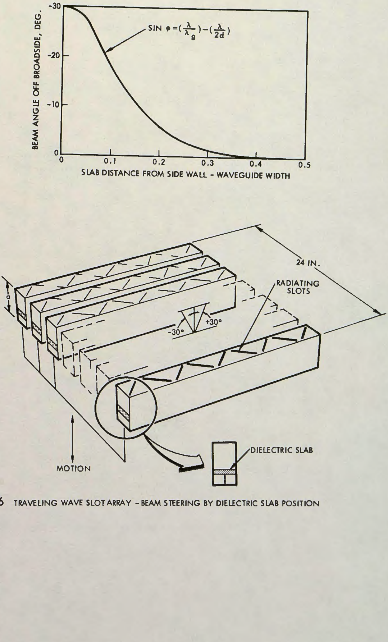


FIG. 6 TRAVELING WAVE SLOT ARRAY - BEAM STEERING BY DIELECTRIC SLAB POSITION

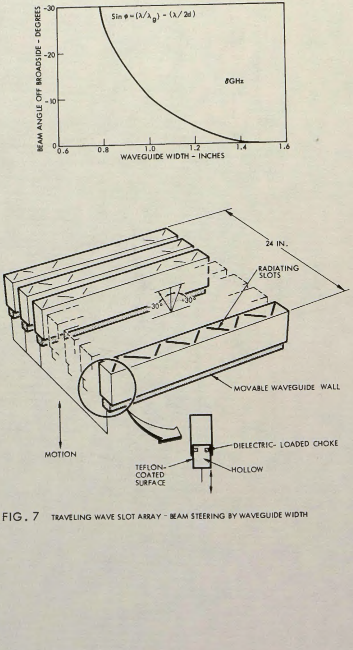


FIG. 7 TRAVELING WAVE SLOT ARRAY - BEAM STEERING BY WAVEGUIDE WIDTH

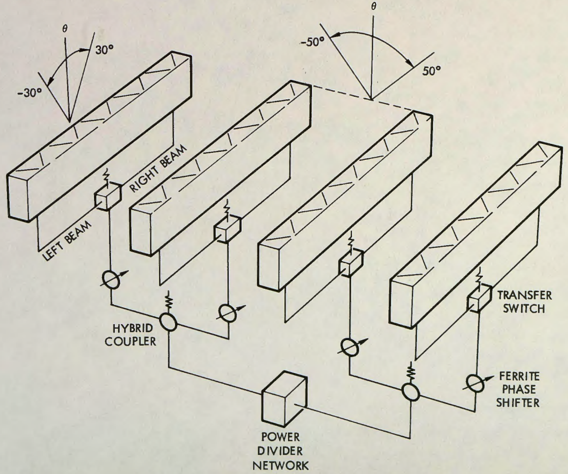
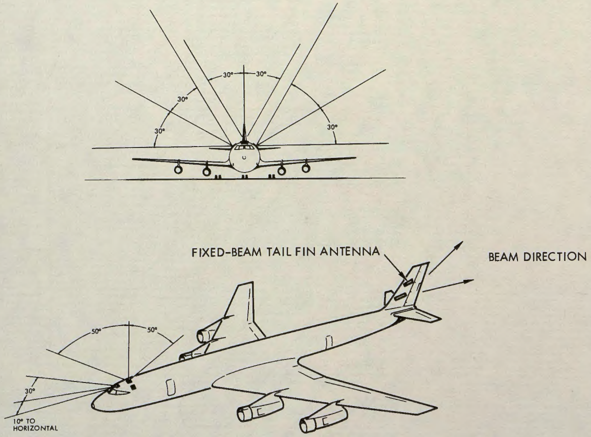


FIG. 8 CORPORATE FEED ARRANGEMENT



MEDIUM-GAIN
FIG. 9 X-BAND ARRAY CONFIGURATION ON AIRCRAFT

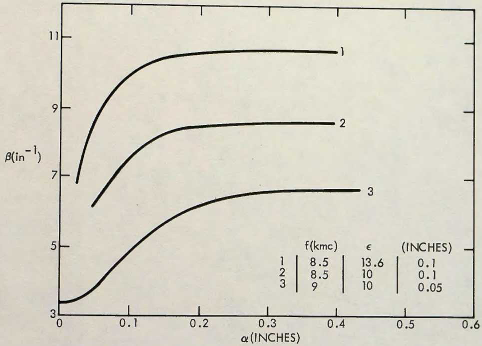


FIG. 10 PROPAGATION CONSTANT AS FUNCTION OF DIELECTRIC SLAB POSITION