REPORT 1047-1

COMPACT ANTENNAS FOR MOBILE SATELLITE COMMUNICATION

(Question 88/8)

(1990)

1. Introduction

There is a need for small earth station antennas for satellite communications in the 1.5/1.6 GHz band not only for aircraft and land mobile terminals, but also for shipboard terminals. For these purposes, many kinds of compact antennas are being studied. Report 921 considers potential new ship earth-station systems and their applications, and in particular new concepts for the INMARSAT Standard-B and Standard-C systems and their possible variants.

Two classes of compact antennas are being considered for mobile satellite applications and are discussed in this Report. The first consists of low-gain antennas with omni-directional azimuth antennas patterns and gains in the range 0-6 dBi. The other consists of medium-gain directional antennas whose directionality is in azimuth, but may also be in elevation. Gains in the range 7-15 dBi are representative. In the latter type, since the beam is directional, steering is required either by mechanical rotation or by electronic steering or switching in order to track the satellite.

Low-gain antennas are expected to cost less because they are simple structures and do not require beam steering when the mobile unit is in transit. However, because of their omni-directional coverage, they will offer potential interference (to other satellites) or receive interference.

Medium-gain antennas may provide some degree of discrimination against external interfering sources. In addition, in multi-satellite systems which are sufficiently separated, orbital reuse may be possible with satellites using the same frequency. This is because the antenna's low sidelobes will receive less interference from the adjacent satellite, and also radiate less in its direction.

2. Antenna characteristics

Various types of antennas systems for mobile satellite applications have been studied [Heckert 1972], and Table I indicates preferred antenna types for the gain range 0-15 dBi.

TABLE I

Preferred antenna types for mobile satellite earth stations

	Gain range (dBi)	Antenna type	Pointing in azimuth (Az)/ elevation (El)	Stabilization
Low Gain	0-3	Hemispherical coverage: - quadrifilar helix /Kilgus, 1975/ - turnstile - microstrip patch - flat spiral - drooping crossed dipole - Lindenblad dipole configuration /‾Lindenblad, 1941_7	No	No
	4-6	Optimized for a given elevation sector with bifolium (near toroidal) pattern: - conical spiral (normal mode) - turnstile on ground plane - quadrifilar helix on ground plane (Note 1) - microstrip patch	No	No
Medium Gain	7-10	- helix - horn - linear array - planar array of 4 crossed dipoles - archimedian spirals, microstrip patches, etc. - conical spiral (beam mode)	Yes in Az and El	Yes (simple gravity?)
	11-15	- short backfire - helix - linear or planar array of 4, 8, or 16 elements - array of microstrip patches	Yes in Az and El	Yes

2.1 Low-gain antennas

The types of low-gain antenna that have been considered for mobile satellite applications are listed in Table I.

All of these antennas provide circular polarization. Some provide this intrinsically, but others require an external quadrature hybrid. They also provide omni-directional or quasi-hemispherical coverage. Where a low antenna profile is necessary, the microstrip patch(es) and the flat spiral have the greatest application. The characteristics of certain of these antennas are discussed below.

2.1.1 Omni-directional type

The quadrifilar helix antenna can achieve circularly polarized and conically shaped radiation patterns with full azimuthal coverage and directional elevation beam [Kilgus, 1975]. Therefore, this antenna requires no additional tracking system.

The various helix parameters (number of turns, pitch, diameter and so on) have effects on the radiation patterns and on the axial ratios. This antenna has a conical radiation pattern and provides a good axial ratio over wide elevation angles. Table II provides the main electrical performance characteristics of the 5-turn quadrifilar helix antenna whose pitch and length are 0.48 and 0.72, respectively, for one turn of helix (normalized by wavelength) [Terada *et al.*, 1987].

TABLE II

Maximum antenna gain	more than 7 dBi
Beamwidth in elevation direction	3 dB = 32° 1 dB = 18°
Axial ratio	less than 2 dB

Another omni-directional antenna which is being considered for mobile satellite earth station applications is the drooping crossed dipole. This is depicted in Figure 1 with its co-pol and cross-pol radiation patterns. The co-pol pattern is quasi hemispherical.

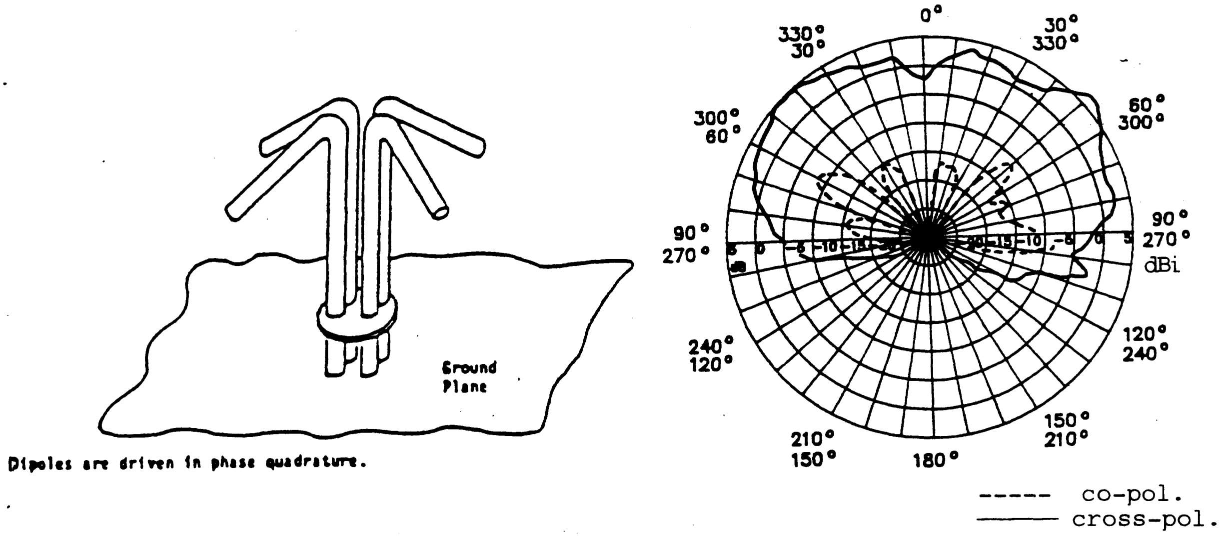


FIGURE 1 - Drooping crossed dipole antenna and typical radiation patterns

2.1.2 Electronically switched - directional type

To achieve a directional antenna using a simple tracking system, a beam-switching antenna has been proposed [Hori *et al.*, 1987]. This antenna consists of 6 radially placed microstrip patch antennas and can point to a satellite in the azimuth angle by switching from one element to another. Though it can achieve a wide beamwidth in elevation direction compared with a conically shaped beam antenna of the same gain, it requires a simple tracking system. Table III provides the main electrical performance characteristics of this antenna.

TABLE III

Maximum antenna gain	more than 8 dBi
Beamwidth	3 dB = 70° 1 dB = 38°
Axial ratio	less than 3 dB

The configuration for the antenna is shown in Figure 2. Six microstrip patches are evenly deployed on the conical dome. Full azimuth coverage is realized by switching from one microstrip patch to another, by the switch shown on the left.

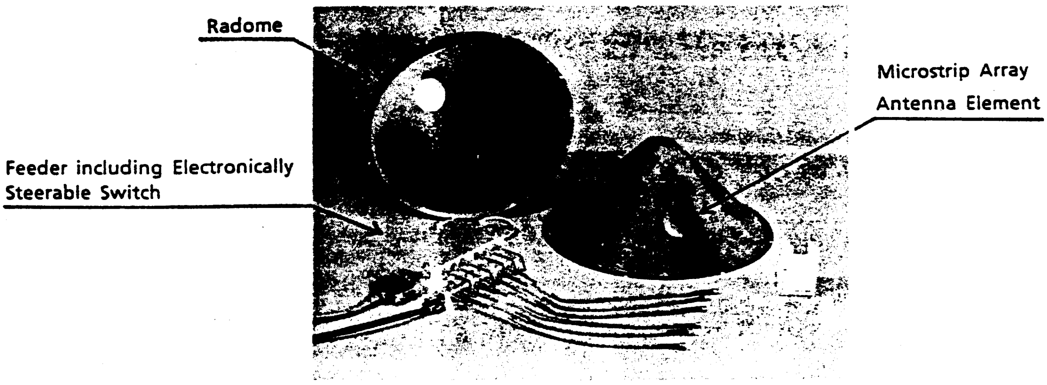


Fig. 2 Electronically Switched Array Antenna

2.2 Medium-gain antennas

Medium-gain antennas, with gains in the range 7-15 dBi, have the following advantages over low-gain antennas:

- o Reduces spacecraft EIRP requirements
  - increases earth station G/T
- o Potentially lowers ground receiver system noise temperature
  - if antenna system losses are reasonably low.
- o Reduces multi-path effects
  - because of lower sidelobes at low elevation angles, thus reducing input signal caused by specular reflected signal and diffused component. This is augmented by using circular polarization and taking advantage of odd bounce rejection, if axial ratio is reasonably low.
- o Contributes to orbital reuse
  - For satellites serving the same area, two or more satellites can use the same frequency if they are separated by an amount which is dictated by the frequency used and the size of the antenna.

However, medium-gain antennas are more expensive to produce than single element low-gain antennas.

2.2.1 Short backfire antenna

A short backfire (SBF) antenna is considered a candidate for mechanically-steered, directional, medium-gain antennas in the range of 12-15 dBi for small ships and vessels.

The conventional short backfire antenna consists of two planar reflectors of different diameters, the main reflector and the sub-reflector separated by one-half wave length. They act as a shallow leaky cavity resonator with the radiation beam normal to the sub-reflector. The antenna, originated by Ehrenspeck [Ehrenspeck, 1965], is fed by a crossed dipole antenna at the midpoint between the two reflectors.

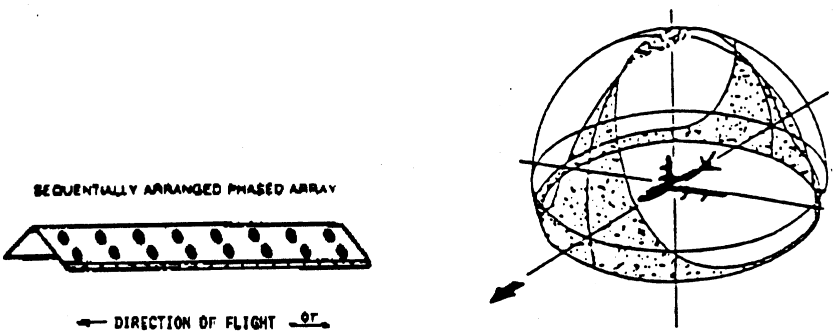
Recently, two types of new SBF antennas have been proposed which improve the electrical characteristics by modifying the shapes of the main and small reflectors and that of the primary exciter. The first type is a SBF antenna that has dual small reflectors and a non-flat main reflector. Another SBF antenna has dual small reflectors and a conical main reflector by which the frequency characteristics of the VSWR is considerably improved [Ohmori et al., 1983] The latter has a step configuration on the main reflector which improves the gain of the SBF antenna by about 1-1.5 dBi [Shiokawa at al., 1983].

2.2.2 Array antenna systems

There are basically two types of arrays which have been considered for mobile satellite applications. The first is an assemblage of antenna elements on a linear or planar surface in which the generated beam is steered by mechanical means. The other is an array of elements whose beam is steered by electronic means by phase shifting or time delay devices usually located in each element path. This latter type of array is generally called a phased array. Examples of the array antennas are depicted in Figure 3.

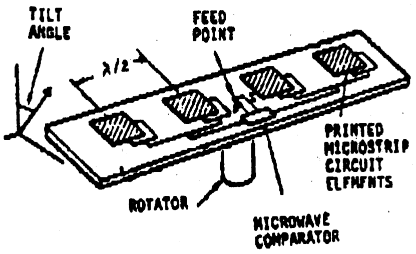
Figure 3a shows an array consisting of two separately driven arrays (back-to-back) with each having two-element tiers (paired elements) and driven by eight phase shifters each. The elements are microstrip patches driven by quadrature hybrids to produce left-hand circular polarization. The structure is mounted on top of the fuselage of an aircraft, and the array which is in operation depends on the east-west flight direction of the aircraft [Ohmori, 1986]. The array is scanned ±60° in the horizontal direction. Experiments have been conducted using the Japanese ETS-5 communication satellite located at 150°E longitude and aircraft on trans-Pacific flights.

Figure 3b shows a simplified version of a mechanically-steered linear array using circularly polarized microstrip patches. The array is partitioned to offer single plane monopulse sensing for closed-loop satellite tracking. Satellite tracking accuracy is affected by the fading signal level received from the satellite. Signal absence or deep fade can be coped with by reverting to open-loop tracking scheme. A practical implementation of a mechanically-steered array is described by Pattan [Pattan, 1987]. The array produces circular polarization, and the beam forming network is weighted for sidelobe control. The array is divided into two halves and phase monopulse is used. The two phase centers are located at the center of each sub-array. The monopulse comparator gives a sum and difference output.

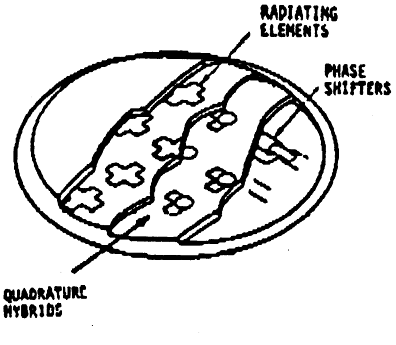


The speckled areas show volumes of space where the phased arrays do not provide coverage because of their practical nominal scanning angle of ±60°.

(a) Two-tier element phased array using circular microstrip patches



(b) Linear array using circularly polarized microstrip patches



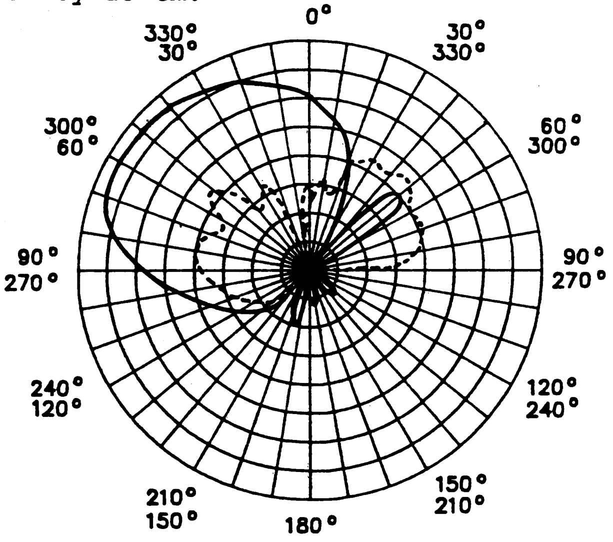
(c) Planar phased array using cross-slot cavity elements showing layers for quadrature hybrids and phase shifters

FIGURE 3 - Representative medium-gain array antennas for mobile satellite applications

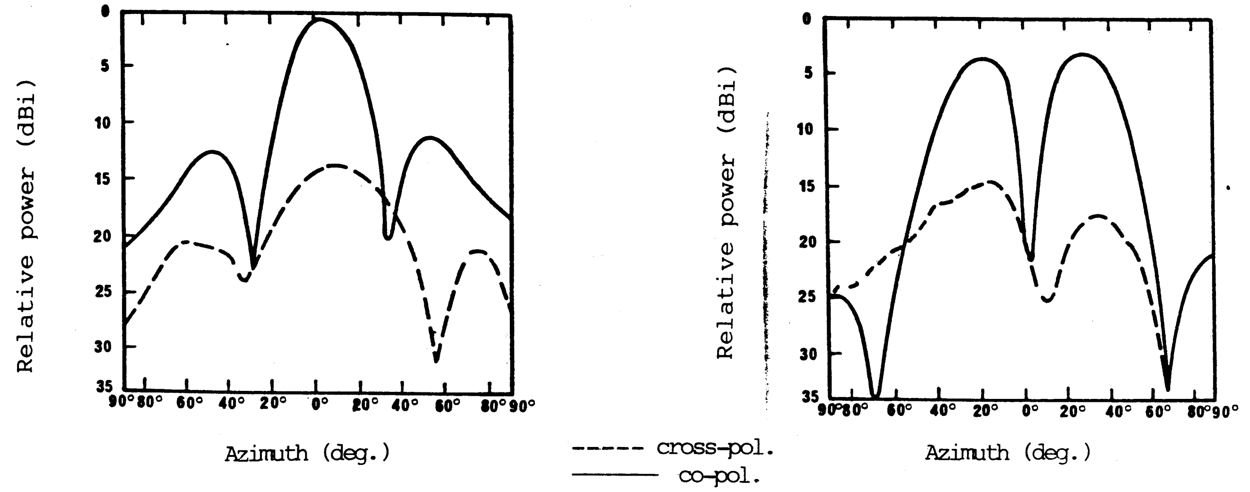
Figure 3c shows a planar phased array about 50 cm in diameter and less than 2 cm high. this structure produces a directional (pencil) beam in all directions and steering is controlled with phase shifters. The elements are cavity-backed crossed slots and radiate circular polarization. The entire unit has been mounted on the roof of an automobile.

2.2.3 Performance of array antennas

Patterns for a four microstrip patch element array are shown in Figure 4 [JPL, 1988]. The top figure indicates the elevation pattern for both the co-pol and cross-pol components for an array elevation tilt angle of 40 deg. The lower figures show the azimuth sum and difference patterns. The array dimensions are 48 cm by 13 cm.



(a) Co-pol and Cross-Pol Elevation Pattern



(b) Co-pol and cross-pol antenna azimuth pattern (also monopulse sum pattern)

(c) Azimuth monopulse difference pattern

FIGURE 4 - Antenna patterns of a mechanically steerable linear array

Two additional planar phased array systems of the type shown in Fig. 3c are under development in the USA. The performance goals for these antennas are indicated in Table IV.

TABLE IV

- Frequency of operation: 1545-1559.0 MHz Receive
  1646.5-1660.5 MHz Transmit
  The bandwidth over which the arrays must operate is about 7%.
- Coverage: 20° to 60° above the horizon, 360° in azimuth
- Antenna Gain: ≥10 dB in the coverage area
- Back-lobe sidelobe level: <-12 dB
- Polarization: RHCP with maximum axial ratio of 4 dB across
  the scan range (30° to 70° off boresight)
- Inter-satellite isolation for orbital reuse: 20 dB for satellite
  separation of 35°

2.2.4 Reference radiation patterns

There are two Recommendations on reference patterns for earth station antennas in the present CCIR texts from Study Group 4 [Recommendations 465 and 580]. These assume large aperture antennas such as Cassegrain parabolic antennas. The minimum antenna diameters to which the Recommendations can be applied are about 42 cm and 35 cm at 1.6 and 1.5 GHz, respectively. Thus the Recommendations cannot applied to most the compact mobile earth station antennas.

Study Group 8 has drafted a new Recommendation 694 which defines a reference radiation pattern for mobile parabolic antennas but it covers only high-gain antennas with diameters of 80 to 130 cm. There is no Recommendation in the present CCIR texts which defines reference radiation patterns for the medium and low-gain antennas which will be used widely in the near future for mobile earth stations.

The effective radiation pattern of installed mobile earth station antennas is influenced by the ground plane and surrounding obstacles. Further consideration of these factors is necessary in establishing realistic reference patterns.

For example, recent experimental measurements of multipath fading in aeronautical satellite communications (Report 1169) show that the fading effects are dependent not only on the basic antenna radiation pattern but also on the location of the antenna on the fuselage. According to the results of an aeronautical satellite experiment using an antenna installed on the top of the fuselage, sea surface-reflected multipath fading has not been observed due to the blockage of reflected components by wings and fuselage. However, slow speed fading due to the reflection by wings has been observed [Hase, Y. et al., 1989].

Further studies about fading effects dependent on antenna location on the fuselage will be required.

The parabolic antenna of an INMARSAT standard A terminal is the only mobile antenna used on a commercial basis at present. Its radiation pattern is symmetrical about the antenna axis, so its radiation characteristics can be expressed by a single reference pattern [Report 922]. In the near future, however, array and phased array antennas are expected to be adopted for mobile applications in order to meet the strict demands for light weight, compact size, low profile, and other requirements.

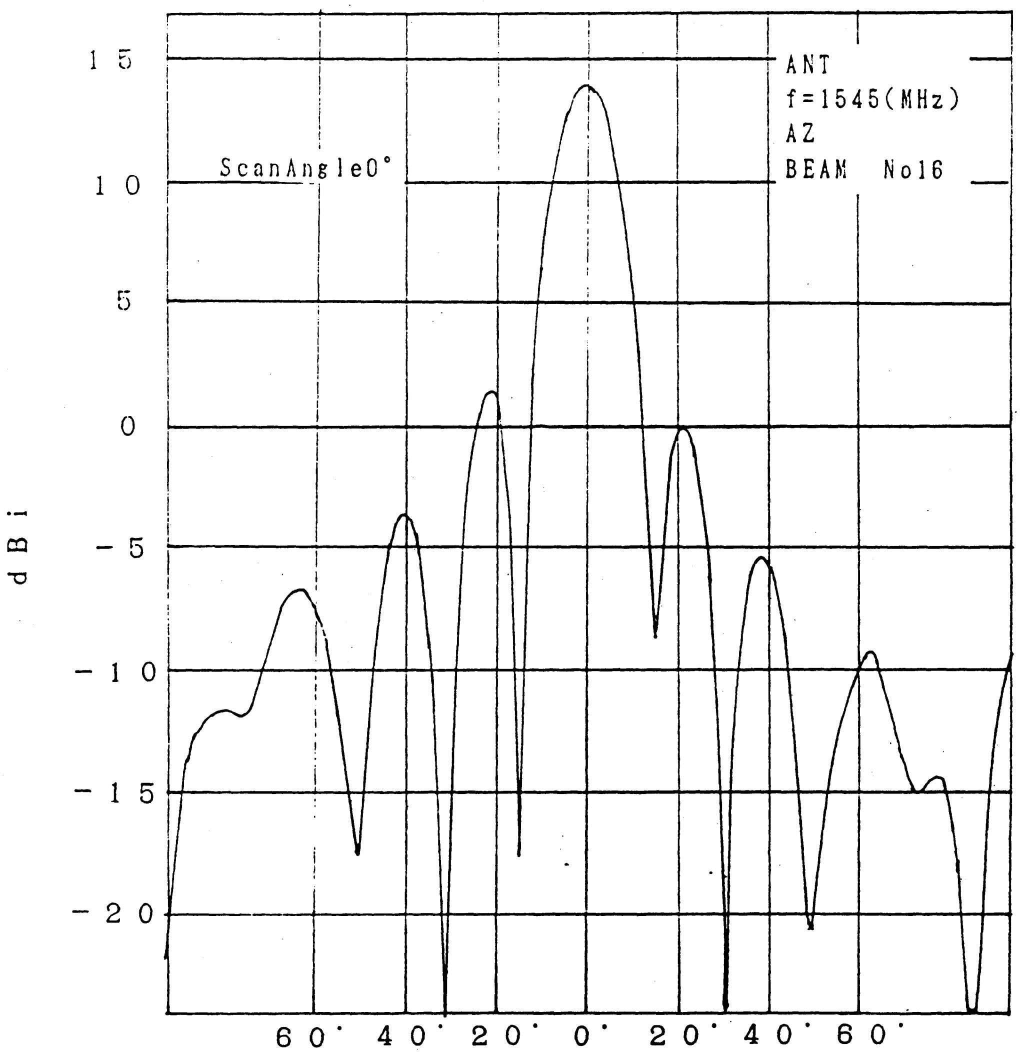
These medium-gain array-type antennas have many attractive characteristics, but their patterns are subject to certain degradations which deserve further study:

(1) Degradation of sidelobe characteristics by main beam scanning

The radiation patterns of an airborne phased array antenna [Hase et al, 1989] used for the ETS-V EMSS experiments are shown in Figs. 5a and 5b. The array consists of 16 elements and the main beam can be scanned within ±60 deg. with respect to the boresight direction. Figs. 5a and 5b show radiation patterns in the case of scanning angle 0 deg. and 60 deg., respectively. The first sidelobes are -14 dBi for a 0 deg. scanning and -8 dBi for 60 deg. scanning. These values are worse than that of a SBF antenna, which is about -20 dBi. The more the beam is scanned at wide angles, the worse the sidelobe characteristic becomes.

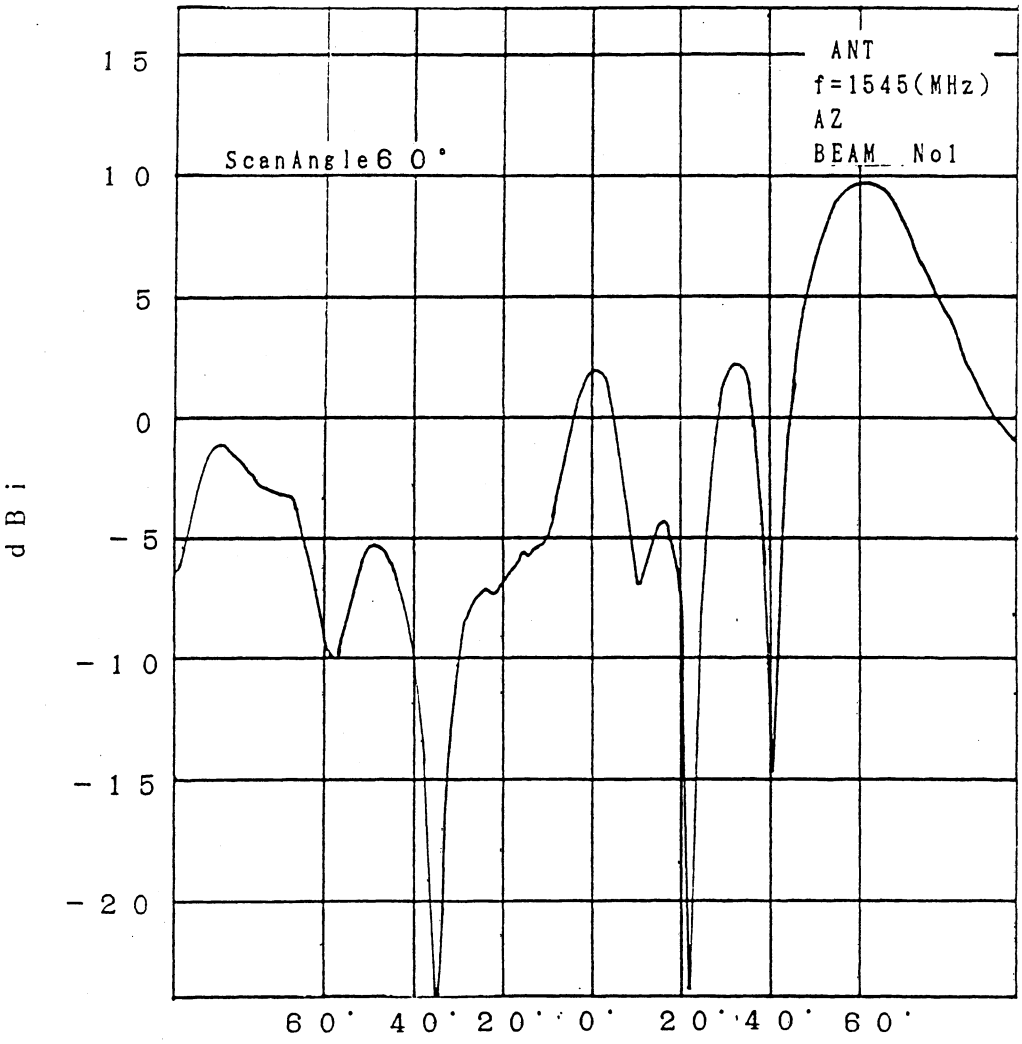
(2) Scanning angular difference between transmit and receive frequencies

In order for a phased array antenna to scan the beam electrically the propagation path differences from each element are adjusted by phase shifters to produce an equiphase plane in the desired direction. The effective electrical propagation path depends on the operational frequency, and this fact causes scanning angular differences between the transmitting and receiving frequencies.



(a) Scan Angle

FIGURE 5



(b) Scan Angle

FIGURE 5

Examples of reference patterns appropriate for certain types of medium-gain mobile antennas are proposed in the draft specifications for sidelobe performance now under development by INMARSAT for its new general mobile satellite telephony system, INMARSAT-M. These specifications are based on experimental measurements for three types of antennas with gains in the range 12 to 15 dBi.

(1) Axis-symmetric antennas

Axis-symmetric antennas have identical azimuth and elevation patterns and would normally require both azimuth and elevation pointing. A short backfire or a helix is a typical example. Such antennas are of particular interest to maritime and transportable mobile terminals. The INMARSAT draft sidelobe specifications based on a 15 dBi short backfire antenna are as follows:

$$G = 43 - 25 \log(A) \text{ dBi}$$

where G is the peak antenna gain at offset angle A from boresight. This expression is valid for offset angles between 40° and 83°. For angles greater than 83° the specification allows sidelobe gain up to -5 dBi.

(2) Horizontal one-dimensional array antennas

This type of antenna has a vertical fan beam pattern and requires only azimuth pointing. Linear arrays of patches or crossed dipoles are typical examples. The sidelobe specifications for this type of antenna are based on measurements of a 4 by 1 cavity backed crossed dipole array with a gain of 12.5 dBi. This type of antenna is of particular interest to vehicles because of its low profile and simple pointing. Sidelobe specifications are different for azimuth and elevation patterns.

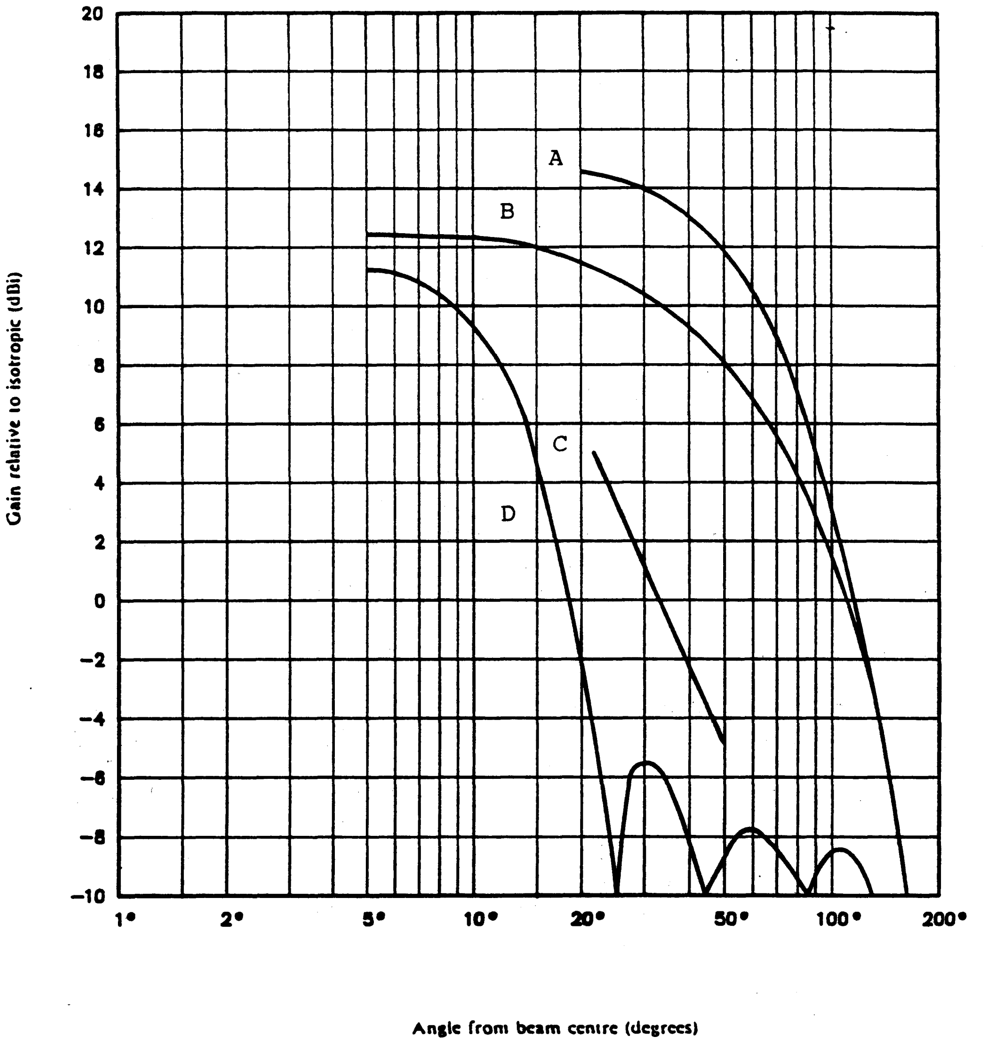
Azimuth pattern: $G = 38 - 25 \log(A)$ dBi

for A between 21° and 48°,
maximum sidelobe gain beyond 48° is -5 dBi.

Elevation pattern: $G = 15 - 0.0012\ A^2$ dBi

for A between 20° and 130°,
maximum sidelobe gain beyond 130° is -5 dBi.

Figure 6 shows the specifications and actual measurements of a 4 by 1 cavity backed crossed dipole array antenna.



A	Elevation specification	C	Azimuth specification
B	Measured elevation pattern	D	Measured azimuth pattern

FIGURE 6 - Fan-beam antenna specifications

(3) Vertical one-dimensional array antenna

A vertical one-dimensional array antenna has a torroidal antenna pattern. The elevation half-power beamwidth for a 12.5 dBi antenna will be in the order of 6°. The pattern is symmetrical in azimuth. This type of antenna will only require elevation tracking. Such an antenna will be particular attractive to small vehicles. Typical dimension of such an antenna could be a diameter of around 30 mm and a length of 500 - 800 mm. the narrow beam will give good discrimination against multipath. The beam will cover the geostationary arc in two positions. No measurements were available for such an antenna and the draft sidelobe specifications given below are based on theoretical approximations:

$$G = 41 - 25 \log(A) \text{ dBi}$$

for angles between 20 and 70°
maximum gain is -5 dBi beyond 70°.

3. Fading reduction technique for ship earth stations

For low G/T ship earth station (SES) antennas, the effect of multipath fading due to sea surface reflection will be more severe at low elevation angles since the antenna beamwidth is wider than that of current standard A SES antenna [Karasawa and Shiokawa, 1984]. For a low G/T SES, the fading reduction method, as well as the antenna, should be simple in configuration, light in weight and inexpensive. With these considerations in mind the polarization shaping method (see Report 1048) was chosen for use with the short backfire antennas described in Section 2.2.1 above. This method is suitable for cross-dipole fed antennas and requires a cross-dipole rotator and variable phase shifter.

4. Antenna mount for ship earth stations

For the current standard A SES, the 4-axis El/Az/Y/X mount with a step track function is most desirable because of its high stabilization capability and pointing accuracy. In the case of a low G/T SES, a 2-axis mount with a programme track function slaved to the navigation equipment may be desirable from the economic and construction viewpoints. Between the 2-axis mounts (El/Az and Y/X), the El/Az mount may be preferable because the Y/X mount has both a large pointing error due to gimbal-lock, and multipath fading effects at low elevation angles.

In this type of mount, the arm which supports the El-axis is U-shaped. Furthermore, the El-axis is mounted near the central axis of the antenna to easily maintain the weight balance of the antenna, LNA, diplexer etc. Accordingly, the weight load on the Az-axis is decreased resulting in a reduction of size and weight to the conventional El/Az mount. In addition, in order to achieve good pointing accuracy from the El/Az mount, the following should be considered:

- reduction of the pointing errors due to gimbal-lock at a high elevation angle of around 85°;
- reduction of the pointing errors due to the rewind operation of the Az-axis.

In the newly developed antenna mount shown in Fig. 7, the El/Az mount is controlled by using a microprocessor with input signals from the ship's navigation equipment and a pitching/rolling sensor. A newly developed control algorithm was adopted in order to improve the pointing error [Shiokawa et al., 1983].

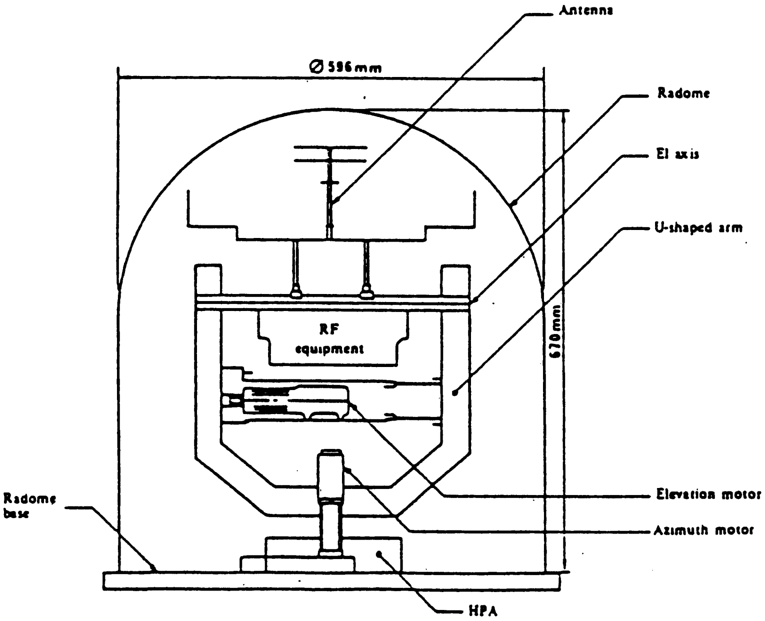


FIGURE 7 - Configuration of newly developed antenna mount for small antenna system

5. Antenna effective noise temperature

Typical earth terminal specifications include a value for the system figure-of-merit G/T_s. For a given antenna gain, G/T_s depends on the combination of antenna noise temperature and receiver noise temperature.

The antenna temperature results from several noise sources external to the antenna. The fraction of the external noise that is accepted by an antenna is a function of the directional properties of the antenna. The antenna noise can be obtained by "slicing" the antenna pattern into discrete sections or rays, and then determining the weighted average of noise from all rays. Physically, the sources of noise include ionosphere, earth, sea, sun, atmosphere, and sky background. Other contributions are made by antenna/receiver components, which add to the antenna noise temperature.

The composite antenna temperature can be expressed by:

$$T_A = \sum W_n T_n$$

where; T_n: effective temperature of noise source
W_n: fraction of power (weighted) contained in the segment of antenna lobe structure. For example, galactic noise through the mainlobe of an antenna is weighted more heavily than its entry via a sidelobe. Similarly, if 10% of the energy enters via the sidelobes (e.g., main beam 80%, 10% backlobes) the earth contribution is 0.1 x 300 = 30°K.

Typical temperatures which are used in this weighting include:

Atmosphere:	5K
Sky Temperature:	15K
Sea Temperature:	120K
Land Temperature:	300K

6. Conclusion

In mobile satellite communications, a number of types of low-gain and medium-gain antennas are under development. The characteristics of these new antennas are not yet represented in the present CCIR Recommendations. Further studies in the following areas are required:

(1) Measured characteristics of low- and medium-gain antennas for earth stations in the land, maritime, and aeronautical satellite services

(2) An examination of the special problems associated with antennas for aeronautical satellite applications.

(3) Development of new reference radiation patterns for array-type antennas for mobile earth stations.

(4) Fading reduction techniques for use at mobile earth stations in the aeronautical- and land-mobile satellite services.

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