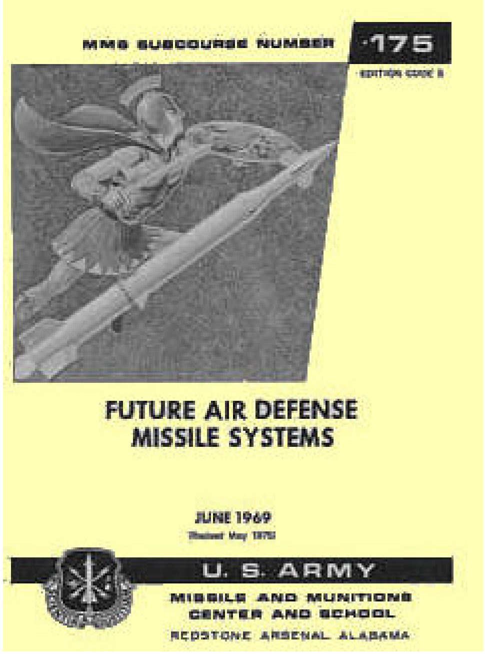
FUTURE AIR DEFENSE MISSILE SYSTEMS
(Part 1)



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READ THIS PAGE

GENERAL INFORMATION

This sub course consists of one or more lessons and an examination. Each of the lessons is divided into two parts; the text and the lesson exercises. For one lesson sub courses the lesson exercises serve as the examination. A heading at the beginning of each lesson gives the title, the hours of credit, and the objectives of the lesson. The final examination consists of questions covering the entire sub course.

If a change sheet is included, be sure to post the changes before starting the sub course.

THE TEXT

All the text material required for this sub course is provided in the packet. The text is the information you must study. Read this very carefully. You may keep the text; however, any unused answer cards and envelopes should be returned.

THE LESSON EXERCISES

Following the text of each lesson are the lesson exercises. After you have studied the text of each lesson, answer the lesson exercises. After you have answered all the questions, go back to the text and check your answers. Remember your answers should be based on what is in the text and not on your own experience or opinions. If there is a conflict, use the text in answering the question.

When you are satisfied with your answers, check them against the answer sheet attached to your exam. Re-study those areas where you have given an incorrect answer by checking the reference given after each answer.

THE EXAMINATION

After you have completed all the lessons and exercises, select the correct answer to all the examination questions. Care fully punch out the correct answer on the exam cards. Be sure to include your social security number, sub course number, and signature. Final exam cards should be mailed in the envelope provided. The exam will be graded and you will be notified of the results. Your final grade for the sub course will be the same as your examination grade.

ASSISTANCE

If you require clarification of anything in this sub course write to us. Also, if you see any information in the text which is incorrect or obsolete, your recommendations will be welcome. Be sure your recommendations are explained in detail, and, if possible, include a reference which gives the correct information. Include your name and social security number. Address all correspondence to:

COMMANDANT
U. S. Army Missile and Munitions Center and School
ATTN: ATSK-CTD-A
Redstone Arsenal, Alabama 35809

CORRESPONDENCE COURSE

OF THE

U. S. ARMY MISSILE AND MUNITIONS

CENTER AND SCHOOL

MMS SUBCOURSE NUMBER 175, FUTURE AIR DEFENSE MISSILE SYSTEMS

(5 Credit Hours)

INTRODUCTION

SAM-D and Safeguard are two new missile systems using a revolutionary new type of radar called Phased-Array Radar. The Safeguard system is being developed as an anti-ICBM system designed to protect America's ability to strike back if attacked. The SAM-D is being developed for battlefield air defense roles against high performance aircraft. The three lessons of this sub course will give you a general knowledge of the new radar used by SAM-D and Safeguard and will give you the purpose, description, and mainte nance concepts of these two missile systems.

This sub course consists of three lessons and a final examination, organized as follows:

Lesson 1	Phased Array Antennas	2 Credit Hours
Lesson 2	Safeguard	1 Credit Hour
Lesson 3	SAM-D	1 Credit Hour
Examination		1 Credit Hour

LESSON 1. PHASED ARRAY ANTENNAS

MNS Sub course No. 175	Future Air Defense Missile Systems
Lesson Objective	To provide you with the concepts used in phased array systems to include basic principles, electronic scanning phase shifting, types of antenna elements and systems, and computer control.
Credit Hours	Two

TEXT

1. INTRODUCTION.

a. Since World War II new technology in radar development has permitted significant migration from the relatively crude transmit-receive systems of that era. Radar, however, is still the best method known for obtaining three- coordinate position data on airborne and space borne targets under all weather conditions. But, today's aircraft, tactical and strategic missiles travelling at tremendous rates of speed are placing severe demands upon receiver sensitivity, transmitter power, and antenna characteristics. It is a fact of life that modern radars are required to deliver position and velocity information more accurately and with better resolution than ever before.

b. Many new techniques have been employed including travelling wave tube amplifiers, tunnel diodes, and MASER`s to greatly increase receiver sensitivity. Very large triode amplifiers and high power klystron oscillators operated in parallel have been effectively used to increase transmitter power. Yet the antenna with which these improvements are employed remains relatively stable. We are still using a single point feed horn coupled to a parabolic reflector rotated mechanically to distribute RF energy into space. The primary disadvantages of these systems are that:
(Note: MASER = Microwave Amplification by Stimulated Emission of Radiation, preferred above 2 GHz. The NIKE HIPAR Radar (1 GHz) used a so called MAVAR = Microwave Amplification by Variable Reactance as a front-end amplifier before the front-end was modified to solid state.)

(1) They have mechanical inertia which increases rapidly with size thus making it difficult to steer a narrow beam width with speed and precision.

(2) The single transmission line connecting the focal point of the antenna with the transmitter has a limited peak power rating.

(3) A separate antenna system is required for each mission function; i.e., acquisition, tracking, missile guidance.

(4) A rotating antenna is extremely difficult to harden from the effects of nuclear blast overpressure.

c. Phased array systems overcome these objections by steering the beam electronically, using a number of radiating elements or transmission lines to raise the power rating, and by encasing the entire system in a hardened structure offering maximum protection from nuclear overpressures.

d. One of the more significant improvements offered by the phased array radar is its multifunction capability. In a ground based missile system a single radar may conduct all the functions of target detection, target track, and missile guidance. Radars may employ separate transmit and receive arrays to perform simultaneous multifunction or they may time share the elements in a single array face for both transmit and receive functions.

e. Phased array systems may detect several hundred objects in space and then select specific targets and collect the required data on these particular targets**.** At the same time the system continues to monitor the remainder of the objects, updates the track data and issues necessary guidance commands to the defensive missile(s). Systems using separate transmit and receive arrays have a minimum loss of their detection capability while performing the additional tracking tasks. Those systems time sharing the same array must necessarily decrease their detection capability during the periods they are tracking targets and commanding the missile. These periods however, are measured in micro-seconds.

f. Phased arrays come in a wide variety of configurations, ranging from compact systems aboard aircraft to ground based sensors for missile systems.

(1) Airborne requirements include ground mapping, terrain following and avoidance, air to ground ranging, weapons guidance and beacon inter rogation. Most of these functions must be conducted simultaneously. How ever the weight and size restrictions dictate the use of a single high data rate radar employing electronic scanning.

(2) Ground based missile systems must cope with a sophisticated air supported threat such as our F-111 aircraft and advanced ballistic missiles accompanied by a wide range of decoys. These threats are already off the drawing board, thus our defending system must be able to search, track and discriminate and pass data back and forth on an almost instantaneous basis. To nullify the threat of mass raids, ground sensors are required to guide more than one defending interceptor simultaneously.

g. Electronically scanned antennas are similar in function to rotating antennas in that they accept energy from the transmitter and concentrate this signal into a radiated beam. The fundamental difference is that electronic scanning provides instant beam switching across a zone of coverage whereas conventional systems must physically move the antenna with electric motors coupled to mechanical drive mechanisms.

h. Comparing the phased array antenna to the human eye, the array would be analogous to the eyeball. The array "looks" by radiating energy from the face. The received energy from an object or target in the "field of view" (figure 1) is processed and utilized by the system computer, the brain, to keep the object in the field of view. Ground based antennas may consist of one or several arrays normally set at right angles to each other and inclined at some angle from the vertical. The array accepts RF energy from the transmitter feed horn, concentrates it into a radiated beam pattern, and steers it to some predetermined point in space. It also receives the incident RF energy from the target and processes it through a signal processing subsystem for use by the data processing subsystem.

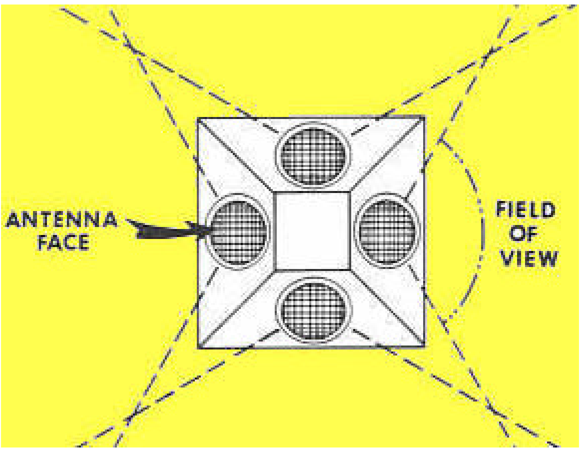

Figure 1. Antenna Field of View.
Top View of Radar.

2. BASIC PRINCIPLES

a. The phased array antenna consists of a number of individual antennas, called elements, which are arrayed in a grid and inter connected so that a specific phase relationship exists between them. The principle of array propagation is based on the fact that the net field strength at any point in space due to radiation from more than one source is the vector sum of the field strengths due to each source, calculated independently at that point. The relationship of each element then, is such that the electra-magnetic waves radiated by these elements add coherently in one direction of propagation and cancel in other directions. Changing the inter-element phase relationship alters the direction in which coherent addition occurs, and thus changes the direction in which the beam of energy radiates.

b. All phased arrays operate on the same basic principle of addition in one direction and cancellation in other directions regardless of whether the array contains four or four thousand elements.

(1) For example the radiators in figure 2 are driven in phase with equal power, arranged so that their electric fields are parallel and spaced one-half wavelength apart. In this example a field strength meter located at "X" which is remote and equidistant from the two elements, will measure the sum of their radiated fields. A field strength meter located at "Y" will measure the difference. The difference is zero **-** providing the distance between the radiators, therefore the difference in path length from "Y" to the radiators is one-half wavelength (currents are 180 degrees out of phase and cancel). The field pattern is symmetrical, that is maximum in the "X" direction and minima in the "Y" direction.

(2) Now consider the situation depicted in figure 3. Here the orientation of the radiators is the same as figure 2; however, this time the current fed to the radiators is 180 degrees out of phase. Under these conditions a field strength meter at "X" will measure the difference of the two fields because although the path length to the radiators is equal, the output of the radiators themselves is 180 degrees out of phase. A field strength meter at "Y" will measure the sum of the fields since the differenc in path length, measured in wavelengths, is exactly equal to the phase difference between the currents in the elements. Again the pattern is symmetrical, only now it is maximum at "Y" and minimum at "X".

(3) These two examples illustrate the basic principle of electronic scanning, that is, the field at any point around an array of two or more elements is equal to the vector sum of the fields from the individual elements at that point.

3. ELECTRONIC SCANNING.

a. Any discussion of electronic scanning must mention the advances in industrial and engineering technology. For it is these technological break troughs that have made phased array systems practical.

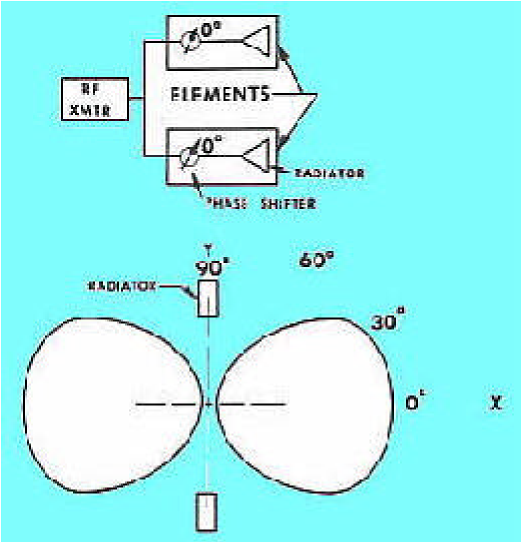

Figure 2. Radiator Array, No Phase Shift.

(1) Improvements in solid state circuitry now permit increased frequency and power handling characteristics. Solid state diode phase shifters may now carry megawatts of power and operate at gigahertz frequencies. Micro -electronics packaging, miniature microwave components and integrated circuits have all contributed materially to the success of phased array systems.

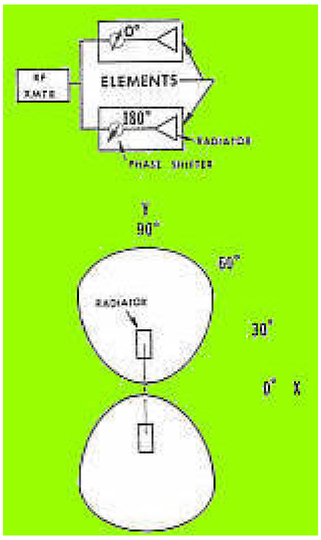

Figure 3. Radiator Array, 180 Degree Phase Shift

(2) The most significant advance however, is the digital computer. Computers store, process, and present vast quantities of data and operate in nanoseconds. Their automatic functions make them ideal as the central control and processing subsystem of complex phased array radars · And equally important, their rapid switching functions enhance electronic scanning to a degree unknown in mechanical rotating radars.

b. In electronic scanning, an electromagnetic beam is positioned in space by wholly electronic means while the antenna aperture remains fixed. Although there are many ways to electronically position an electromagnetic beam, only three basic techniques are involved: frequency scanning, feed switching and phase scanning.

(1) Frequency scanning was the first technique to be implemented in an actual radar. In this method, a frequency band is employed to change the phase relationships among the elements of an array in such a manner that each frequency produces a unique scan angle. This technique makes use of the fact that, for elements at a given spacing, the scan angle produced depends on the ratio of the wavelength to the spacing. Thus by continuously varying frequency over the proper band a continuous scan is produced.

(2) In the feed switching method, each element is fed by its own individually connected power amplifier. This permits beam switching at the low power level prior to final amplification. Again, the RF energy emerging from the elements is scanned or switched across the array face electronically.

(3) In phase scanning the beam is positioned electronically by varying the phase of energy emitted from the separate elements of an array. In its simplest form a number of radiating elements are equally spaced along a straight line as in figure 4.

(a) If all the elements are fed signals that are in-phase, the individual radiating waves combine, forming a wave front that propagates out from the array face along this direction called "broadside". The waves travel approximately the same distance, arrive at the see time, and having started out in-phase, remain in-phase. Therefore they add coherently.

(b) In an off-broadside direction, figure 5, some waves reach a point in space sooner than others because they travel different distances. Though these distances are small, they cause these waves to be out of phase with each other and they tend to cancel. In the case of a large array, composed of many elements, most side lobes cancel each other for angles even slightly off-broadside, resulting in the formation of a very narrow beam perpendicular to the array.

(c) The beam can be steered to a direction off-broadside as shown in figure 5 by electronically compensating for the delay between waves associated with the desired direction. This is accomplished by using either time-delay circuits or phase-shift circuits in series with each element, phase-shift being equivalent to time-delay at any given frequency.

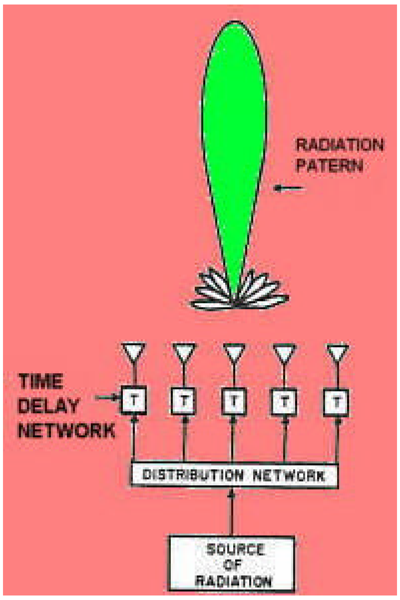

Figure 4. Broadside Radiation

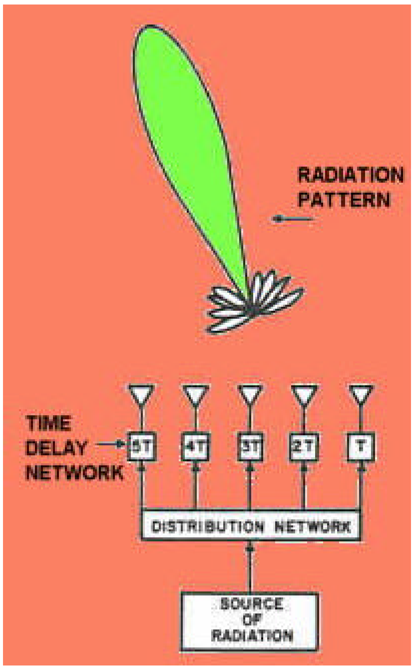

Figure 5. Off-Broadside Radiation.

(4) Regardless of bow the beam is steered, the net effect is always to combine the individual waves to form a composite wave front that is steered to the direction desired.

c. The simple linear array is of limited value because it can steer a beam in only one dimension. Moreover, this beam is narrow only in the plane containing the array.

(1) To obtain a composite narrow beam, one that is steerable in two dimensions, elements must be arranged in two dimensions.

(2) This is often done by constructing a planar array antenna where elements are arranged in rows and columns, forming a grid on a planar surface, figure 6. When all elements are in-phase, their waves add coherently in both a horizontal and vertical plane , and again perpendicular to the plane of the array.

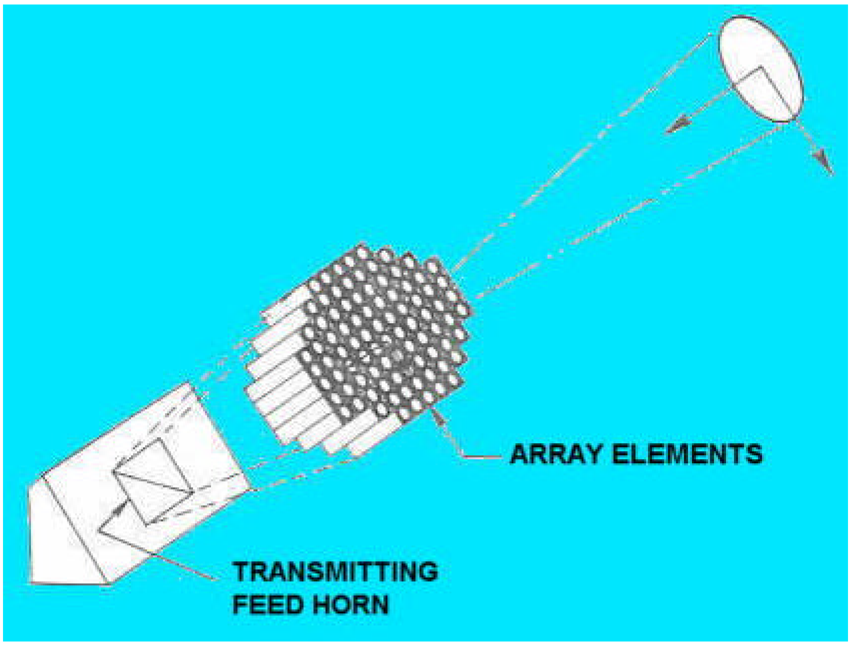

Figure 6. Planar Array

4. PHASE SHIFTING.

a. The primary requirement for electronic beam steering is a method of systematically varying the phase angle between the currents in adjacent elements of the array. There are two requirements to be considered. The first is the general pattern or arrangement of the phase shifters to be employed, and the second is the type of phase shifters to be used in each location.

b. In planar antennas employing one power amplifier and many phase shifters, there are various methods of dividing and feeding the power to the phase shifters. This time sharing of the elements for both transmitting and receiving permits greater traffic handling capacity with a minimum number of elements.

c. Phase shifters can be reciprocal and non-reciprocal, analog and digital, ferrite and diode. Reciprocal phase shifters introduce the same phase regardless of which way the power passes through them. Thus the same set ting can be used for receiving and transmitting. Analog phase shifters produce a phase shift proportional to an applied voltage or current. The digital phase shifter produces phase shifts in incremental binary fashion.

(1) In the technique of phase shifting, each bit, diode or ferrite is analogous to and serves principally as, a "switch". Two examples are used to represent the operation of phase shifters when commanded by the beam steering computer to change the phase of the RF energy.

(a) In figure 7, a zero degree phase shift is required so the four bit digital word (0000) is initiated in the computer. When the digital word is initiated, all four "switches" are closed; thus the phase shifter acts as a straight transmission line with no phase delay (phase shift). The RF energy output from across the complete face is in phase.

(b) In figure 8, a 112.5 shift is required. The beam steering computer now selects a 112.5 degree four bit digital word (0101). In this case switch S1 is opened causing a 22.5 degree phase shift; switch S2 remains closed causing no phase shift. S3 is opened providing a 90 degree phase shift while S4 remains closed, again no phase shift. The results of opening S1 and S3 (22.5 and 90 degrees) provides the total shift of 112.5 degrees. The process of delaying the energy as it passes through the transmission line is the same regardless of whether the method uses a three, four or five bit phase shifter.

(2) Employing thousands of these elements in an array and controlling the phase of each element, several functions such as beam steering, beam shaping and multiple beam formation may be accomplished. The phase shifter is the essential part of the element in pointing or directing the beam. The phase shifter carries the RF energy between the front and rear radiators in both directions.

d. Arrangements of phase shifters can be series, parallel, or a combination of series and parallel. There are advantages and disadvantages involving power loss, ease of control, and simplicity of hardware with each] method.

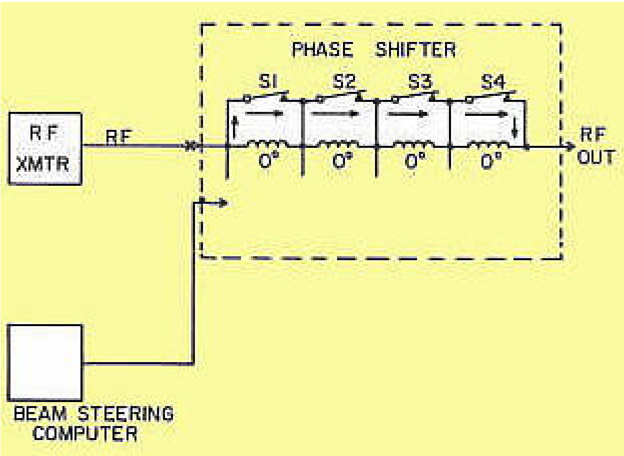

Figure 7. Zero Degree Phase Shift.

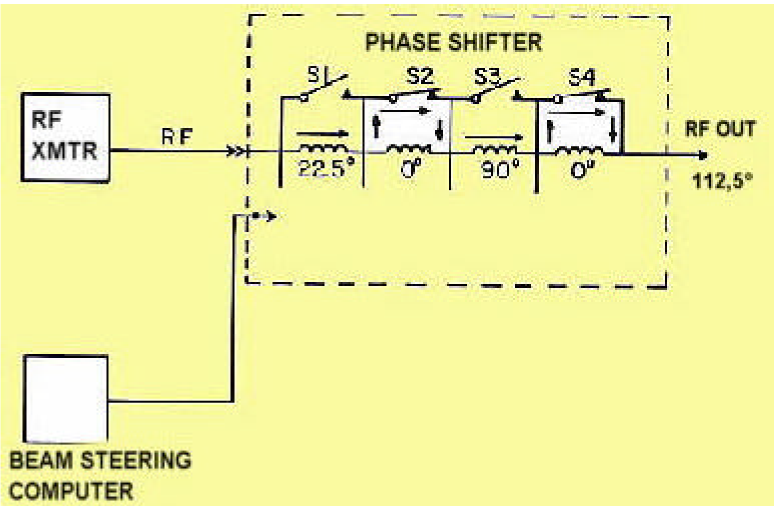

Figure 8. 112.5 Degree Phase Shift.

(1) The simplest arrangement of the phase shifters for a linear array is called the end fed series system, depicted in figure 9. Its primary advantage is that the delays of the individual phase shifters are additive so that only one value of phase shift or delay is required at each phase shifter. This arrangement has these disadvantages: losses in individual phase shifters are additive and the excitation of individual elements is not easily controlled.

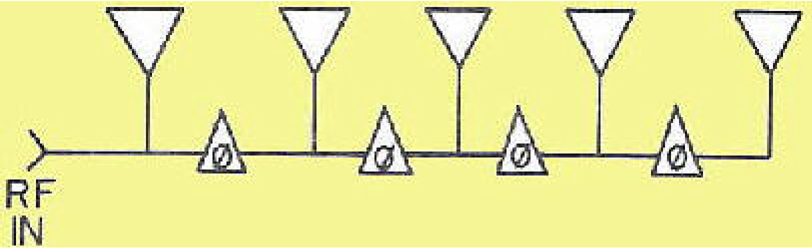

Figure 9. End Fed Series Array.

(2) The parallel or corporate system eliminates these problems, but necessitates different values of phase shift in each phase shifter along the array. A parallel phase shift arrangement is shown in figure 10. One problem, however, encountered with large parallel fed arrays is the grossly increased value of phase shift required toward the ends of the array.

(3) In order to achieve two dimensional steering with planar arrays it is necessary to use two dimensional phase shifting schemes. The simplest is the series-series arrangement, figure 11. In this arrangement, "H" represents the phase shift required for the horizontal angle and "V" the vertical angle. This arrangement may be either center or end fed, and possesses the same advantages and disadvantages as the other series systems.

(4) Combinations of corporate systems may also be employed. Although they permit greater flexibility they still suffer the same disadvantages as the single parallel method. Combinations of series and parallel methods are possible, each possessing advantages and disadvantages depending on its configuration.

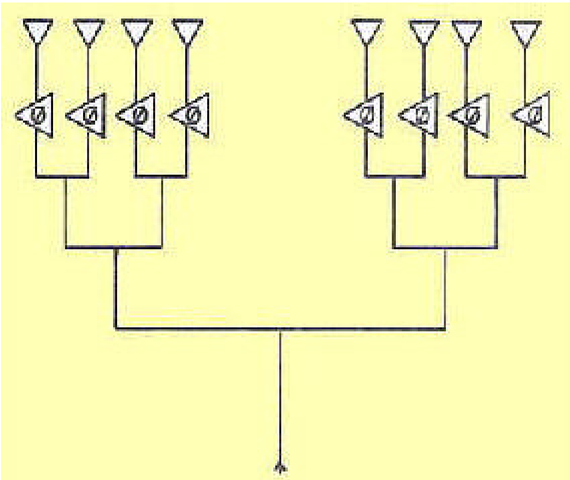

Figure 10. Parallel Fed Array

e. As with phase shifters, delay lines may be applied for a series feed, parallel feed or, in the case of planar arrays combinations of series
and parallel feeds. Since the delays associated with each element are inherently incremental, it is

advantageous to make the line lengths associated with each element a binary series, e.g., 1, 2, 4, 8, etc. This choice of delay lines also lends itself to control by a digital computer.

f. The devices which may be used to produce the necessary phase shift for each element are far too numerous to be listed here. Essentially, they fall into two broad categories, mechanical and electrical.

(1) Mechanical devices possess inertia and hence require considerable time to switch position. They also require very precise positioning, which in an array of thousands of elements becomes virtually an insurmountable problem.

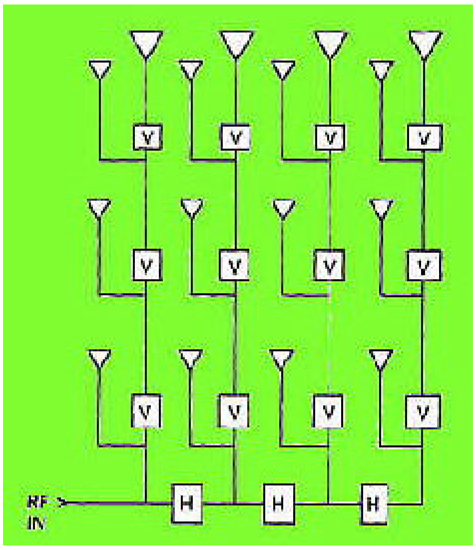

Figure 11. Series-Series Fed Array

(2) Electrical devices include transmission line stubs terminated with variable capacitance diodes, electronically switched delay lines, and diode and ferrite shifters.

5. ANTENNA ELEMENTS.

a. Radiation and reception from the array antenna is accomplished through many individual elements or cartridges. These elements serve the vital functions of accepting RF energy from the transmitter, changing its phase and radiating it out into free space. During the receive mode the element receives the return echo from space, again alters its phase and radiates it to the receiver feed horns.

b. Each element, regardless of type, is composed of: front radiator, phase shifting circuitry, waveguide or coaxial cable and the rear radiator. Discussion here, is limited to two digital types, one using diodes and the other ferrite cores, for phase shifting.

(1) The overall characteristics of a diode phase shifter are determined, to a large extent, by the diode itself. The power handling capability of a diode phase shifter is given by the peak current and voltage ratings of the diode. When both ratings are reached simultaneously, the maximum safe power level of the phase shifter is obtained. The power handling capability can be increased by either reducing the phase shift or increasing the number of diodes. Diode phasers are now capable of accommodating power levels beyond 100 KW, and reach cut-off frequencies well into the giga hertz range.

(2) One type of diode phaser is depicted in figure 12. This device has a phase length which i. digitally variable to provide the rapid change in the transmitted bean position. It is approximately four feet in length. The cartridge ii composed of : the rear radiator, a rigid coaxial transmission line, the phase shifter and the front radiator.

(a) The rear radiator receives RF energy from the transmitter feed horn and transfers it to the coaxial transmission line. In the receive mode, it transmits return signals back to the receiver network.

(b) The rigid coaxial transmission line, located between the phase shifter and the rear radiator, has a gold plated center conductor. The rear of the transmission line has a filter which blocks all DC from the input section but allows the RF energy to pass.

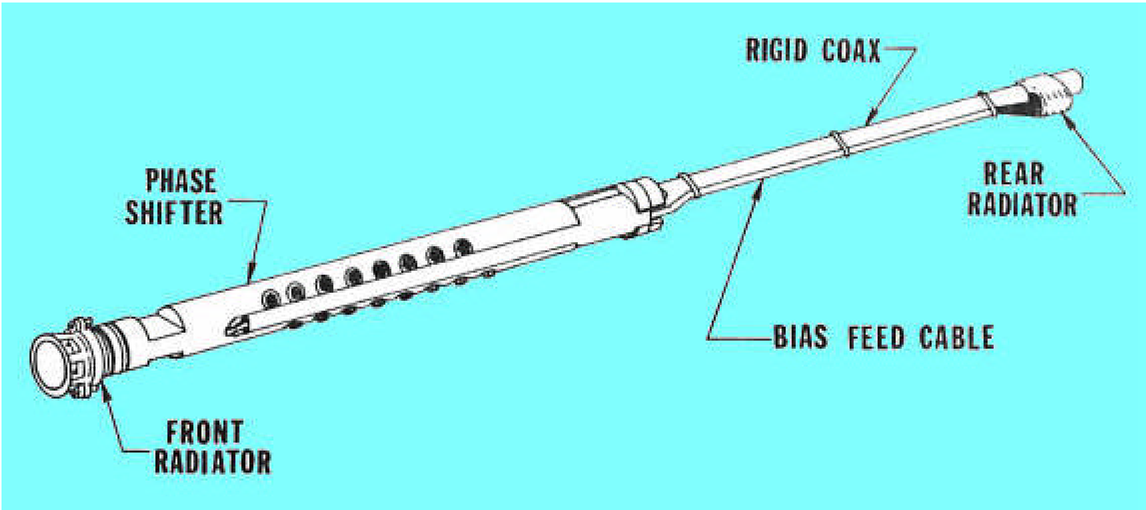

Figure 12. Diode Element

(c) The phase shifter provides accurate phase control of the RF signal within the element through the use of bias signal, which originate in the beam steering computer as digital bits. This device is a four bit element. If it were a low power and low frequency device, there would be four individual diodes, one for each digital word of phase shift. However, it is a high power and frequency element. Therefore it employs 16 stub circuits. The diode stub circuit. are grouped into four discrete bits capable of increasing the relative phase length of the phase shifter from zero to 337.5 degrees in increments of approximately 22.5 degrees. Regardless of the number of diodes or bits used, the phase shifter still operates essentially as depicted in figures 7 and 8. The body is fabricated from aluminium bar stock and has a precision drilled hole running the entire length of it with 16 critically located intersecting tapped holes. These 16 holes are used as sockets for the diode assembly.

(d) The front radiator couples the RF energy from the coaxial transmission line to a circular waveguide. A ceramic window on the front serves as the radome.

(3) In ferrite phase shifters, several cores of ferri-magnetic material are installed along the longitudinal axis of waveguides or transmission lines, figure 13. The cores are so spaced that the propagated waves will couple to the cores in a non-reciprocal manner (with the same setting incoming radiation is shifted differently from outgoing radiation). The cores are composed of a highly efficient microwave material.

(a) The length of the core is selected in accordance with the ligit requirements. For example, in a three bit phaser, one core (called a bit) is provided for each phase shift of 180, 90, and 45 degrees. Each successive core is half the length of the previous core in this design.

(b) Two charging or latching wires are used in this case for each core so that only positive pulses are required from each Driver. effectively, latching in or out the cones determines the apparent length of waveguide seen by radiation. For example, for a 90 degree phase shift, the 90 degree core would be latched in making the apparent length of the wave guide one quarter wavelength shorter than its normal length, thus shifting the phase of the radiation at the fan end by one quarter wavelength or 90 degrees.

c) The best waveguide for use with ferrite phasers is approximately square, measuring one third wavelength on each side. This small size results in a phase whose edge dimension is one half the free space wavelength of the operating frequency.

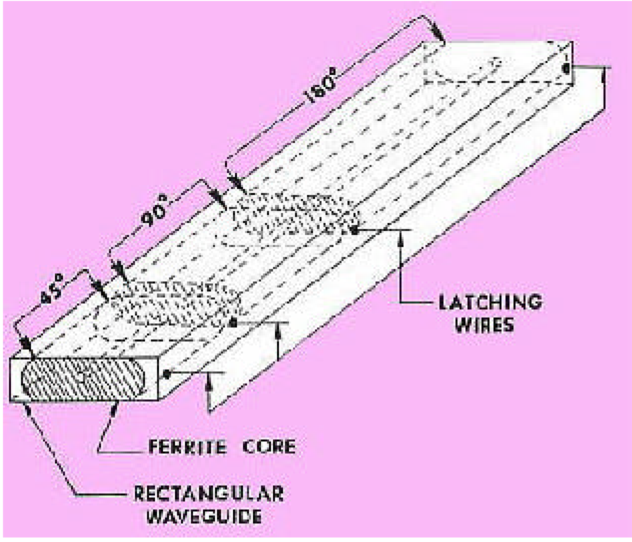

Figure 13.   Ferrite Core Locations.

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