A Multiple-Beam Spherical Reflector Antenna

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A spherical reflector with multiple feeds is an attractive possibility for application in future communications satellite systems. Data are presented which show that spherical reflectors possessing relatively high gain (40 dB) and very small phase path error ($<\lambda/32$) are feasible. A design of a spherical reflector utilizing corrugated horn feeds is considered. Radiation patterns are computed using the physical-optics technique. The designed antenna is approximately 60λ in diameter. Calculations performed for this antenna with three beams indicate that each beam has a gain of about 42 dB, a beamwidth of 1.4 deg, and sidelobes that can be expected to be at least 28 dB down. These results indicate that the feature of low sidelobes makes the spherical reflector a promising candidate for a multiple-beam communications satellite antenna.

Introduction

Advanced communications satellite technology will be applied to future information transfer systems such as biomedical data nets, law enforcement networks, adult education, etc. The communications satellite will be in synchronous equatorial orbit and will provide a wideband point-to-point communication capability between any two points within the continental United States. This capability will be achieved by developing a multiplicity of satellite antenna beams which cover the region and operate in conjunction with a series of small ground terminals. The multiple-beam satellite antenna is required to have a field of view of 7 deg for complete coverage. Another critical requirement is that the satellite antenna must possess low sidelobe levels to reduce interference with adjacent beams. A spherical reflector with multiple feeds appears to be an attractive possibility and represents the subject of this study.

The Spherical Reflector Antenna

The spherical reflector antenna has been studied extensively (References 1 and 2) because of its wide scanning capability (i.e., movement of the beam by movement of the feed). Spherical reflector antennas may generally be separated into two types: (1) those representing a large portion, and (2) those representing a small portion of a sphere. In the first type, the spherical reflector deviates substantially from a paraboloidal reflector and large amounts of spherical aberration are introduced. This spherical aberration can be corrected by using phased line-source feeds, auxiliary reflectors, multiple-source feeds or correcting lenses (References 1 and 2). Aside from the complexity in feed design, these antennas are generally narrow band and some suffer from high sidelobes. In the second type, the spherical reflector deviates very little from a paraboloidal reflector and spherical aberration is consequently minimal. For such a reflector, a single-point source feed can be used and the feed design is a relatively simple one. Ashmead and Pippard (Reference 3) and Li (Reference 4) have studied this antenna for wide-angle scanning. Sidelobe levels of 20 dB were obtained. The communications satellite multiple-beam antenna is essentially a narrow-angle scanning antenna. For narrow-angle scanning the sidelobes of the feed do not illuminate the reflector and an improvement in sidelobe levels can be expected.

The purpose of this study is to determine the feasibility of using a spherical reflector representing a small portion of a sphere as a communications satellite multiple-beam antenna and to calculate typical sidelobe levels for such an antenna. Several feeds placed at various scan angles provide the multiple beams required.

Phase Path Error

By comparing a parabola and a sphere, Ashmead and Pippard (Reference 3) and Li (Reference 4) have shown that the phase path error $\Delta\ell$ in a spherical reflector is given by

$$\Delta\ell = \frac{D^4}{2048f^3} \tag{1}$$

where $\Delta\ell$ is the phase path error, D is the reflector diameter, and f is the focal length. (f and D are shown in Figure 1. The dimensions given in Figure

1 are referred to in the next section.) Equation 1 may be expressed in a more useful form:

$$\frac{\Delta \ell}{\lambda} = \frac{1}{2048} \frac{D}{\lambda} \frac{1}{\left(\frac{f}{D}\right)^3} \tag{2}$$

where λ is the wavelength. The focal length f is defined as

$$f = \frac{1}{4}\left[R + \sqrt{R^2 - \left(\frac{D}{2}\right)^2} \right] \tag{3}$$

where R is the radius of the sphere (Figure 1). Equations 1–3 were derived under the approximation that the spherical reflector represented a small portion of a sphere. This requirement means that f/D should generally be greater than 0.5. Under these conditions, $D/2$ is smaller than R and Equation 3 approaches $R/2$, which is known as the paraxial focus of the spherical reflector.
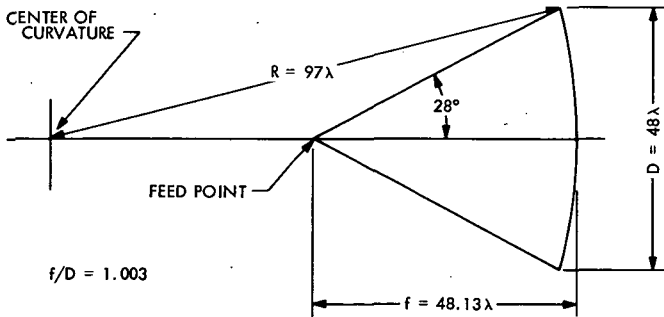

Figure 1. Spherical reflector geometry

The focal length given by Equation 3 is the focal length for which the total phase error is least over the aperture. For non-uniform illumination, this focal length does not necessarily yield the best radiation pattern. The optimum focal length for non-uniform illumination can be determined by a series of computations involving slight deviations from the value of f given by Equation 3.

Spencer (Reference 5) studied the degradation in antenna gain for uniform illumination in the spherical reflector caused by spherical aberration and found that

$$\frac{\Delta G}{G} = 3.5092 \left(\frac{\Delta \ell}{\lambda}\right)^2 \tag{4}$$

where G is the antenna gain.

The information contained in Equations 2 and 4 is shown in Figure 2. Corresponding values of gain for a paraboloid with uniform illumination are also shown. For a given spherical reflector, the phase path error and net antenna gain for uniform illumination can easily be obtained. For a fixed diameter reflector it is seen that the phase path error decreases rapidly with increasing f/D. Even for relatively large reflectors, phase path errors less than $\lambda/32$ are still practical. However, it must be kept in mind that for increasing values of f/D the illumination angle decreases. Consequently, higher gain feeds are needed and aperture blocking effects become significant. Another point worth mentioning is that for large values of f/D, the phase path errors may be smaller than the fabrication tolerances and the question of whether the reflector is a sphere or a paraboloid is merely an academic one. However, as will be seen in the next section, the reflector must be conceived as a spherical reflector and designed as such lest the virtues of a spherical reflector be lost.
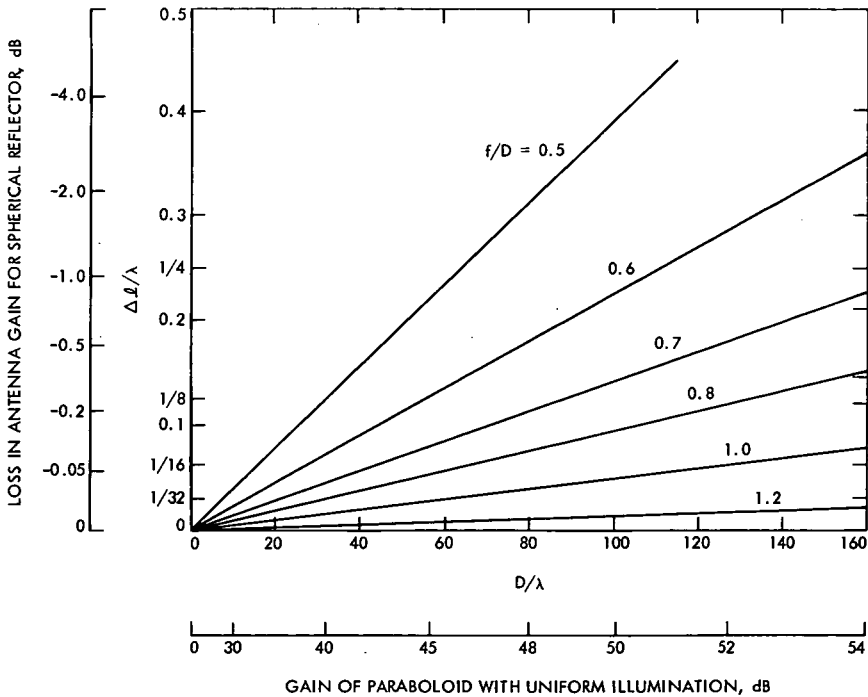

Figure 2. Phase path error of spherical reflectors

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Antenna Requirements and a Multiple-Beam Antenna Design

A system study for the 12-GHz band (11.7 to 12.2 GHz) has suggested the use of four reflector antennas to cover the continental United States (Reference 6). Each reflector would have the following characteristics:

(1) Gain: ~40 dB.

(2) Beamwidth: ~1.4 deg.

(3) Number of beams: 3.

(4) Sidelobe isolation: >23 dB.

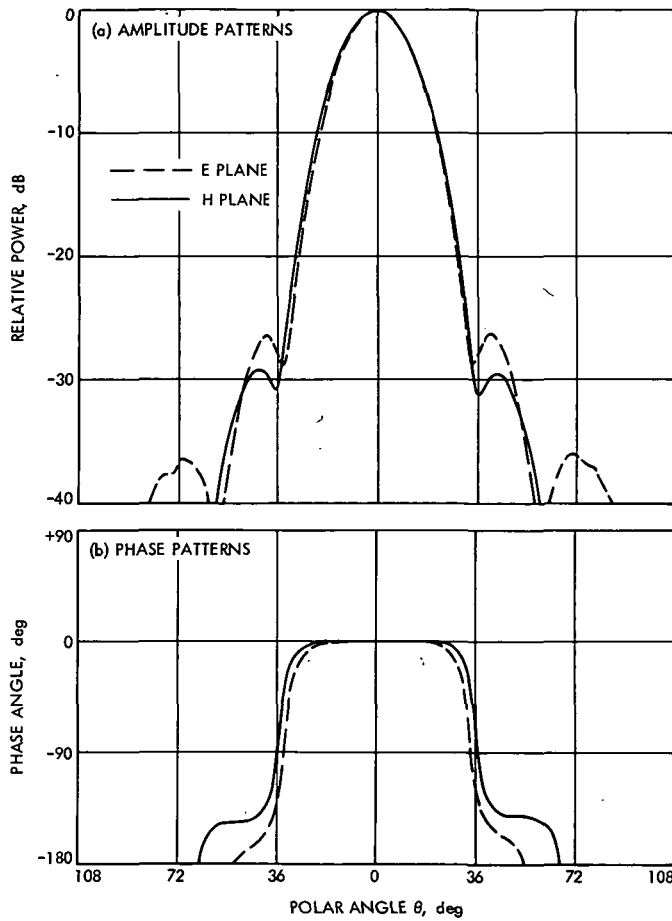(5) Beam separation: up to 5–6 beamwidths.

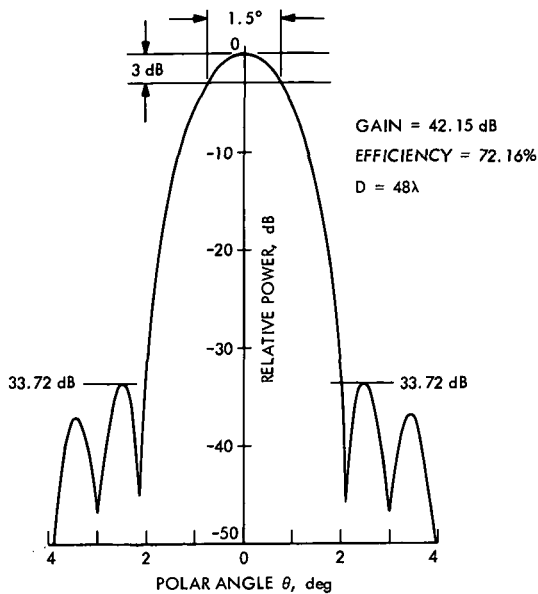Figure 3. Measured corrugated horn feed patterns

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Figure 4. E-plane pattern for feed located on-axis

A spherical reflector offering these approximate characteristics has been designed and its radiation patterns obtained using the physical-optics technique (Reference 7). Efficiency is computed numerically and the results include the effects of both non-uniform illumination and spillover, but not blockage.

To achieve low sidelobes, (1) spherical aberration must be minimized, and (2) an illumination that is non-uniform and tapers toward the reflector edge must be employed. An aperture diameter of 48λ was chosen for the proper gain and beamwidth. (See Figure 1 for other antenna dimensions.) The f/D ratio is 1.003 and, according to Figure 2, the phase path error is less than λ/32. An edge taper of 18–19 dB results when the reflector is fed with a corrugated horn whose measured patterns are shown in Figure 3. Similar feed patterns with varying edge tapers were tried and it was found that the feed pattern in Figure 3 yielded the best results. The calculated radiation patterns are shown in Figure 4. Aperture blocking has been neglected. As can be seen, the sidelobes are at least 33.72 dB down. The antenna gain is 42.15 dB, while the antenna efficiency is 72.16%.

The spherical reflector must be made oversized if the sidelobes are to remain low for the two off-axis feeds. As seen in Figure 5, the reflector diameter must be increased to 60.14λ to ensure a phase path error less than λ/32 and an edge taper of at least 18 dB over a 4-deg scan. Typical radiation patterns are shown in Figure 6. Again, aperture blocking has been neglected. For a scan of over ±2 beamwidths, the patterns are essentially similar with the sidelobes remaining at least 34.9 dB down. It should be pointed out that
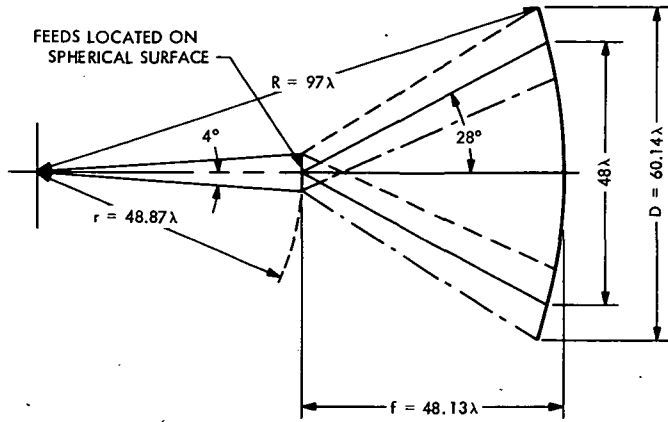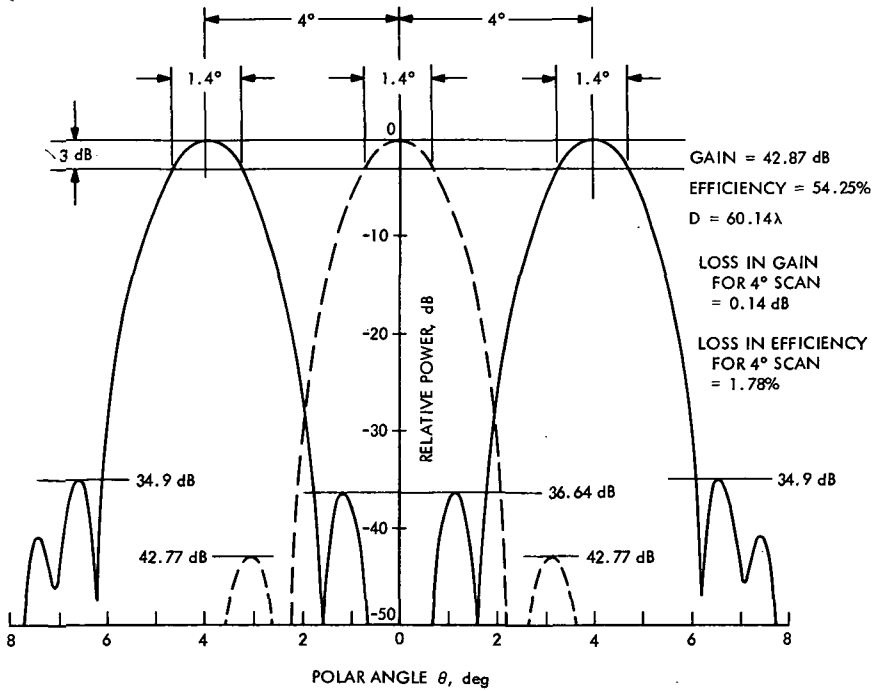
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Figure 5. Multiple-beam spherical reflector

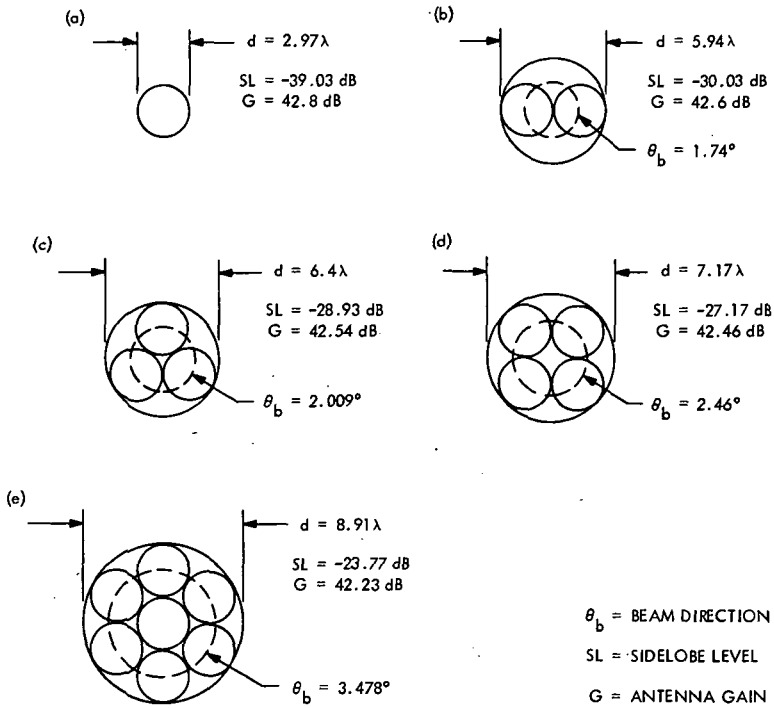Figure 6. E-plane patterns for feed located 4 deg off-axis in the E-plane

Figure 7. Circular blockage regions used for: (a) 1 horn, (b) 2 horns, (c) 3 horns, (d) 4 horns, and (e) 7 horns

these low sidelobes are obtained at the expense of antenna efficiency. Thus, to maintain the specified gain, a somewhat larger reflector is needed.

So far, aperture blocking effects have been neglected. For large values of f/D, these effects are important since the percentage of blocked area becomes significant. An exact analysis of aperture blocking is very difficult. Nevertheless, an indication of their effects can be obtained by omitting the current distribution over a blocked area which is the projection of the feed on the reflector. This has been carried out for circular blocked regions with diameters varying between 2.97λ and 8.91λ. The correspondence between the number of feeds and the circular blocked regions is illustrated in Figure 7. In all cases, the feed is located on the axis of the reflector. The calculated antenna gain and sidelobe level results are summarized in Figure 7. These calculations are approximate, but they do serve to indicate that even with three beams, sidelobe levels better than 28 dB can be expected. The exact sidelobe levels must, of course, be determined by constructing and testing an experimental model. The effects of mutual coupling between adjacent feeds are expected to be small but these must also be determined experimentally. Note, also from Figure 7, that as many as seven beams may be utilized within a field of view of 7 deg. The sidelobe levels are raised substantially but they are still better than 23 dB.

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It was mentioned in the previous section that with the phase path error less than $\lambda/32$, the spherical reflector is very nearly a paraboloidal reflector. It is, however, important that the reflector be conceived and designed as a spherical reflector, otherwise the virtues of a spherical reflector would be lost. To illustrate this point, if the orientation of the two off-axis feeds in Figure 6 is changed so that they point to the center of the reflector, then the spherical symmetry is lost and, although the antenna is more efficient (an increase in efficiency of 0.88%), the sidelobes are substantially higher (an increase of 6.5 dB).

Concluding Remarks

Data have been presented to show that the feature of low sidelobes makes the spherical reflector a promising candidate for a multiple-beam communications satellite antenna. These low sidelobes are achieved at the expense of antenna efficiency. Sidelobe levels are very sensitive to aperture blocking and, although an estimate of these effects was obtained, the calculations were very crude. The exact sidelobes must be determined experimentally.

References

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