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ANTENNAS FOR MOBILE SATELLITE COMMUNICATIONS

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ABSTRACT

A NASA sponsored program, called the Mobile Satellite (MSAT) system, has prompted the development of several innovative antennas at L-band frequencies. In the space segment of the MSAT system, an efficient, light weight, circularly polarized microstrip array that uses linearly polarized elements has been developed as a multiple-beam reflector feed system. In the ground segment, a low-cost, low-profile, and very efficient microstrip Yagi array has been developed as a medium-gain mechanically steered vehicle antenna. Circularly shaped microstrip patches excited at higher-order modes were also developed as low-gain vehicle antennas. A more recent effort called for the development of a 20/30 GHz mobile terminal antenna for future-generation mobile satellite communications. To combat the high insertion loss encountered at 20/30 GHz, series-fed MMIC (Monolithic Microwave Integrated Circuit) microstrip array antennas are currently being developed. These MMIC arrays may lead to the development of several small but high-gain Ka-band antennas for the Personal Access Satellite Service (PASS) planned for the 2000s.

INTRODUCTION

The Mobile Satellite (MSAT) system is a satellite-based L-band communications network that is capable of providing telephone and data services to mobile users throughout a vast geographical area. Studies in the early 1980s by NASA, Canada, private sector, and others all point to the fact that the high capacity mobile satellite systems are viable only if certain high-risk enabling technologies are developed[1]. Currently, the Jet Propulsion Laboratory (JPL) has completed the managing of the development tasks[2] for the NASA sponsored MSAT program initiated in 1984. It is now the responsibility of the private industry to further develop, manufacture, own, and operate the MSAT as a commercial system.

One of the concentrated areas of technology development by JPL is antennas for satellite and land vehicles. In the space segment, since both the satellite and land vehicles are power limited, it is essential to develop a high-gain and efficient satellite antenna system. A circularly polarized microstrip array composed of simple linearly polarized elements[3] has been developed as an efficient, compact, and light-weight array feed for a high-gain multiple-beam reflector antenna system[4,5]. In the ground segment, the vehicle antenna not only needs to be affordable to users in price but also should be aerodynamically and aesthetically appealing. Both a mechanically steered medium-gain microstrip Yagi array[6] and a low-gain higher-order mode circular microstrip patch[7] have been developed as the low-profile and low-cost vehicle antennas.

For the NASA's Advanced Communication Technology Satellite (ACTS) to be launched in 1992, various experiments have been planned to demonstrate communication technologies at Ka-band frequencies. One of the AMT's (ACTS Mobile Terminal) high risk technologies that are currently being developed at JPL is a compact and low-cost mobile antenna system. This is a mechanically steered series-fed microstrip array using active MMIC components. This antenna development, along with other Ka-band technologies, will lead to the development of several compact hand-held terminals in a future Personal Access Satellite Services (PASS) system[13].

Both the above mentioned L-band and Ka-band satellite communication antenna developments and concepts are individually described in the following sections.

CIRCULARLY POLARIZED ARRAY COMPOSED OF LINEARLY POLARIZED ELEMENTS

Very large multiple-beam reflector antennas in the 20 to 50-meter range have been proposed for the MSAT satellite[1]. From 40 to 90 contiguous beams covering continental U.S. (CONUS) are to be generated from the reflector via an overlapping cluster feed array[4,5] with dimensions up to 6 meters. A structure of this size should have the capability of being folded and stowed in a space-limited satellite launching vehicle. As a consequence, the feed array should be low in profile and light in weight. Microstrip radiator was selected to meet these challenges. In order for the array to cover both the downlink frequencies (1545 to 1559 MHz) and the uplink frequencies (1646 to 1660 MHz), either a single patch with relatively thick substrate (0.5 inch) and 4 feeds or a dual-stacked patches with two feeds are needed to meet the bandwidth and circular polarization (CP) requirements. For a large array, such as relatively complicated element would increase the complexity of an already complex beam-forming feed network. Circularly polarized array composed of single-feed linearly polarized microstrip elements[3] has been developed to counter this complexity problem. The CP is achieved by having a basic 2x2 subarray, as shown in Figure 1, with elements' angular orientation and feed phases arranged in the sequential 0°, 90°, 180°, 270° manner. With such a system, not only is the feed complexity reduced, but also the bandwidth performance is improved. It has been found, however, that the basic 2x2 array does not generate acceptable CP away from principal planes (worst in the diagonal planes). Large cross-pol radiations (approximately -5 dB below main beam peak) are found in the off-broadside region due to amplitude and phase imbalances. This high cross-pol in the diagonal planes can be suppressed in a large array due to array factor's narrower beam and due to an averaging effect so that the imbalances are averaged out.

One of the arrays that have been fabricated and tested to demonstrate the above achievement is a 28-element microstrip array[5] as illustrated in Figures 2 and 3. It is only a single cluster array out of the many cluster arrays to be used in the multiple-beam reflector feed system. Amplitude taper is introduced in the array to suppress the grating lobes caused by large element spacings and to generate proper edge taper for the reflector. Each element is a single-probe fed half-inch thick honeycomb-supported square patch. Measured spinning-dipole patterns in the diagonal plane of the array are given in Figure 4 where excellent CP performance can be observed within the bandwidth (7.5%) of the uplink and downlink frequencies.

One important note on this antenna concept is that, even in a large array, if the element spacing becomes large (>0.55 wavelength) the antenna will start to lose gain[8] (up to 3 dB) due to the high cross-pol and grating lobes formed in the diagonal planes. Consequently, when designing this antenna concept, careful attention should be given to the element spacing. One other note is that this array concept of generating CP by using LP elements can be applied not only on microstrip patches but also on other types of radiators such as dipoles, horns, helixes, etc.

MICROSTRIP YAGI ARRAY

A major element of the MSAT program has been the development of several types of medium-gain L-band vehicle antennas. These antennas are required to generate CP with 10 dBic of minimum gain within the angular region of 20° to 60° above the horizon and shall be able to track the geostationary satellite while the vehicle is moving about in the CONUS. Previously, two types of medium-gain antennas have been developed and field tested with successful results. One is electronically steered planar phased array[9] and the other is the mechanically steered 1x4 tilted microstrip patch array[10]. The phased array offers the advantages of low-profile (1.0-inch thick) and beam agility at the expense of very high production cost (several thousand dollars per unit). On the other hand, the mechanically steered 1x4 array antenna offers a low production cost (several hundred dollars per unit) with a high profile (6-inch tall).

To combat the disadvantages of high cost and high profile of the above antennas, a new antenna concept, called the microstrip Yagi array[6], has been developed, which not only offers low profile and low cost but also shows excellent efficiency in its beamforming circuitry. This antenna system, as depicted in Figure 5, is a mechanically steered low-profile array composed of twelve parasitic director and reflector patch elements and four driven elements. The reflector and director patches, based on Yagi-Uda's principle, tilt the array's beam close to endfire for satellite pointing. Because only few driven elements are directly connected to the RF power distributing circuitry, the complexity and loss of this circuit are dramatically reduced, resulting in improved antenna noise temperature and antenna gain. The overall height of the integrated antenna, as shown in Figure 6, is only 1.5 inches, which includes both the RF portion and the mechanical rotating platform. Diameter of the radome is 21 inches. The rotation in azimuth is accomplished by the thin pancake motor. The control of this motor, or the beam pointing, is done by a monopulse system that is uniquely designed[11] for the communication antenna to provide simultaneous transmit and receive signals. Since the beamwidth in elevation is fairly wide, no elevation tracking of the satellite is necessary. To facilitate the ease of design and have a complete understanding of this microstrip Yagi array, a theoretically model based on the Method of Moments has been developed by the University of Massachusetts[12].

The microstrip Yagi array utilizes the same principle as a conventional dipole Yagi array where the electromagnetic energy is coupled from the driven element through space into the parasitic elements and then re-radiated to form a directional beam. For the microstrip Yagi, however, the adjacent patches need to be placed very close to each other so that significant amount of coupling can be formed through surface wave and radiation. Since the amount of surface wave is a strong function of the dielectric constant and substrate thickness, the pattern shape of the microstrip Yagi is also a function of these two parameters. Detailed antenna dimensions, description of the beamformer circuitry, and performance results are given in references 6 and 11. Good CP quality, adequate bandwidth, and excellent gain have been achieved by the microstrip Yagi array for the MSAT system. A typical elevation pattern showing both the calculated and measured results is presented in Figure 7. Since two major components of the antenna system, the radiating patches and the beamformer, can be manufactured by simple etching process, a relatively low-cost antenna system have been realized. The estimated manufacturing cost with a 10,000-unit per year and a 5-year production is about $450 per unit.

HIGHER-ORDER MODE CIRCULAR MICROSTRIP ANTENNA

An alternative approach to the MSAT medium-gain vehicle antenna is to increase the capacity of the spacecraft antenna while having a low-cost and low-gain vehicle antenna. When produced in mass quantity, this low-gain antenna is expected to cost only ten's of dollars and thus making the ground terminal more affordable to average consumers. This vehicle antenna should have a minimum gain of 3 to 4 dBic throughout the elevation angular region of 20° to 60° above the horizon. To provide such a coverage, a conical pattern (null at zenith) is preferred. Two antennas that have been thoroughly investigated for this application are the crossed drooping-dipoles and the quardrifilar helix. A third antenna, that has a low-profile and can be conformal to the car's rooftop, is the higher-order mode circular microstrip patch[7]. It is not only aesthetically appealing but also has a better chance to survive the abuses of a car wash.

When a circular patch has a dimension that is larger than the fundamental mode ($TM_{mn} = TM_{11}$) patch, higher-order mode (TM_{nl}) can be excited. The higher-order modes will produce conical patterns while the fundamental mode can only radiate a broadside beam. Two feeds with proper angular spacing and 90° phase differential are required to generate CP from a circular patch. Besides the desirable mode, there are generally many undesirable modes present in the patch cavity with less magnitudes. To preserve pattern symmetry and to keep cross-polarization low, especially for relatively thick substrate, the undesirable modes need to be suppressed. Generally, the two neighboring modes of a desirable resonant mode have the next highest magnitude. One way to suppress these adjacent modes is to employ two additional feeds located diametrically across from the two original feeds. Together, these four feeds, as illustrated in Figure 8, should have a phase arrangement of 0°, 90°, 0°, 90° for even-order modes and 0°, 90°, 180°, 270° for odd-order modes, so that the fields of the undesirable modes from the two opposing feeds cancel. It was found that the peak of the conical pattern can be changed over a wide angular range from 35° to about 60° from the disk broadside, depending on the substrate's dielectric constant and the resonant mode order. The higher the dielectric constant or the mode order, the larger the peak angle of the antenna is from the broadside.

Two circular microstrip antennas with CP have been constructed and tested. One was constructed on a honeycomb substrate (relative dielectric constant = 1.2) with TM_{21} mode excitation. It has a measured radiation peak at 36° from the broadside. The other was constructed on a fiberglass-reinforced teflon substrate (relative dielectric constant = 2.17) with TM_{41} mode excitation. It has a measured radiation peak at 55° from the broadside. Both antennas show good agreement between measured and calculated results as presented in Figure 9. The calculation was done by employing the Multimode Cavity Theory augmented with the Geometrical Theory of Diffraction[7].

Ka-BAND SMALL TERMINAL ARRAYS

The NASA/JPL AMT project is currently developing a mechanically steered Ka-band microstrip array with active MMIC components. To combat the high antenna insertion loss that incurred at Ka-band, the distributed MMIC high-power amplifiers (HPA) and low-noise amplifiers (LNA), along with a series-fed microstrip array technology, are being developed. The planar array, as shown in Figure 10, will be tilted and fixed in elevation and mechanically rotated in azimuth to track the satellite as the vehicle is in motion. It will have an elevation beamwidth of 12° and an azimuth beamwidth of 3° to 5° with a peak gain of 25 dBi. The 20 GHz receive array will be vertically polarized, while the 30 GHz transmit array is to be horizontally polarized. Total size of the antenna radome should be within 8-inch in diameter and 3-inch in height. The technical challenge in developing this antenna are: 1) to minimize the insertion loss in the series-fed microstrip array, 2) to achieve the required antenna gain within the given size limit, and 3) to package the MMIC components effectively.

The experience that is being learned from the AMT antenna development will lead to the development of several compact "hand-held" terminals that are being planned for the future 20/30 GHz PASS program. Several antenna concepts have been generated and are illustrated in Figures 11 through 15. The chief advantage of the head-mounted antennas is to minimize possible RF damage to the human eyes. Microstrip type of radiating elements along with compact and low-loss array feed technologies, as well as MMIC active devices, are again to be the areas of vital technology developments.

SUMMARY

Several innovative antenna techniques have been developed for the L-band MSAT system, as well as a number of antenna concepts are being developed or proposed for the Ka-band satellite communication systems. Due to the required small size and low cost for these antennas, microstrip printed antenna technologies have been the main thrust of the development effort. Several challenging areas in developing these antenna are the effective generation of circular polarization, insertion loss minimization, antenna size and manufacturing cost reduction, and effective packaging of the MMIC components.

ACKNOWLEDGEMENT

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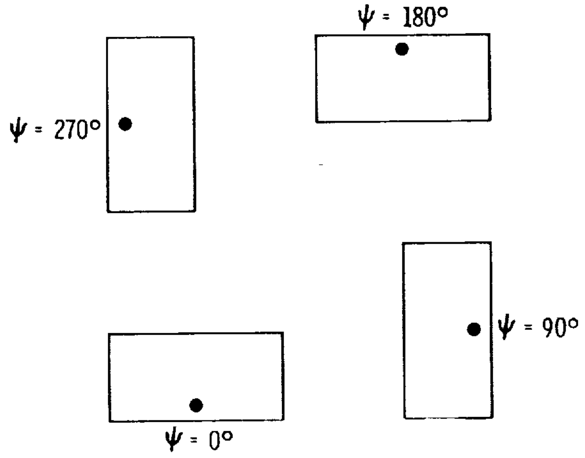

Figure 1. Basic 2x2 LP microstrip elements that generate CP.

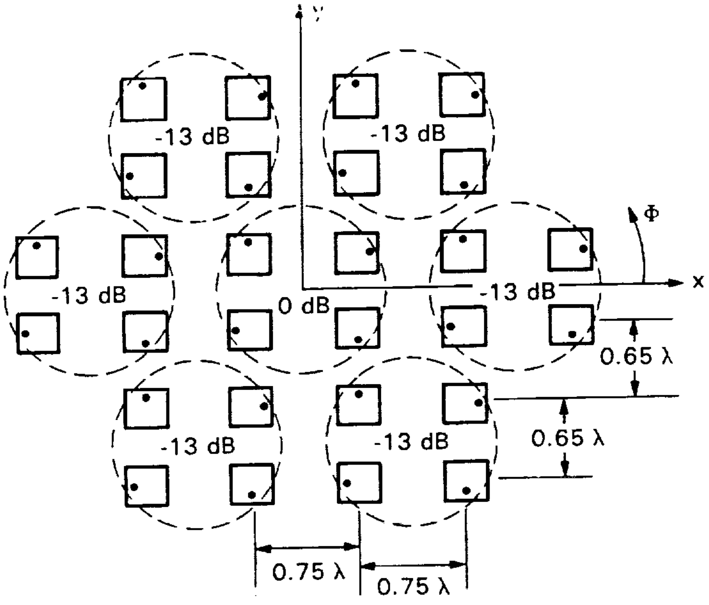

Figure 2. Single cluster 7-subarray microstrip array feed design.

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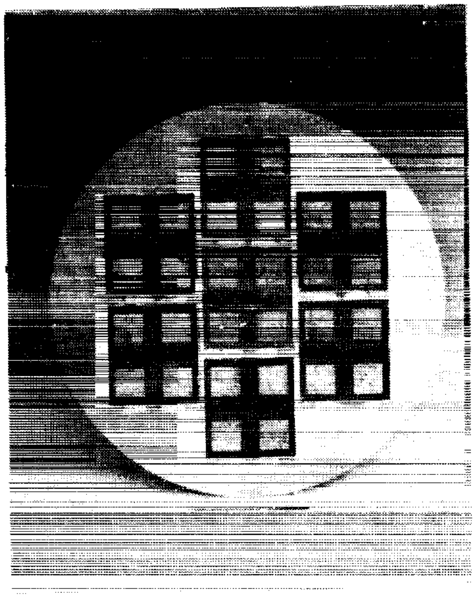

Figure 3. Constructed single cluster 7-subarray microstrip array feed.

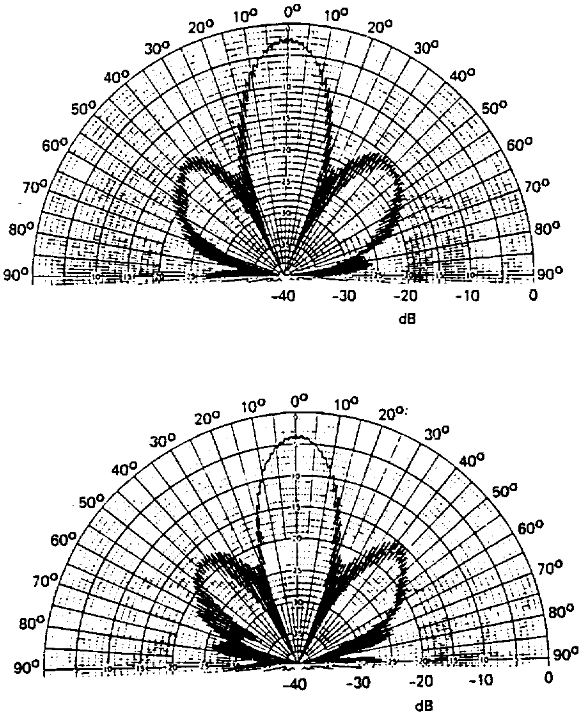

Figure 4. Spinning dipole patterns. Top 1.54 GHz, bottom 1.66 GHz.

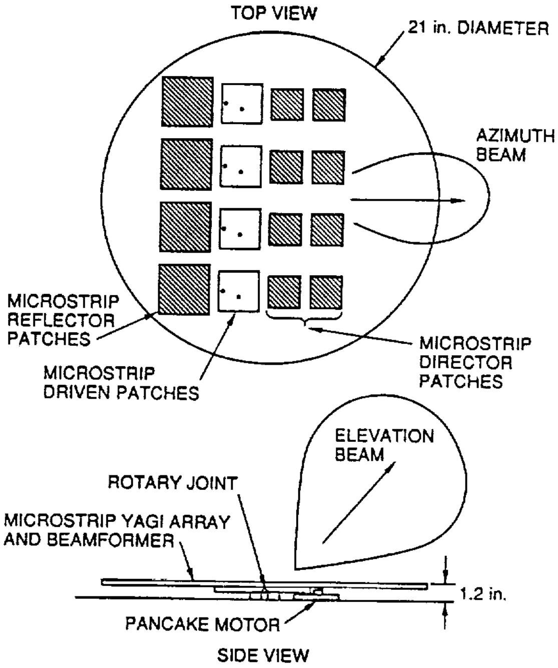

Figure 5. Configuration of MSAT microstrip Yagi array antenna.

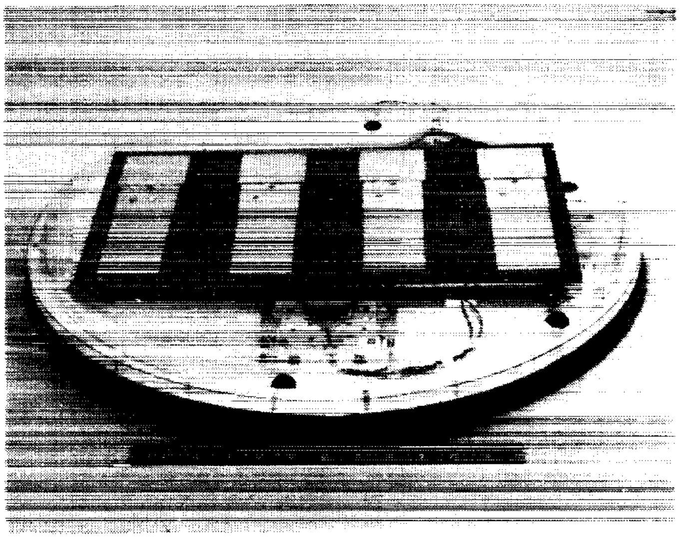

Figure 6. Integrated MSAT microstrip Yagi array antenna.

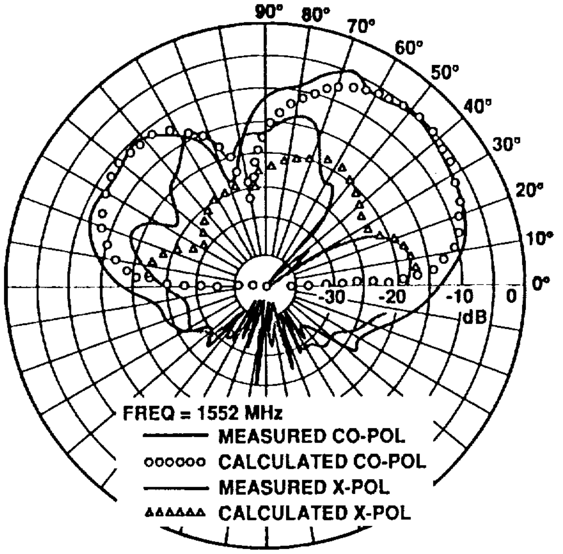

Figure 7. Elevation pattern of microstrip Yagi array.

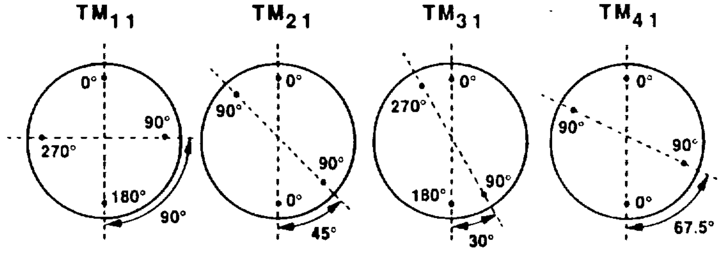

Figure 8. Four-probe feeds for circular patch at different resonant modes.

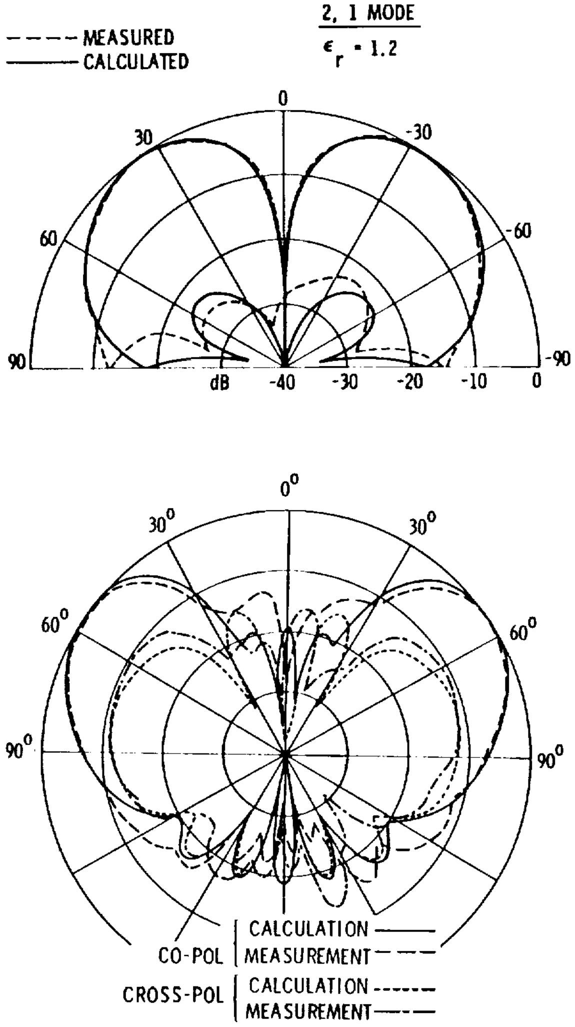

Figure 9. Patterns of circular microstrip patches with CP. (a) TM_{21} mode, (b) TM_{41} mode.

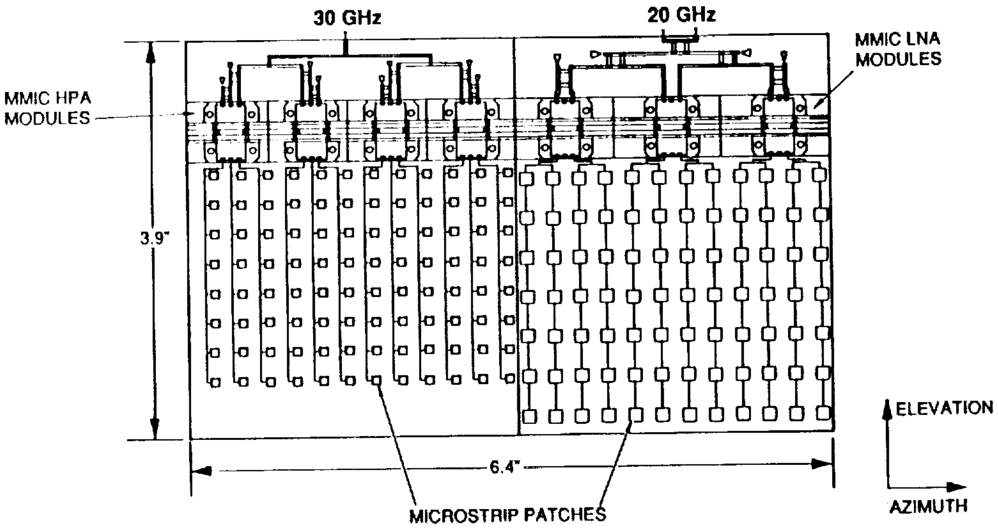

Figure 10. Ka-band microstrip array antenna with MMIC components.

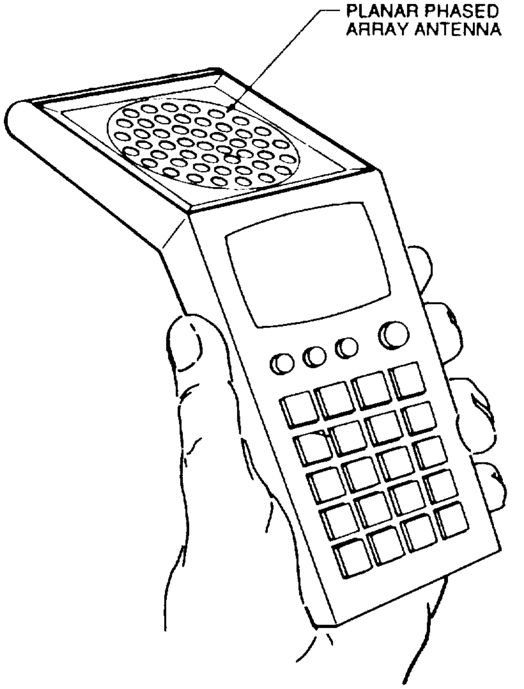

Figure 11. Hand-held terminal with MMIC microstrip phased array.

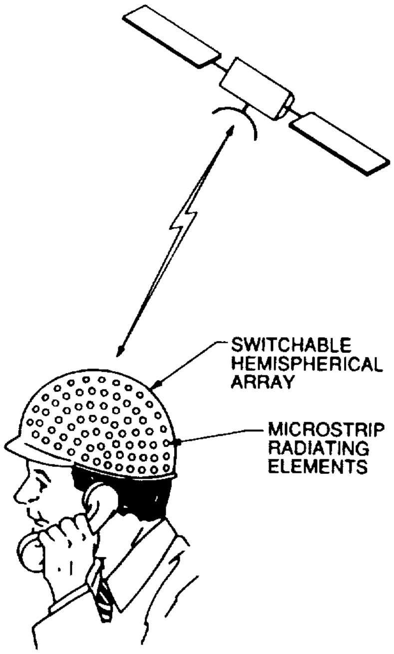

Figure 12. Hemispherical switching array.

Figure 13. Head-mounted array antenna.

Figure 14. Hand-held terminal with mechanically steered antenna.

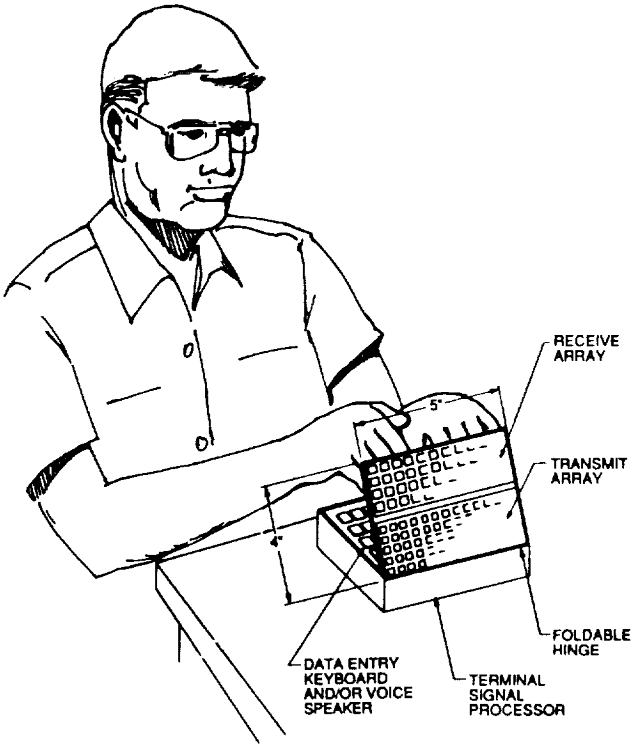

Figure 15. Lap-top or desk-top terminal with microstrip array antennas.