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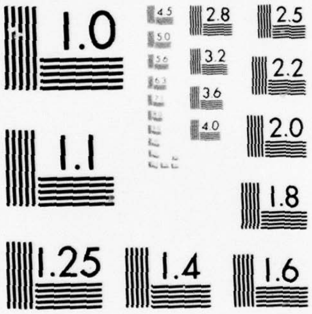

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A SURVEY OF ANTENNA ARRAY TECHNOLOGY FOR SURVEILLANCE SYSTEMS

Major Walter S. Gregorwich, USAFR

ROME AIR DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
GRIFFISS AIR FORCE BASE, NEW YORK 13441

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This report acquaints the reader with a survey of the latest state-of-the-art technology that may be applicable to various types of ground signal collection systems. An overview of the performance parameters of both planar and lens fed arrays is presented. An extensive bibliography is a key feature of this report.

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INTRODUCTION

Ideally a ground based RF monitoring system should be capable of full hemispherical wideband antenna coverage with the additional capability of monitoring several signals at the same time. The signals may be in the form of simple signals to complex radar signals having very narrow pulse widths such as those found on antenna or missile test ranges. Phased array antennas can easily meet the above criteria. They are superior to rotating reflectors with wideband feeds since they can simultaneously monitor multiple signals. Because the array has no moving parts, it does not require the periodic maintenance necessary in a rotating reflector system.

The purpose of this report is to acquaint the reader with a survey of the latest state-of-the-art array technology that may be applicable to such systems. An overview of the performance parameters of both planar and lens fed arrays is presented. One of the key features of this report is the extensive bibliography of current array systems. By means of the bibliography, the reader can explore in depth any aspect of array technology for passive monitoring.

In Section I, broadband planar arrays are discussed that provide either wide angle or complete hemispherical coverage. Various wideband aperture techniques and feed networks with their associated broadband components are presented.

Cylindrical arrays that provide multiple signal surveillance over 360° azimuthal coverage are discussed in Section II.

A comprehensive bibliography of wideband planar and cylindrical arrays is contained in Section III.

SECTION I

Plan Array Aperture Techniques

Many systems require at the very least wide angle azimuthal antenna coverage and in some cases complete hemispherical coverage. Planar array systems can provide the necessary coverage by means of either a single array for wide angle coverage or the utilization of a three-dimensional multi array system for hemispherical coverage. Three-dimensional antennas are obtained by placing planar arrays in the following configurations: on the four faces of a pyramid or five faces of a pyramidal frustum Knittel (1) and Kmetzo (2) and by a single planar array covered with a hemispherical bootlace lens Schwartzman et al (3). The state-of-the-art lens are limited to a 50% bandwidth; whereas the pyramidal configurations have a bandwidth as wide as that of the individual arrays mounted on its faces.

The bandwidth of an array is a function of the bandwidth of the individual radiating elements and the interelement spacing which in turn determines the maximum scan angle of the antenna beam. Widely spaced radiating elements produce multiple beams as one electronically scans the array off axis. To prevent unwanted beams from occurring, say over 120° scan range (±60°), the interelement spacing should not exceed 0.6 of a free space wavelength (4). The 0.6 spacing sets the upper frequency limit of the array. The lower limit is set by the physical packing of the elements and the magnitude of the mutual coupling mismatch. Generally, the closest one can pack, for example, dielectrically loaded waveguide elements, is 0.3 in a triangular lattice configuration, Tsandoulas (4). The triangular arrangement has the advantage of requiring 15% fewer elements for equal suppression of unwanted beams (grating lobes). Since 0.3 sets the lower frequency limit, the operating bandwidth of the array is limited to an octave (i.e. 0.3 through 0.6). However, in practice, passive systems operate in the receiver mode only and therefore can conceivably perform with a high aperture mismatch and/or unwanted beams. A mismatch due to mutual coupling (i.e. close radiating element packing) results in power loss which can be tolerated in high sensitivity receiver systems. A mismatch may also appear in the form of sidelobes. Unwanted beams (grating lobes), however, can only be tolerated if they are present in regions where incoming signals do not exist. Taking into account these limitations, some systems can operate over bandwidths much greater than an octave.

Wideband array aperture techniques can be found in the following literature: (4) - (7).

Broadband aperture techniques are not as advanced as the current state-of-the-art feed components that drive an array; therefore, aperture design is the critical factor in some systems. The wideband feed techniques and components will be reviewed in the next two sections.

Planar Feed Network Techniques

The function of a feed system is to provide the desired amplitude distribution across an array aperture. There are two basic methods of feeding an array: the constrained feed and the space feed.

Constrained Feeds

By means of RF transmission line circuits, the constrained feed technique interconnects the signals from the array radiators to the central feed point. There are three types of constrained feed systems: the series-feed, parallel feed, and hybrid system formed by the combination of series and parallel-feed networks.

The series-feed couples the signal to the radiators in series by means of a common transmission line. In most cases this technique results in a different path length to each radiator, therefore a progressive incremental phase shift must be introduced in each path to compensate for the difference in path length. More versatile feed techniques that are not frequency sensitive can be found in the parallel method.

The parallel-feed technique combines the radiating elements into subarrays having equal length transmission lines. The two most utilized beam forming networks in array systems are classified as parallel-feeds: the standard corporate feed and the Butler matrix. The corporate feed has the form of a tree; it consists of a single transmission line emanating from a central point which consecutively branches out in a binary split. This concept is shown in Figure 1. The junctions at which each branch splits can be either simple 2-way power dividers or hybrid couplers such as magic-T's. The hybrid couplers provide isolation between adjacent branches in case a radiator or phase shifter fails causing a high mismatch. Variable phase shifters are placed at each radiator to achieve beam scanning.

Even more versatile than the standard corporate feed, the Butler matrix, shown schematically in Figure 1, allows the generation of simultaneous beams. A wide range of directional beams are produced by controlling the relative excitations of the signals applied to the multi-input ports of the matrix network. By means of the Butler multibeam feed, an operator of the surveillance system can monitor many independent signals simultaneously. Since the Butler matrix was first introduced in 1960, there have been many variations of this technique. Articles that deal with the design and application of general N-port Butler matrices can be found in references (8) and (9). The typical performance of a Butler matrix system is an octave bandwidth with 20dB average adjacent beam isolation.

A description of current hardware systems employing constrained feeds can be found in Hill (10). Exotic beam steering techniques for constrained feed systems are found in (11) - (14).

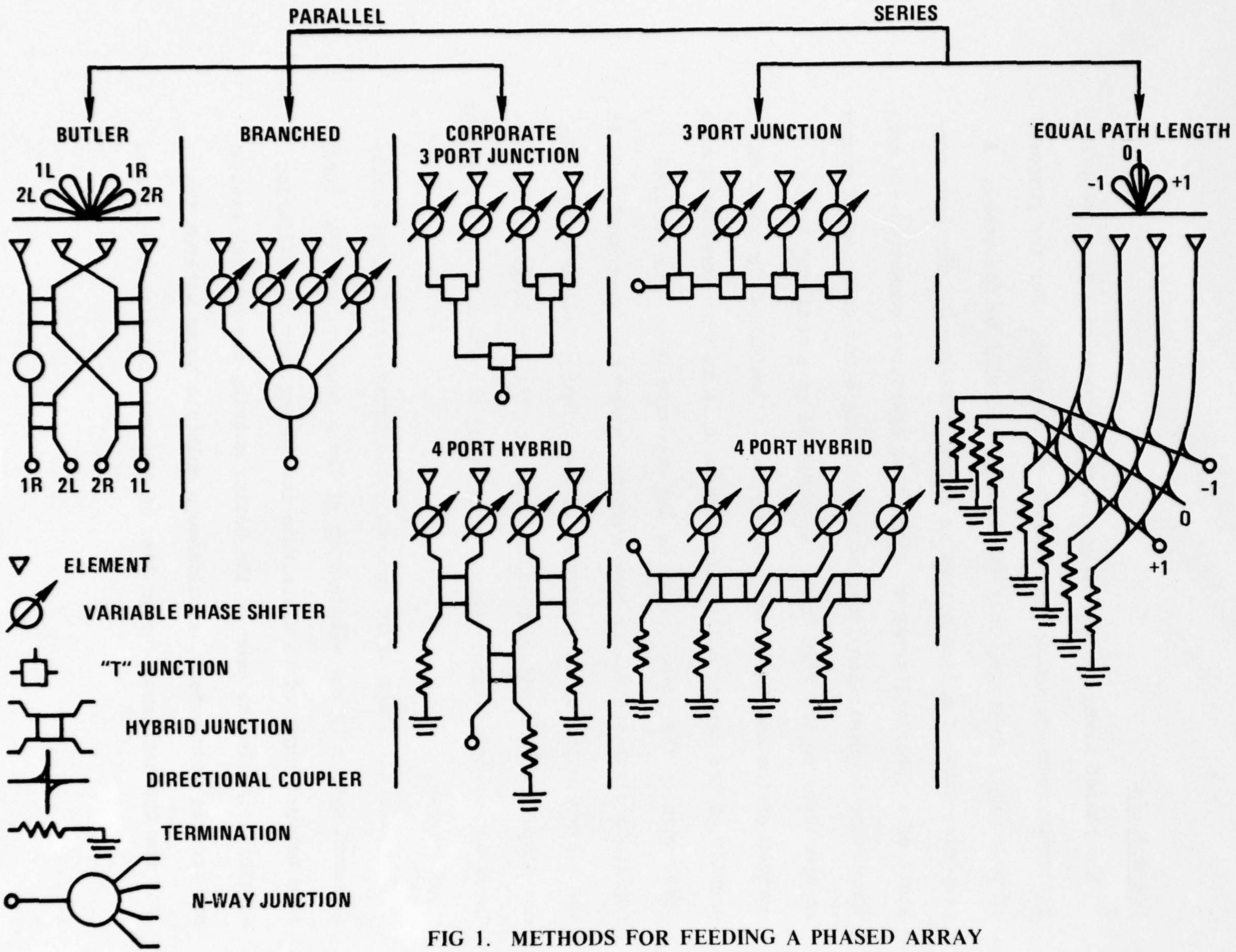

FIG 1. METHODS FOR FEEDING A PHASED ARRAY

Space Feeds

The phased array is optically fed in the form of a lens or reflector when employing the space feed technique. For the purposes of wide angle coverage, only the lens method will be discussed. A pictorial view of a lens system is shown in Figure 2. The lens consists of a spherical array of collecting apertures connected via non-dispersive transmission lines to a radiating array of an equal number of apertures on the flat face. A spherical wave radiated from a portion of the smaller primary array feed illuminates the spherical surface of the larger collecting array and is in turn reradiated as a plane wave by the planar array on the opposite face. The desired amplitude distribution for beam shaping, such as a fan-shaped beam in the elevation plane, is generated in the primary cluster array. The non-dispersive transmission lines that join the two larger array surfaces act as delay lines thereby equalizing the phase front across the planar array.

The main advantage of an optically fed array over that of a constrained system is the elimination of the expensive, complex, lossy feed network required to distribute the energy over the radiating aperture. As in the case of the Butler matrix, the optical system can provide independent, simultaneous multiple beams without the need for the nonplanar, power limited transmission line circuits of

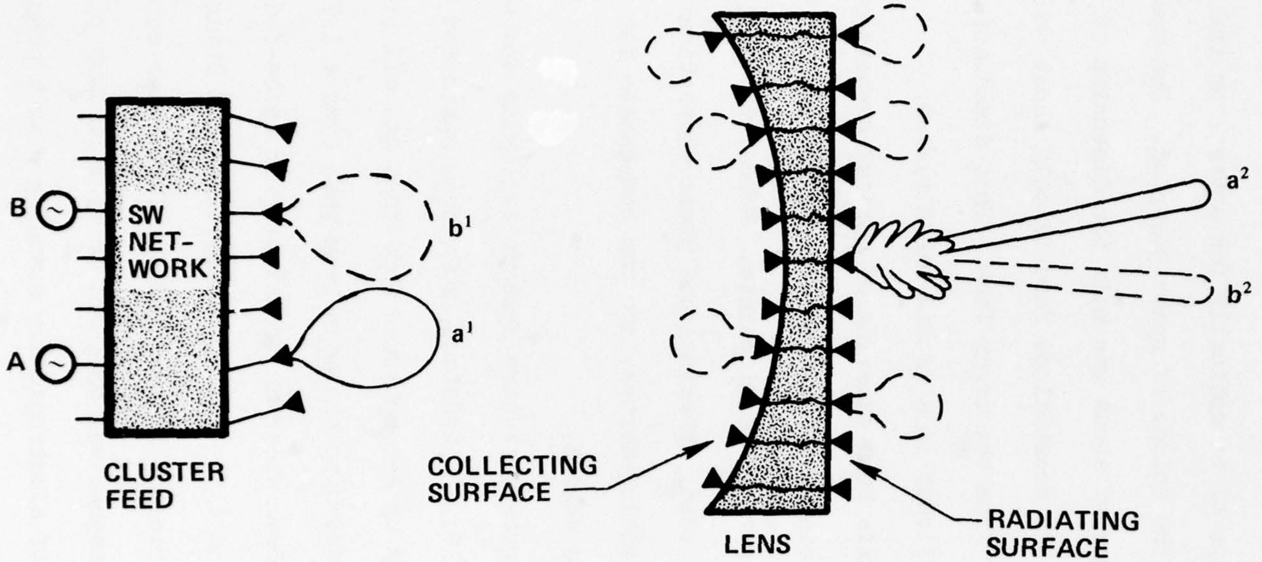

FIG 2. LENS – MULTIBEAM CLUSTER FEED SYSTEM

the Butler feed.

The only disadvantage of an optically fed array over that of a constrained system is the volume of space occupied. The space feed has a depth of the order of about one half the dimension of the aperture face whereas the constrained feed is only about one tenth of the aperture size away from the array face. This disadvantage in compactness is insignificant in a ground based system.

Of necessity, off-axis beam steering of optical systems must utilize feeds of the primary array that are off the axis of the system. A lens has only three perfect focal points. Hence, the optical systems are subject to coma, spherical and phase aberrations. In order to avoid beam pointing errors, one can compensate for the aberrations in the feed design.

A description of current hardware systems employing space feeds can be found in Hill (10). A wideband, multibeam space-fed array has recently been developed by Aeronutronic Ford that has all sidelobes depressed by 35 dB relative to the main beam peak over a 1.7 to 1 frequency bandwidth. Beam steering techniques for space-fed systems are described in (3) and (15) - (17). Schwartzman and Stangel (3) have developed a new concept in space feeds. The design consists of a lens shaped as a hemispherical dome driven by a primary planar array. The system is capable of electronically scanning over a complete hemisphere.

SECTION II

Planar Wideband Components

In Section I, the techniques for implementing the antenna array were discussed; this section will review the individual RF components that make up the array. These components are not unique to any single array configuration, but can be utilized in all configurations from planar arrays to conformal cylindrical arrays.

Radiating Elements

Once the element spacing (generally not less than 0.3) and the element lattice (triangular for minimum number of elements) has been determined, one must choose a broadband element that will meet these spatial constraints.

Since the radiator is the transducer between the feed system and free space, it must be broadband matched over the entire scan angle. The close proximity of the elements in a large wideband array will create mutual coupling mismatches. To diminish mutual coupling effects, one must choose a low gain (i.e. small aperture) element. Radiators that are normally wideband in an isolated environment may have an aperture size that cannot be packaged into the required tight lattice geometry of a large array.

An array element that meets all the above criteria and for that reason is most widely used in broadband arrays is the open-ended rectangular waveguide. By loading the waveguide with dielectric or ridges, one can reduce the aperture size and thus permit close element packing.

The simple waveguide radiator easily lends itself to several wideband matching techniques: multi-section waveguide transformers; a metal iris at the aperture; dual ridges at the center of the broadwall of the waveguide (18) and a thin dielectric sheet placed in front of the array aperture. The use of the dielectric sheet for wide-angle impedance matching (19) may cause an aperture resonance as the array is scanned. This resonance, which was experimentally verified by Gregorwich (20), will destroy the main beam and therefore must be calculated in the design phase using the work by Knittel (21). All of the above matching techniques may be employed individually or in combination.

Once it has been matched in an array environment, the rectangular waveguide element is capable of radiating a linear polarized signal over ±60° for greater than an octave bandwidth (5). To achieve arbitrary polarization, one must utilize an open-ended, dielectric and/or ridge loaded, circular waveguide. However, the bandwidth is now limited to only 20% over the ±60° conical scan volume. Circular waveguide radiating elements are discussed in (5) and (22). Wideband arrays of rectangular waveguide elements are discussed in (4) and (23).

Feed Components

The three major RF components found in array feeds are: phase shifters, switches and directional coupler/power dividers. All three are capable of multi-octave performance.

There are basically two types of phase shifters - the diode and the ferrite phase shifter. Diode phase shifters can be categorized as follows: a reflection device in which the diodes cause signal reflection at different intervals along a transmission line; a line-stretcher device in which different lengths of transmission line are switched into the propagation path and a loaded-line device in which quarter-wavelengths of transmission line are switched onto the main line to change the phase. Ferrite phase shifters change phase by means of their variable electric properties. The permeability of a ferrite is a function of the magnetic flux passing through it. The two types, non-reciprocal and reciprocal, are energized by applying an external biasing signal to produce different magnetization directions in the ferrite material.

The salient features of the diode shifter are its small size and rapid switching capability (i.e. about one nanosecond). The ferrite shifter can handle higher power and has less loss than the diode shifter but will not switch in less than one microsecond. Surveillance systems, however, require fast response especially when monitoring radar signals. Also, these systems are in the receive mode only which is not detrimental to the low power requirements of the diode. For these reasons and the fact that it is less expensive than the ferrite shifter, the diode shifter is the logical choice for some antenna arrays. Typical performance parameters of a Ku-Band diode phase shifter are: switching speed of one nanosecond with an insertion loss of less than 2 dB. For a ferrite shifter, they are: switching speed of one microsecond with a 0.8 dB insertion loss.

It might be noted that phase-shift accuracy will affect the beam pointing accuracy to a small degree; therefore the phase shifter should not attenuate the RF signals by much more than 1.0 dB. Papers on diode phase shifters can be found in (7) and (24). Papers on ferrite phase shifters can be found in (6), (25), and (26).

A broadband, extremely fast switch can be constructed using pin diode microstrip techniques. The multi-port switch is etched on a copper clad substrate with all transmission lines joined at a center junction. The switching action is accomplished by a single shunt pin diode in each of the 50 ohm output lines. The diode, which is mounted $\lambda/4$ away from the center junction is grounded at one end and fed at the other end. In the on-condition the diode appears as a short to ground, $\lambda/4$ away from the center junction. This $\lambda/4$ stub makes the short appear as an open circuit effectively placing the switched arm out of the microwave path and no signal flows. When the diode is biased off, the path from any input to the center junction is completed and signal flows. Typical performance parameters of this type of switch at Ku-Band are as follows: switching speed of one nanosecond; insertion loss of 2.5 dB; port-to-port isolation and balance 25 dB and ±0.5 dB respectively. A discussion on wideband microwave switches can be found in (26).

Multi-octave directional coupler/power dividers have been developed using stripline techniques. By arranging in tandem over-under, $\lambda/4$ sections having low coupling coefficients, one can achieve coupling values of any ratio. Typical performance parameters of this component at Ku-Band are as follows: isolation 20dB or greater; insertion loss less than 0.8 dB; port-to-port amplitude balance less than ±0.5 dB and 2 degree maximum phase imbalance. Tandem couplers are discussed in (27).

Planar System Performance Summary

The bandwidth of an antenna array system is limited by three constraints: the technique of radiating element placement in the aperture; the bandwidth of the system RF components, including the radiator; and the arrangement of the RF components into a feed network that drives the array.

Wideband aperture techniques, because they are not as advanced as the state-of-the-art RF feed components, are the most difficult areas of design in wide angle scanning arrays. Without performance degradation, one can operate a planar array over an octave bandwidth keeping in mind that the interelement spacing should not be less than 0.3 or exceed 0.6 . Under these conditions, the maximum scan angle is 120 degrees (i.e. ±60 degrees) over a conical scan volume or with the option of a wide angle fan beam in the elevation plane. By placing several planar arrays in a three dimensional configuration or employing a hemispherical dome lens, one can scan over a complete hemisphere.

Multibeam feed systems, such as the Butler Matrix and the cluster fed lens, appear to be the most versatile for simultaneous beam surveillance antennas. The optical feed offers the most efficient method of driving an array. Since the optical system requires less hardware than a constrained feed, it is less lossy and expensive. The feed can be designed such that the energy distribution in the elevation plane has relatively low levels at all angles below the horizon (i.e. co-secant square radiation pattern).

The loaded, open-ended, rectangular waveguide radiator appears to be the best element for a linear polarized, wide band, wide scan angle array. If arbitrary polarization is necessary, one can use a loaded, circular waveguide radiator; however, the array bandwidth is reduced to only 20%.

Up to 20 GHZ, the RF components are capable of operating over multi-octave bandwidths with an individual insertion loss of less than 2 dB and switching speeds of one nanosecond. The fast switching speed of the diode switches and phase shifters is essential when monitoring radar signals.

Cylindrical Array Aperture Techniques

Cylindrical arrays are a natural choice for 360° circumferential coverage. Unlike planar arrays, the beam directions are invariant with frequency change and the beams do not deteriorate with increasing off-axis scan angle. In addition, azimuth scan by several planar arrays in a pyramidal configuration as discussed in Section I require switching between faces which generates a difficult data handover problem. Azimuth scan by a cylindrical array is simply accomplished by rotation of the active portion of the array. Either by phase shifting or switching, the feed system performs the function of electronically connecting a set of adjacent radiators in succession as the active portion is rotated, see Gregorwich (28).

The aperture techniques for cylindrical arrays are essentially the same as those of the planar arrays discussed in Section I. The cylindrical arrays can also operate over an octave bandwidth, see Provencher (29). Because of the array curvature and the fact that it is not necessary to scan off-axis as in planar array operation, the cylindrical array elements experience far less mutual coupling and are, therefore, easier to match. The curvature does necessitate phase correction and sidelobe reduction techniques in the feed system.

The feed techniques outlined in Section I are the same techniques that are used in cylindrical arrays with a different packaging arrangement. They are classified as: constrained feeds and space feeds.

Constrained Feeds

As was the case for the planar arrays, the simultaneous beamforming Butler Matrix is the most versatile constrained feed system for cylindrical arrays. Papers dealing with the Butler Matrix can be found in (30) - (33). Papers on other general cylindrical array feeds are found in (13) and (34) - (40).

Cylindrical Array Feed Network Techniques

The feed techniques outlined in Section I are the same techniques that are used in cylindrical arrays with a different packaging arrangement. The feeds are categorized as: constrained feeds and space feeds.

Constrained Feeds

As was the case for the planar arrays, the simultaneous beamforming, Butler Matrix is the most versatile constrained feed system for cylindrical arrays. Papers dealing with the Butler Matrix can be found in (30) - (33). Papers on other general cylindrical array feeds are found in (13) and (34) - (42). The focusing of an elevation fan beam is specifically discussed in (42); this is an important design feature in ground systems with variable topography.

Space Feeds

A comparison of the merits and disadvantages of various cylindrical space feeds can be found in (43). This paper also discusses a synthesis procedure for the design of elevation fan beams with extremely low azimuth sidelobes. Additional references on diverse space feed techniques are found in (15) and (44) - (46).

System Performance Summary

The Feed networks and the RF components that cylindrical arrays are comprised of are essentially the same as those of the planar arrays described in Section I. The octave bandwidth performance is, therefore, essentially the same as that of planar arrays. For 360° scan, cylindrical arrays are much easier to implement. A description of current hardware systems employing cylindrical arrays can be found in (10), (29) and (47).

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METRIC SYSTEM

BASE UNITS:

Quantity	Unit	SI Symbol	Formula
length	metre	m	...
mass	kilogram	kg	...
time	second	s	...
electric current	ampere	A	...
thermodynamic temperature	kelvin	K	...
amount of substance	mole	mol	...
luminous intensity	candela	cd	...

SUPPLEMENTARY UNITS:

Quantity	Unit	SI Symbol	Formula
plane angle	radian	rad	...
solid angle	steradian	sr	...

DERIVED UNITS:

Quantity	Unit	SI Symbol	Formula
Acceleration	metre per second squared	...	m/s
activity (of a radioactive source)	disintegration per second	...	(disintegration)/s
angular acceleration	radian per second squared	...	rad/s
angular velocity	radian per second	...	rad/s
area	square metre	...	m
density	kilogram per cubic metre	...	kg/m
electric capacitance	farad	F	A·s/V
electrical conductance	siemens	S	A/V
electric field strength	volt per metre	...	V/m
electric inductance	henry	H	V·s/A
electric potential difference	volt	V	W/A
electric resistance	ohm		V/A
electromotive force	volt	V	W/A
energy	joule	J	N·m
entropy	joule per kelvin	...	J/K
force	newton	N	kg·m/s
frequency	hertz	Hz	(cycle)/s
illuminance	lux	lx	lm/m
luminance	candela per square metre	...	cd/m
luminous flux	lumen	lm	cd·sr
magnetic field strength	ampere per metre	...	A/m
magnetic flux	weber	Wb	V·s
magnetic flux density	tesla	T	Wb/m
magnetomotive force	ampere	A	...
power	watt	W	J/s
pressure	pascal	Pa	N/m
quantity of electricity	coulomb	C	A·s
quantity of heat	joule	J	N·m
radiant intensity	watt per steradian	...	W/sr
specific heat	joule per kilogram-kelvin	...	J/kg·K
stress	pascal	Pa	N/m
thermal conductivity	watt per metre-kelvin	...	W/m·K
velocity	metre per second	...	m/s
viscosity, dynamic	pascal-second	...	Pa·s
viscosity, kinematic	square metre per second	...	m/s
voltage	volt	V	W/A
volume	cubic metre	...	m
wavenumber	reciprocal metre	...	(wave)/m
work	joule	J	N·m

SI PREFIXES:

Multiplication Factors	Prefix	SI Symbol
1 000 000 000 000 = 10^{12}	tera	T
1 000 000 000 = 10^{9}	giga	G
1 000 000 = 10^{6}	mega	M
1 000 = 10^{3}	kilo	k
100 = 10^{2}	hecto*	h
10 = 10^{1}	deka*	da
0.1 = 10^{-1}	deci*	d
0.01 = 10^{-2}	centi*	c
0.001 = 10^{-3}	milli	m
0.000 001 = 10^{-6}	micro	µ
0.000 000 001 = 10^{-9}	nano	n
0.000 000 000 001 = 10^{-12}	pico	p
0.000 000 000 000 001 = 10^{-15}	femto	f
0.000 000 000 000 000 001 = 10^{-18}	atto	a

* To be avoided where possible.