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ELECTRONICALLY STEERABLE ANTENNAS FOR COMMUNICATION SATELLITES

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ABSTRACT

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This paper presents several electronically steerable antenna techniques which, for frequencies from 1 to 35 gc, show promise for application to communications satellites. It is indicated that such antennas can be realistically designed to provide maximum antenna gain for given weight, maximum bandwidth, and the capability of illuminating only desired geographical areas. Moreover, by incorporating self-tracking capability into the antenna, spacecraft stabilization requirements can be relaxed even to the extent that high gain inertialess antenna systems with omnidirectional response are possible in the case of unstabilized vehicles.

Selected beam forming techniques are presented and it is shown that many steerable antenna designs are derived from these basic techniques. An examination of the circuitry required to implement the design is utilized to prove that the antenna is no longer solely an input or output to a given system but becomes now an inseparable part of the system. Basic problem areas of beam forming, self tracking, and scanning are outlined. Moreover, evidence is given to indicate that lightweight, low loss stripline componentry is presently available to construct real systems.

Several promising techniques, namely the retrodirective and transdirective, are applied to earth-space-earth and space-space communication links. System parameters are listed which show that increased performance and flexibility can be attained.

Author

List of Illustrations

ELECTRONICALLY STEERABLE ANTENNAS
FOR COMMUNICATION SATELLITES

Present activities underway in space depend in large measure on the communications that can be initiated and maintained with and between the participating vehicles. This requirement for sensory contact is ever present in the planning of anticipated future missions. Substantial effort is being made to establish space communication links from point to point on the earth's surface by means of artificial satellites. Courier, Echo, Telstar, and Syncom are classic examples. The intense interest of the military in satellite data transmission is only an additional example of the recognized promise for such communication links.

Generally, developments and exploration in space require point to point communications where the space vehicle may constitute either a point of origin of transmission or simply a relay station, depending on the particular mission. Figure 1 shows typical data links involving earth, spacecraft and aircraft.

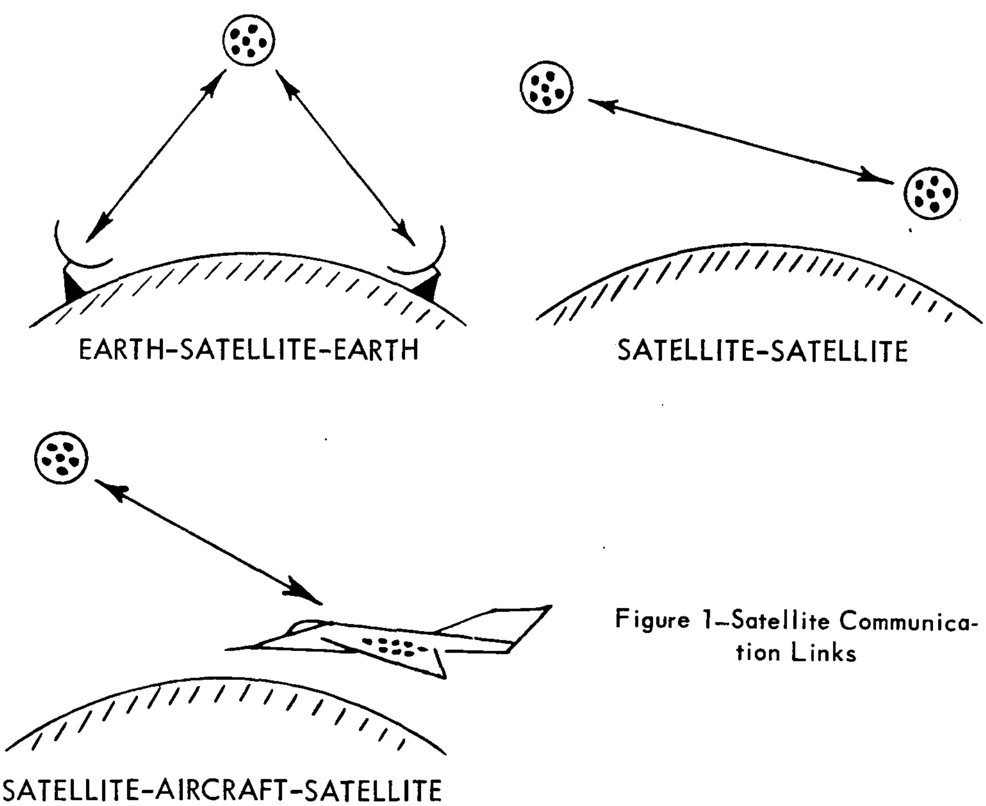


Figure 1–Satellite Communication Links

Motion is to be expected of either or both terminals of the link with respect to an arbitrary frame of reference. The volume through which an antenna system must operate is determined by the orientation of the two ends of a communication link. Usually this orientation is described in terms of the satellite stabilization listed in Figure 2.

When the link is satellite-to-satellite, then the stabilization characteristic must be defined between satellites. However, except in special cases, this system is considered to be unstabilized from the antenna standpoint since control of the orientation between satellites is technically difficult and also expensive in terms of fuel consumption. From the general orbit categories mentioned above six have been chosen to typify communication satellite systems. These are listed in Figure 3.

(1) Fully stabilized – control is obtained over three axes (e.g. Nimbus, OAO)

(2) Spin stabilized in plane of orbit (e.g. Telstar, Relay) – the satellite spins rapidly about one axis – a maximum of 150 revolutions per minute.

(3) Spin stabilized perpendicular to orbiting plane (e.g. Syncom) – normally the satellite spin axis lies in the orbiting plane and reorientation is necessary.

(4) Gravity Stabilized (e.g. ATS) – the satellite has one axis coincident with a line through the center of the earth. Slow oscillations or librations do occur, however.

(5) Unstabilized – the satellite may take any orientation. The change in orientation, called tumbling, is usually rather slow.

Figure 2–Degrees of Stabilization

(1) Synchronous orbit – 22,300 miles – spin stabilized
(2) Synchronous orbit – 22,300 miles – gravity stabilized
(3) Synchronous orbit – 22,300 miles – unstabilized
(4) Six thousand mile orbit – spin stabilized
(5) Six thousand mile orbit – gravity stabilized
(6) Medium altitude orbit – unstabilized

Figure 3–Satellite Orbits

New environmental demands must be met including those imposed by the ambient vacuum, by temperature extremes, and by micrometeorite bombardment as examples. Restrictions of weight and power consumption become severe, and reliability assumes extreme importance since time and access for repair or service are nonexistent. A stringent weight restriction on equipment is inherent in all space missions. This restriction may be translated rather directly into limitations on available power and on the size of communication equipment. Another factor of extreme significance is that the transmission of signals to and from space vehicles involves communication over great distances. The ranges involved are long even in the instance of an earth orbiting satellite, although such a situation involves short distances for what would be considered a space mission. These two considerations, the importance of weight and the long distances involved, point to the desirability and necessity of achieving as much directivity and efficiency in the antenna structure as the mission situation will permit.

In the past, communication satellite designers have used antennas which are either omnidirectional or quasi-isotropic on spin stabilized spacecraft. Other designs have called for directive horn or reflector antennas placed on spacecraft of varying degrees of stabilization and in certain cases employing electromechanical means to control the beam pattern as dictated by point-to-point spacial variation of the data link. Although generally reliable, and in many applications an optimum design based on system tradeoffs, such antenna/vehicle combinations suffer from a number of limitations (see Figure 4). Reduction in system communication capacity is actually an inherent result of their use. Fig. 5 diagramatically displays the typical scattering of radio frequency energy throughout space by a transmitting omnidirectional antenna on a communication satellite.

Only the energy impinging on the surface of the ground antenna is usefully recovered. The remaining energy can become a significant contributor to the increasing problem of R.F. interference on the ground. In receive operation the omnidirectional antenna becomes an efficient collector of galactic noise and man-made interference from a large number of geometrically displaced sources.

Certain factors complicate the practical problem. As directivity is increased, the necessary degree of pointing accuracy required also increases. The antenna designer encounters certain limitations. One of these is the capability of the vehicle to control its mechanical orientation. Another is the accuracy with which the orientation may be determined at any given time. One questions to what extent it is advisable in a given set of circumstances to attempt to control the vehicle attitude. The answer is of course a practical compromise of those techniques available for antenna searching and tracking, and the degree of vehicle attitude control required.

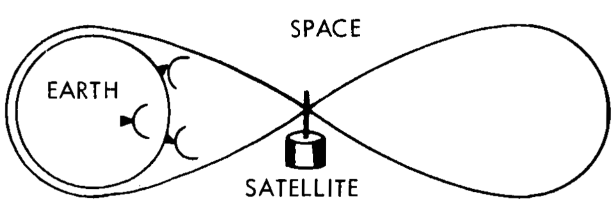
(1) Low gain figure
   (a) results in mediocre system performance
   (b) for high signal-to-noise ratios, bandwidth is limited
   (c) require expensive high quality ground terminals (30 foot dish or larger).
   (d) Space-space operation requires a high power transmitter on the spacecraft.

(2) Poor directivity
   (a) antenna does not place the major portion of its effective radiated power at the terminal point.
   (b) omnidirectional and "earth angle" antenna radiation can cause R.F. interference.
   (c) antenna exposes spacecraft receiver to noise and man made interference from spacially separated sources.

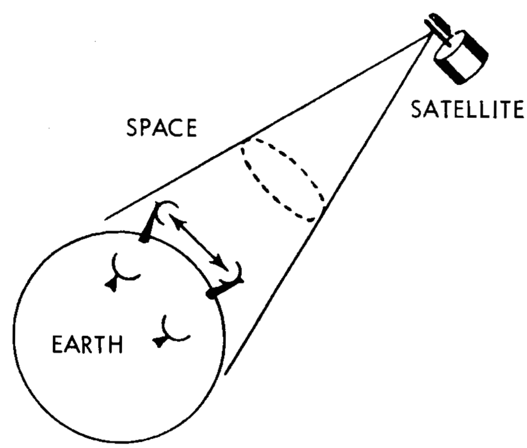
(3) Mechanical Inertia
   (a) electromechanically scanned antennas require spacecraft torque compensators, are subject to bearing and motor failure, in certain applications require rotary joints, and are limited in the scan angle and number of functions they perform.

(4) Limited Functional Performance
   (a) electromagnetic access is not selectively controlled by the antenna.
   (b) the multiple access beam forming capability inherent in inertialess antennas is generally not utilized.
   (c) the system performance of small aperture ground antennas can be below CCIR standards for T.V. bandwidths.

Figure 4—Communication Satellite Antenna Limitations



(a) Omnidirectional antenna pattern



(b) Earth Angle antenna pattern

Figure 5—Indiscriminant Radiation of R.F. Energy and Susceptibility to Noise

Inertialess electronically steerable antenna systems are particularly applicable to spacecraft mission problems. Such systems which permit a large number of beams to be independently steered can be made light in weight, low in loss and small in size so that gain and bandwidth can be increased to give better system performance without R.F. interference with existing facilities. Antenna beams can be placed selectively to cover desired geographical areas. A consideration of the antenna techniques must be incorporated in the overall system design for the mission in order to determine essential trade-offs in overall system weight, accuracy, and reliability.

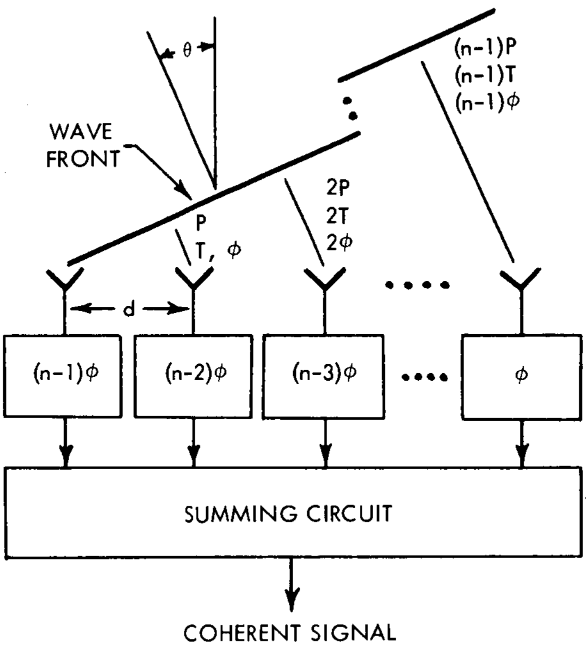
Before presenting two promising antenna systems for space vehicle application, a brief discussion of the special properties of electronically steered antennas is in order. The assembly and functional operation of a steerable array can begin by referring to Figure 6 which depicts an n-element linear array. The vector normal to the array is defined as the boresight direction. On receive operation energy arrives at the array from some angle θ with respect to boresight. Let the distance separating the wavefront from each antenna element be 0, P, 2P, 3P. . . (n-1)P. This will result in a corresponding time delay 0, T, 2T, 3T. . . (n-1)T. Equations are given in Figure 6 which relate the differential time delay to the differential phase shift between adjacent elements of the array. The energy is added incoherently since the phase in any channel differs from the others. The addition of a variable phase shifter behind each element allows the channel outputs to be coherently summed by forcing equivalence of the total argument of the phase function at each channel output. Phase shifts of 0, ϕ, 2ϕ, 3ϕ. . . (n-1)ϕ would be required. The response of the array or beam pattern is indicated by the magnitude of the sum pattern and will be less for angles of arrival different from θ. The output of the summing bus is more commonly called the beam output; the process of summation is referred to as beam forming.

In conventional arrays, element spacing is approximately one-half wavelength. Spacings less than 0.4λ give mechanical as well as mutual coupling problems, while spacings larger than 0.7λ produce grating lobes in the beam pattern. Under the condition of 0.5λ spacing, the array beamwidth is less that obtained with a reflector antenna of the same dimensions. This is in agreement with the higher aperture efficiency of the array. As is experienced in conventional antennas, control of side lobe level can be achieved by proper weighting of the illumination function. The signals in each channel are weighted in amplitude prior to summation. This allows the side lobe level of the antenna beam pattern to be set at practical levels.

An infinite number of orientations of the phase front in Figure 6 are possible. If the phase shifter setting ϕ, 2ϕ. . .(n-1)ϕ are varied proportionately, the differential phase shift across the aperture must also change in order to achieve coherent summing. In effect, the angle of arrival θ of R.F. energy which is added coherently by this antenna has been altered. This is generally referred to as beam steering.

The point of importance to be made here is that considerable variation in beam pattern shape can be achieved by exercising proper control of phase and amplitude at each element of the array. Simultaneous beam formation by the antenna in a typical space-earth and space-space link is shown in Figure 7.

Considerable effort has been expended in the area of beam forming and steering by certain investigators. Although much of the earlier work has been applied to the development of large ground antennas, in comparison, little (few exceptions)* has been done to further the development of electronically steerable antennas for communication satellites. A large number of



$$T = \frac{P}{C} \qquad P = d \sin \theta$$

$$\phi = \frac{2\Pi d}{\lambda} \sin \theta$$

where, θ = the beam angle
ϕ = differential phase shift
T = differential time delay
P = differential path length
d = element spacing
n = number of elements
c = speed of light

Figure 6–Special Properties of an Electronically Steered Array

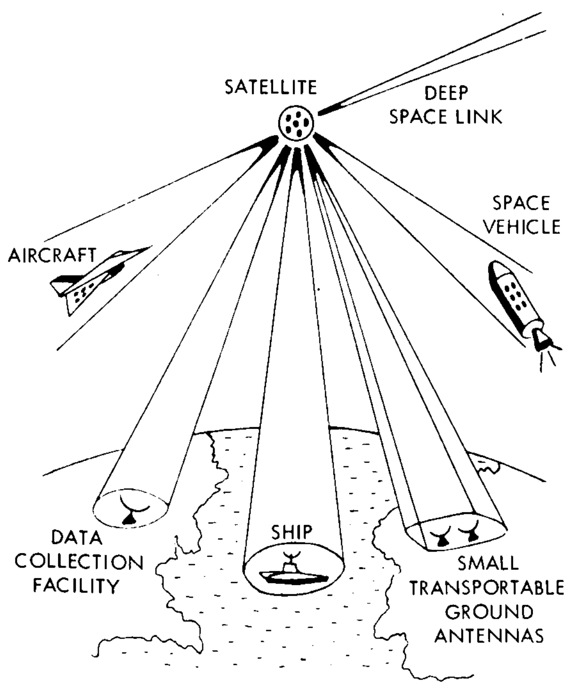


Figure 7–Formation of Simultaneous Steerable Beams by the Spacecraft Antenna in space-earth and space-space Data Links

*See reference.

techniques for beam forming and steering are available, but only a few are suitable for space application. Two promising techniques, namely the Retrodirective and the Transdirective appear to be practical in the sense that components required for their demonstration are presently available in the frequency range of interest (1 to 10 gc).

The Retrodirective principle in its simplest form is illustrated in Figure 8. A CW signal received by the n^{th} element of an array can be represented by sin (wt +θn), where w is the angular frequency and θn is the phase of the incoming signal at the n^{th} element, relative to some common reference. The signal is subtracted from (mixed with) a common local oscillator, sin 2wt, to obtain a transmit signal sin (wt-θn) which is the same as the received signal except that it has an inverted phase angle. The transmit signal is amplified and transmitted out the same antenna element. A circulator is used to separate the transmit and receive signals. The phase angle is similarly inverted at every element; this is the condition for transmitted energy to form a beam in the same direction as the received signal. Such an array works as an active device to reflect a signal back towards its source. No frequency shift between the uplink and the downlink is accomplished and no signal output is available at the satellite.

A practical variation of the retrodirective principle is given in Figure 9. This design is called a Retro-Redirective Antenna since it has the capability to

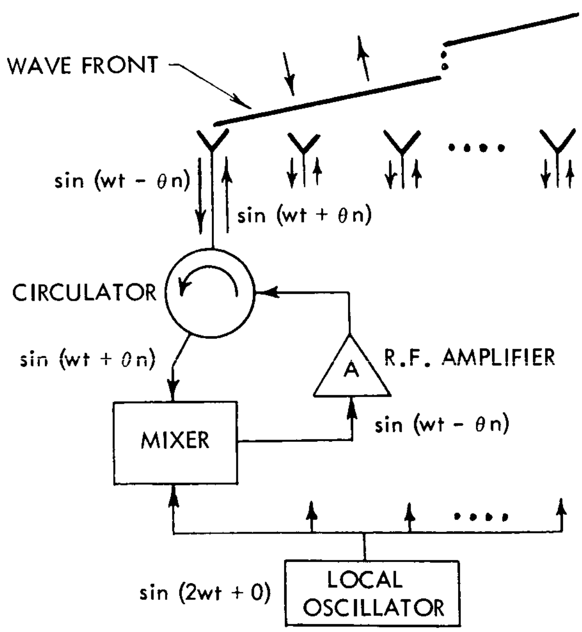


Figure 8–Simplified Retrodirective Principle

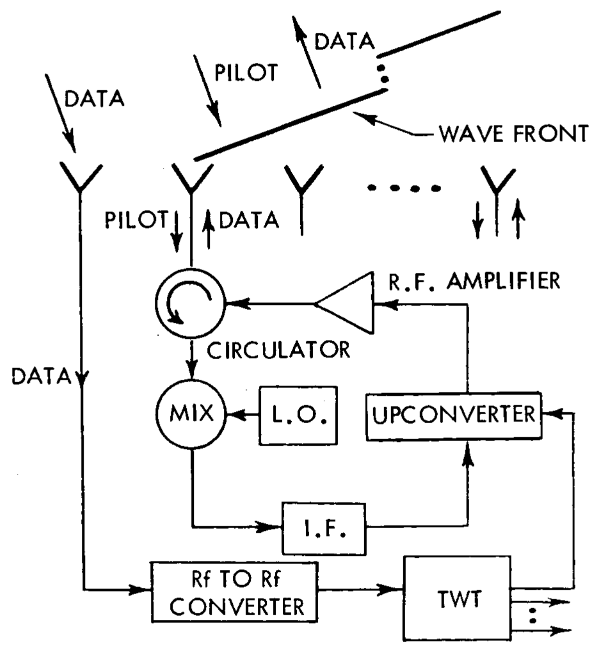


Figure 9–A Retro-Redirective Antenna System

receive energy from one direction at frequency f_1 and re-transmit it in another arbitrary direction at frequency f_2. In addition, the array may be operated in the simple retro-directive mode similar to that of Figure 8 but with the advantage of frequency separation between the transmit and receive signals. In its present form the more directive array is not used to receive the wideband signal (normally in earth-space communications the uplink is the strong link). In this system a pilot signal at frequency f_p arrives at the array from station B, and is mixed to accomplish phase inversion. A wideband signal at frequency f_1 from station A is received by a horn antenna of earth angle coverage, is frequency shifted to f_2 in an RF to RF converter, and amplified in a traveling wave tube. The inverted phase information is applied to the wideband signal at f_2 in a upconverter, is amplified in a tunnel diode amplifier, and radiated from the array with a high gain figure toward station B.

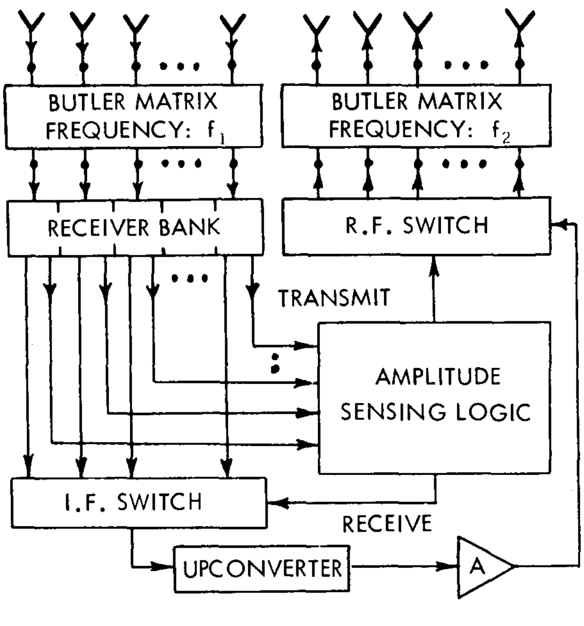
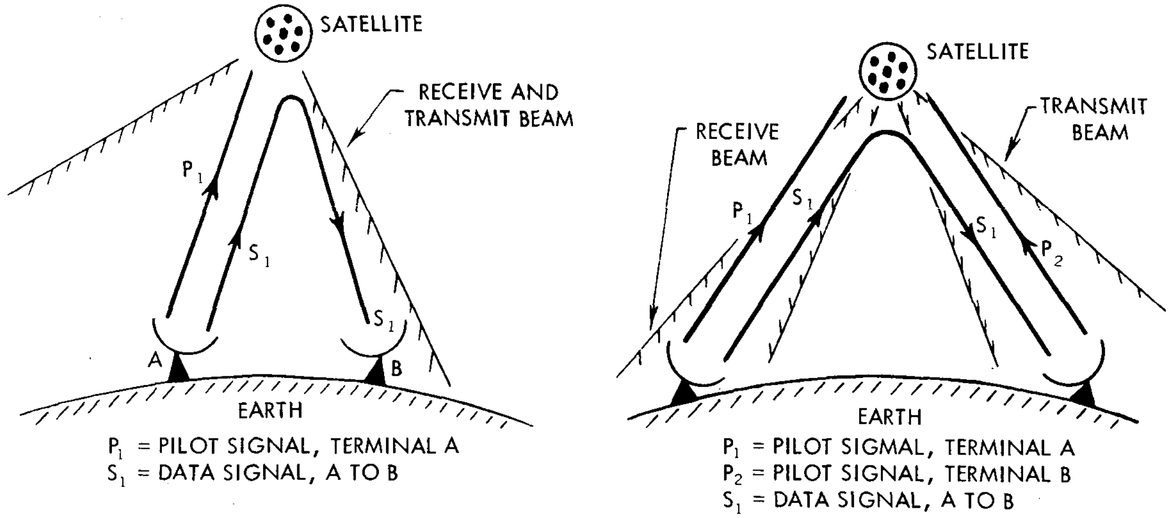


Figure 10-A Transdirective Antenna System

The system block diagram for a Transdirective Antenna System is indicated by Figure 10. This technique makes use of the properties of a Butler matrix array to form multiple beams throughout a 2 Π steradiam volume at two separated frequencies. Similar arrays are utilized at each frequency; the elements of each spaced at approximately one-half of a wavelength. The N by M Butler Array will then form approximately $N \times M = n$ discrete beams which are spacially superimposed at the frequencies f_1 and f_2. Therefore, corresponding terminals of the matrices actually represent two identical beams displaced only in frequency. Self tracking is accomplished by sensing the amplitude of pilot signals transmitted from each ground terminal. An I.F. switch is used to select the receive beam. Although amplitude variation is expected due to the 4 db crossover between adjacent beams, cross coupling circuitry should reduce this excursion.

The basic techniques presented can be extended to allow multi-station operations in a multiple access mode. Additional work is required in this area in order to facilitate a practical design. Typical earth-space-earth Retro-directive and Re-directive links for communication satellite application are given in Figure 11.



(a) Retrodirective Antenna (Monostatic)

(b) Re-Directive Antenna (Bistatic)

Figure 11

Conclusion

System calculations are provided in Figures 12 and 13 which show that increased system performance can be attained in the data link through the use of high gain inertialess antennas. Wideband communication between small inexpensive ground terminals is possible while stabilization requirements on the spacecraft are actually relaxed.

A number of high gain independently steered beams can be formed. Beamwidths can be synthesized to cover only desired earth or space areas, reducing R.F. interference with existing facilities. Power densities resulting from spacecraft radiation will be high at the terminal points, but such is not the case elsewhere. To achieve the system performance predicted by Figures 12 and 13, the recommended earth power density limits of the CCIR might have to be exceeded; however, favorable location of the ground terminals should preclude any problem of interference. Beamwidths of 3 or 4 degrees appear appropriate for most applications. Alternately, fan beams can be used as the mission requires particularly where narrow ground areas are to be illuminated. The availability of lightweight, low loss stripline componentry used in the antenna element circuitry is a requirement if electronically steerable antenna systems similar to ones discussed are to become spacecraft hardware. Extension of the ideas presented to the millimeter wavelength region of the electromagnetic spectrum could result in the development of high performance, high resolution, self tracking antenna

Link Frequency gc.	earth-space 6	space-earth 4
Xmtr Power, dbm	70 (10 KW)	33 (2 W)
Xmt Antenna Gain (15' dia. dish), db	46.5	3
Space Loss, db	-186.5	-183
Rcv. Ant. Gain, db	3	43
Rcvr. Noise Density dbm/mc	-104.5 (10 dbNF)	-116 (2 dbNF)
Rcvr. Noise Bandwidth (10 mc), db mc	10.0	10.0
Rcvr. Signal Power, db	-67.0	-104
Rcvr. Noise Power, dbm	-94.5	-106
Predetection Carrier to Noise, db	27.5	2

A. Dipole "earth angle" Spacecraft Antenna

Link Frequency gc.	earth-space 6	space-earth 4
Xmtr Power, dbm	70 (10 KW)	33 (2 W)
Xmt Antenna Gain (15' dia. dish), db	46.5	30
Space Loss, db	-186.5	-183
Rcv. Ant. Gain, db	30	43
Rcvr. Noise Density dbm/mc	-104.5 (10 dbNF)	-116 (2 dbNF)
Rcvr. Noise Bandwidth (10 mc), db mc	10.0	10.0
Rcvr. Signal Power, db	-40.0	-77
Rcvr. Noise Power, dbm	-94.5	-106
Predetection Carrier to Noise, db	54.5	29

B. Electronically Steerable Spacecraft Antenna (3 foot by 3 foot aperture)

Figure 12–Predicted Performance of a 5000 mile Orbit Communication Satellite System Utilizing a 15 foot Diameter Ground Antenna

Link Frequency, gc	earth-space 6	space-earth 4
Xmtr Power, dbm Xmt Ant. Gain (15' dia. dish) db Space Loss, db Rcv. Ant. Gain, db.	70 (10 KW) 46.5 -201 5	33 (2 W) 5 -197.3 43
Rcvr. Noise Density, dbm/mc Rcvr. Noise Bandwidth (10 mc), db mc	 -104.5 (10 dbNF) 10.0	 -116 (2 dbNF) 10.0
Rcvr Signal Power, dbm	-79.5	-116.3
Rcvr Noise Power, dbm	-94.5	-106
Predetection Carrier to Noise, db	15.0	-10.3

A. Dipole "earth angle" Spacecraft Antenna

Link Frequency, gc	earth-space 6	space-earth 4
Xmtr Power, dbm Xmtr Antenna Gain (15' dia. dish), db Space Loss, db Rcv Ant. Gain, db	70 (10 KW) 46.5 -201 30	33 (2 W) 30 -197.3 43
Rcvr Noise Density, dbm/mc Rcvr Noise Bandwidth (10 mc), db mc	 -104.5 (10 dbNF) 10.0	 -116 (2 dbNF) 10.0
Rcvr Signal Power, dbm	-54.5	-91.3
Rcvr Noise Power, dbm	-94.5	-106
Predetection Carrier to Noise, db	40.0	14.7

B. Electronically Steerable Spacecraft Antenna (3 foot by 3 foot aperture)

Figure 13—Predicted Performance of a 22,300 mile Synchronous Communications Satellite System Utilizing a 15 foot Diameter Ground Antenna

systems with larger information bandwidths than are presently available with existing systems. It should be noted that while the term "antenna" is generally used to describe conventional designs, the antenna techniques presented require that the spacecraft antenna be an inseparable part of the receiving/transmitting system. This salient difference demands that the more accurate term "antenna system" be used.

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