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A SURVEY OF ATL-COMPATIBLE RADIOMETER ANTENNAS

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ABSTRACT

A survey has been made of antennas suitable for remote sensing of the earth's surface, in particular the world ocean, by means of microwave radiometers operating in the 1 to 26 GHz frequency region and carried on board the Shuttle-launched Advanced Technology Laboratory.

Array antennas are found to be unattractive and unsuited to the task. Reflectors, including cassegrain and offset types, as well as horn-reflectors are possible candidates but all have shortcomings that will impair the accuracy of measurement.

Horns, of the corrugated type, have excellent electrical characteristics. Although they are physically very large and will require development of suitable deployment mechanisms they appear to be valid candidates for the task.

The evolution of the periscope antenna is outlined and it is shown to possess nearly ideal electrical characteristics for the intended application. Its only shortcoming is that the feed horn creates aperture blocking; however, there is no blocking due to struts or any other source. The periscope antenna can be recommended for ATL radiometry.

FOREWORD

Several reports have been prepared under contract NAS1-10691 covering various phases of investigations into the problem of remote measurement of sea surface temperature by means of microwave radiometry. This one deals with the results of a survey of generic antenna types that was aimed at finding those most suited to radiometric use in the low-orbiting Advanced Technology Laboratory.

Earlier reports covered; (a) the design and (b) the operation and maintenance of a precision airborne radiometer at 2.65 GHz, (c) a feasibility study of swept frequency radiometer techniques, (d) the results of measurements of the dielectric properties of sea water at 1.43 GHz and (e) the engineering design of a 4.5 to 7.2 GHz stepped frequency radiometer.

In these investigations invaluable assistance was rendered by Rockwell International personnel M. J. Van Melle of Space Division and Dr. W. W. Ho of the Science Center.

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1.0 INTRODUCTION

The use of microwave radiometry as a remote sensing tool from a satellite in low earth orbit offers the potential for synoptic observation of a number of parameters and characteristics of the earth's surface. Of particular interest insofar as the Advanced Technology Laboratory (ATL) is concerned are the following: detection of ice-water boundaries, measurement of salinity, temperature and roughness (wave slopes) of the ocean surface, sensing of snow cover and perma-frost regions and determination of clouds, rain and water vapor content in the earth's atmosphere.

There is one other phenomenon, not associated with the earth's surface at all, whose quantitative measurement is of great importance, namely the cosmic background radiation that permeates all of space in an apparently isotropic manner. Accurate determination of the radiant temperature associated with this black-body radiation, and thought to be about 2.7 Kelvins, can best be carried out from a space platform above the earth's atmosphere. The measurement is of value in its own right, and is also of great importance in establishing a precise calibration temperature for all radiometers operating in the microwave and millimeter wave regions.

The frequency range associated with these measurements is a broad one, encompassing between a decade and a decade and a half. Thus, the measurement of salinity is best done at a low frequency, not much more than 1 GHz, while atmospheric parameters can be determined accurately only at much higher frequencies, up to 30 GHz. Ocean surface temperature measurement accuracy is highest in the region from 2.5 to about 4.5 GHz. Radiometers operating in any of the above frequency bands will "see through" the atmosphere to the surface, so that it is important to know the salinity and temperature of the ocean's surface. Thus it is necessary to choose frequency bands that will optimize both salinity measurement and temperature determination. The octaves 1.4 to 2.8 GHz and 4.0 to 8.0 (or as much of these octaves as can practically be used) have tentatively been chosen as satisfying most requirements for surface parameter measurement. For atmospheric effects the standard waveguide band 18.0 to 26.5 GHz has been chosen since it is unrealistic to expect to achieve octave band performance in this region. A minimum of three swept frequency radiometers is therefore necessary to meet these requirements.

Each radiometer should be capable of measuring both components of emission, namely the vertical component, polarized parallel to the plane of incidence, and the horizontal component, polarized perpendicular to the plane of incidence. To avoid the need for two separate radiometers in each channel we assume that the components are measured sequentially by means of a switch, instead of simultaneously. If a circular polarizing device is provided then this scheme has the flexibility to measure the average of the two components of emission.

Along with the need to measure cosmic thermal radiation it is desirable to make surface measurements as a function of angle of incidence, so that at least a cross-track scan capability is necessary.

Finally, in order to satisfy the needs of the oceanographer for high spatial resolution, the footprint diameter should lie in the range 10 to 20 km.

2.0 ANTENNA REQUIREMENTS

The radiometric requirements discussed above, when coupled with the need for high beam efficiency and low ohmic loss, translate into a set of stringent antenna specifications that are extremely difficult to meet. It is fortunate, indeed, that the Shuttle-launched ATL imposes only minimal requirements on antenna size and structural configuration.

The ATL pallet is 4.2 m wide but only 3.2 m high, so that it appears necessary to restrict antenna size to 3 meters maximum. An aperture of this diameter (14.3λ) at 1.43 GHz will generate a radiation pattern having a half-power beam-width of about 4.9 degrees. The minimum realistic orbital altitude for ATL is about 185 km (100 n.m.) and in this case the footprint diameter will be about 16 km. This appears to be within the acceptable resolution range needed by the oceanographers. For the two higher frequency bands no antenna size constraints are imposed and the desired 10 km resolution can be achieved with apertures that are 22.7λ in diameter. These are 1.7 m and 0.38 m, respectively, at 4 and 18 GHz and the corresponding half-power beamwidths are each 3.1 degrees.

High beam efficiency and very low ohmic loss are needed over nearly an octave bandwidth for the two lower frequency channels and over a 36% bandwidth for the high frequency one. In addition, the cross-polarization content in the radiation patterns must be very low at all frequencies and each antenna must be capable of dual, orthogonally polarized, operation. Finally, scan capability through $\pm$ 50° in at least one plane is required.

We now turn, in the light of these requirements, to an examination of several basic candidate antenna types. These generic types are:

<u>Arrays</u>	Electronically scanned Non-scanned
<u>Reflectors</u>	Prime focus-fed Cassegrain Spherical Parabolic torus
<u>Horns</u>	Multimode Corrugated
<u>Horn/Reflectors</u>	Conventional Folded Cassegrain Periscope

3.0 ANTENNA CONFIGURATIONS

Before discussing the various antenna types it is worth noting how ohmic loss in the antenna can affect the measurement of brightness temperature. The error introduced is given by

$$\Delta T = (T_{ant} - T_{sea})\ell \qquad (1)$$

where T_{ant} is the physical temperature of the antenna, T_{sea} the brightness temperature of the sea and ℓ the fractional loss. Due to the impracticality of cooling physically large antennas the temperature difference above will necessarily be in the order of 170 K. A loss of 0.1 db corresponds to $\ell = 2.3\%$, so that each 0.1 db of loss introduces an error of 4 K in brightness temperature measurement. Accurate correction for such errors is hardly feasible due to variability in the loss and temperature terms in equation (1). Therefore it is mandatory to keep antenna losses as small as possible; one or two tenths of a db is a practical upper limit.

3.1 Arrays

Electronically scanned arrays can be eliminated as candidates for radiometric use almost at once, chiefly on grounds of high ohmic loss. The need for diode or ferrite phase shifters for scanning is sure to introduce losses of 1 to 2 db, and these losses are invariably quite temperature sensitive. Additionally, traveling wave arrays always leave a fractional amount of power unradiated. This power must either be radiated as a conjugate lobe, impairing beam efficiency, or be absorbed in a load which constitutes added ohmic loss.

Elimination of phase shifter losses by use of a non-electronically scanned array helps, but ohmic losses still tend to be excessively high.

For our purpose we need an array containing of the order of 2000 elements, e.g. microstrip discs [1]. Any corporate feed arrangement, in stripline or microstrip, is bound to create a loss of 1 db or more. To attempt to reduce these losses by using waveguide feed lines introduces so much dispersion that near octave bandwidth operation is out of the question. Slotted waveguide arrays have very limited bandwidths for the same reason and the problem is further compounded by the narrow impedance bandwidth of the slots and the fact that element spacing is not constant in wavelengths. Staggered longitudinal slots and inclined shunt slots generate, respectively, high sidelobes and high cross-polarized radiation levels, so that the slotted waveguide array is a very poor candidate for this application.

A broadside radiating square array does have one thing in its favor. By the principle of pattern multiplication the side lobes are largely confined to the principal planes and beam efficiency is therefore high. An array that takes advantage of this fact has been investigated for radiometric use in a meteorological satellite [2]. Basically, this antenna consists of an array of identical line sources placed side by side in the H plane. Each line source is a multimoded E plane sectoral horn, utilizing the dominant TE_{10} plus hybrid TE_{12}/TM_{12} modes. Some means of providing a tapered power distribution across the array must be provided, but use of hybrid couplers and/or magic-T's would introduce considerable ohmic loss. Optical power dividing techniques may offer the best solution; one example would be a folded H-plane pill-box.

Unless the sectoral horns are flared very gently and are therefore very long, the E plane pattern will be distorted due to phase error in the aperture. In the Metsat application the use of dielectric lenses was proposed to correct the phase error, but only at the expense of a drastic weight penalty. Due to frequency limitations imposed by the multimoding technique the bandwidth of such an array is less than 10%. Though this could be greatly increased by use of corrugated sectoral horns this array is not a very attractive candidate.

On top of the above difficulties, it appears to be almost impossible to provide acceptable dual polarization characteristics from an array except over a narrow band of frequencies. We conclude that even a mechanically scanned array cannot meet the requirements set out for use as a radiometer antenna in the ATL.

3.2 Reflectors

The conventional and simple paraboloidal reflector has relatively low beam efficiency when fed directly at its prime focus. However, an improvement in performance has been reported [3] when a small focal ratio ($F/D < .25$) reflector is used. This is due to shielding of the wide angle feed radiation by the reflector itself, since the feed is actually below the rim of the dish. Aperture efficiency is quite low and a much larger dish is required for a given beamwidth. Similar results could probably be achieved by use of a "tunnel" or shroud around the rim of a normal dish.

Another contribution to poor beam efficiency is due to wide angle radiation scattered by the feed supporting struts and the feed transmission line. Ohmic loss is by no means insignificant (a few tenths db) since the feed transmission line must be at least 10λ long, unless the radiometer's RF circuits are placed at the prime focus along with the feed horn. This practice, however, only increases aperture blocking and causes more wide angle scattering, further impairing the beam efficiency.

In its favor, the simple, prime focus-fed reflector, can, with a suitable feed, provide near octave band operation with acceptable dual polarization characteristics. It must be scanned mechanically by rotation of the whole reflector system. This is not an objectionable feature for ATL use, although it would present difficulties for use in a small, unmanned satellite. Such an antenna is a possible, though not too promising, candidate for our application.

For ground based work the Cassegrain configuration [4], [5], [6], usually offers lower noise temperature than the prime focus-fed system, because feed spillover radiation is directed toward the cold sky. Magnification factors of 3 to 5 are commonly used with the result that the cross-polarized radiation can be very low in a Cassegrain system, and dual-polarized performance is excellent.

In space-borne usage, however, the feed spillover is directed toward the warm earth and the Cassegrain configuration, in this respect, offers but a slight advantage over the prime focus-fed system. Ohmic loss will be reduced because the RF circuitry can be mounted at the feed horn location, directly behind the main reflector. Cassegrain reflectors are not usually considered unless the aperture diameter exceeds about 50 wavelengths. This is because the combined spherical wave blocking by the feed and plane wave blocking by the sub-reflector amounts to an area several wavelengths in diameter and consequently is excessively high in smaller aperture systems. The near-field Cassegrain [7] is certainly no better in this respect.

Aperture blocking is eliminated in the open-Cassegrain system [8] through use of offset reflectors, but this introduces a significant level of undesired cross-polarized radiation. For the above reasons the Cassegrain configuration can be considered a possible, but somewhat unlikely, candidate for ATL use.

The spherical reflector can provide scan capability by movement of the feed alone, but, unless correction of spherical aberration is provided, the area utilization factor is very poor and the reflector must be extremely large. The line source feed [9] affords an excellent means of correcting the aberration but is inherently a narrow band device. Gregorian correctors have been investigated [10] but are not promising because they cause excessive aperture blocking and create an inverse amplitude taper that gives rise to very high sidelobes. An offset portion of a sphere can be fed with a sectoral hog horn [11] and offers wide band operation with freedom from aperture blocking. It will, of course, suffer from high cross-polarization levels due to use of an offset reflector. Discussions of cross-polarization effects in reflector antennas may be found in references [12] to [16].

A cross between spherical and paraboloidal reflectors is to be found in the parabolic torus [17]. The surface of this reflector is a figure of revolution formed by rotation of a parabola about a line perpendicular to its axis. The orthogonal central sections through this surface are thus parabolic in one plane and circular in the other so that spherical aberration occurs only in one plane. Single axis scanning is possible in this plane by simple feed motion. However, a thorough investigation of practical feed systems for this reflector is required before it can be considered a serious candidate. Studies along these lines are already in progress elsewhere [18].

In sum, the common forms of reflectors are evidently possible candidates for ATL radiometer use, but all have faults that will compromise system accuracy and performance to a significant degree.

3.3 Horns

Probably no antenna can approach the high beam efficiency of the multimode or the corrugated horn. Since the former is inherently a narrow band device, due to the fact that the required modes propagate with different phase velocities within the horn, we can dismiss it from consideration. For the corrugated horn the HE_{11} balanced hybrid mode, [19] to [22], occurs when the corrugation depth is exactly one quarter wavelength. In this case the radiation pattern is ideal in the sense that it is axially symmetric (equal E and H plane beamwidths) and contains no cross-polarized component. The beam efficiency is exceptionally high, being typically 98% at an angle equal to three times the half-power angle.

Although balanced hybrid mode operation occurs, strictly speaking, only at the frequency for which corrugation depth is exactly $\lambda/4$, there is, nevertheless, good reason to expect no great degradation in performance until the depth approaches $\lambda/2$ [20]. The literature suggests that a frequency range of 1.5 or 1.6:1 should be possible, both for impedance and bandwidth, [21], [23], [24]. In a very recent paper Frank, [25], describes the use of tapered slot corrugations and claims that bandwidths in excess of 3:1 are possible. He gives supporting data on an experimental model over the range 8 - 18 GHz, in which performance is said to have been limited by the coaxial-to-waveguide transition, not by the horn itself.

Leaving aside the question of operating bandwidth, the corrugated horn, either conical or pyramidal, can meet all RF requirements of high beam efficiency, low ohmic loss and dual polarization with high polarization purity. It must, of course, be mechanically scanned and this requires a somewhat cumbersome gimballing structure for the 1.43 GHz horn. This horn, of necessity, is physically large and will have a large phase error across its aperture unless it is impractically long. Hence its beam will be broadened and it may not be possible to achieve the desired spatial resolution at 1.43 GHz. This point deserves further consideration, so we digress.

To determine the extent of beam broadening due to aperture phase error we make use of calculations by Croswell [26] in which he computed patterns of a conical horn having various degrees of quadratic phase error. Figure 1, based on this data, shows the half power beamwidth constant, K, as a function of the maximum phase error, ϕ. These parameters are defined by the relations

$$\mathrm{HPBW} = \theta = K\lambda/d \tag{2}$$

$$\phi = \frac{2\pi}{\lambda} \cdot \frac{d^2}{8L} \tag{3}$$

where d and L are aperture diameter and slant length of the horn, respectively. The dashed curve in figure 1 represents a reasonably good parabolic fit to the computed data for phase errors up to 4π radians. The equation of this curve is

$$K \simeq 72 + 27 \left(\frac{\phi}{\pi}\right)^2 \text{ degrees.} \tag{4}$$

Using the value of ϕ/π given by (3) yields

$$K \simeq 72 + 1.69 \left(\frac{d}{\lambda}\right)^4 \left(\frac{\lambda}{L}\right)^2 \tag{5}$$

whence

$$\Theta \simeq 72 \frac{\lambda}{d} + 1.69 \left(\frac{d}{\lambda} \right)^3 \left(\frac{\lambda}{L} \right)^2 . \tag{6}$$

For fixed length of horn the beamwidth is minimized when

$$\frac{d}{\lambda} = 1.94 \sqrt{\frac{L}{\lambda}} \tag{7}$$

as can be seen by equating to zero the derivative of (6) with respect to $\frac{d}{\lambda}$.
The minimum beamwidth is found to be

$$\Theta \simeq 50 \sqrt{\frac{\lambda}{L}} \tag{8}$$

and occurs when $K \simeq 97°$, corresponding to a phase error, ϕ, equal to π radians. This is a simple and interesting result, although not surprising in view of the predictions of Barrow and Chu [27] many years ago, and the observations, by Kay [28] concerning the wide flare horn.

The results embodied in equations (7) and (8) are displayed graphically in figure 2 which shows that a horn 3 meters in diameter would have to be 11.4 meters long in order to attain its minimum beamwidth of about 6.8° at 1.43 GHz and that the corresponding footprint diameter would be about 22 km. Alternatively, if we specify a maximum length of 6 m for the horn then minimum possible beamwidth at 1.43 GHz will be about 9.3°. This will occur for a diameter of 2.2 m and the footprint diameter will be 30 km.

If a minimum beamwidth horn is designed in accordance with the above principles at 1.43 GHz, then it is easy to show that its beamwidth will remain almost constant for all higher frequencies within its near octave bandwidth. Measured in wavelengths, its aperture becomes larger as frequency increases but the beam does not become narrower because of the counteracting effect of the increasing phase error.

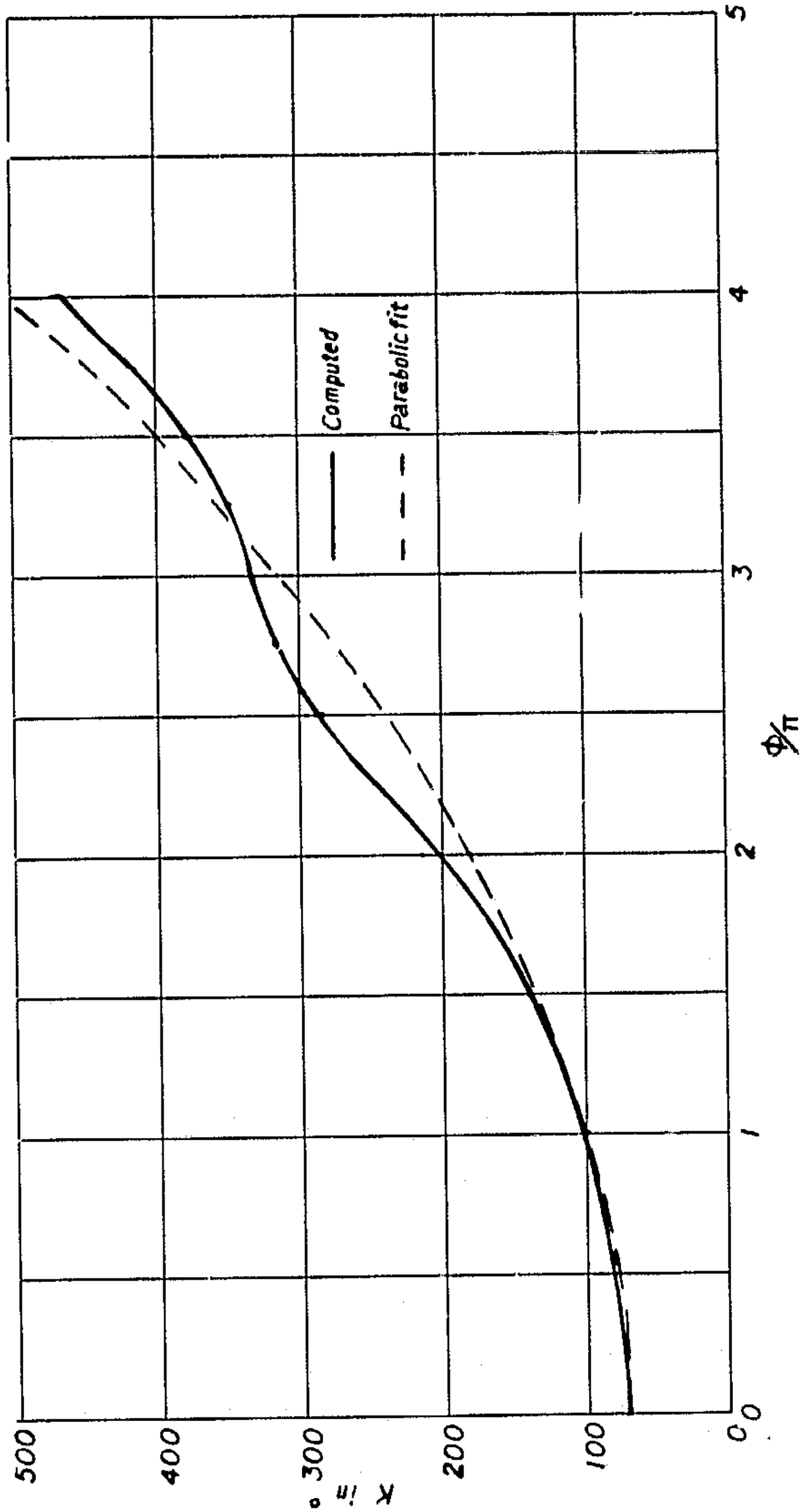


Fig. 1 Variation of Half-Power Beamwidth Constant with Phase Error

The corrugated horn, it would appear, is a good candidate for ATL radiometric use if it can definitely be established that it is capable of operating over a 1.6:1 bandwidth. Because of the horn's large size a collapsible structure must necessarily be devised.

3.4 Horn-Reflectors and Other Offset Systems

The chief objection to the horn is its excessively large size at low frequencies. We have seen that if a horn is to radiate a diffraction limited pattern, in the sense that a plane wave exists in its aperture, then the horn must be monstrously long to yield the desired resolution at 1.43 GHz. If the horn is to be shortened to a practical and reasonable length then we have seen that we must give up diffraction limited optics in order to obtain an optimum design. In this case the horn's aperture diameter must be increased by about 35% over that for the diffraction limited case.

There are two ways of realizing the benefits of diffraction limited optics without using an excessively long horn. Both involve the conversion of the spherical wave in the horn's mouth into a plane wave, in the one case by a curved reflector, in the other by use of a lens. The latter approach is impractical; a solid dielectric lens (phase delay type) would be impossibly heavy, while a metal plate lens (phase advance type) would seriously limit bandwidth. On the other hand, the combination of a horn with a reflector does not impose a significant weight penalty and results in a reasonably compact antenna with very high beam and ohmic efficiencies, without imposing bandwidth limitations. The horn-reflector, sometimes called the cornucopia antenna, has been used by the Bell System for many years for ground to ground and for ground to satellite links and it yields

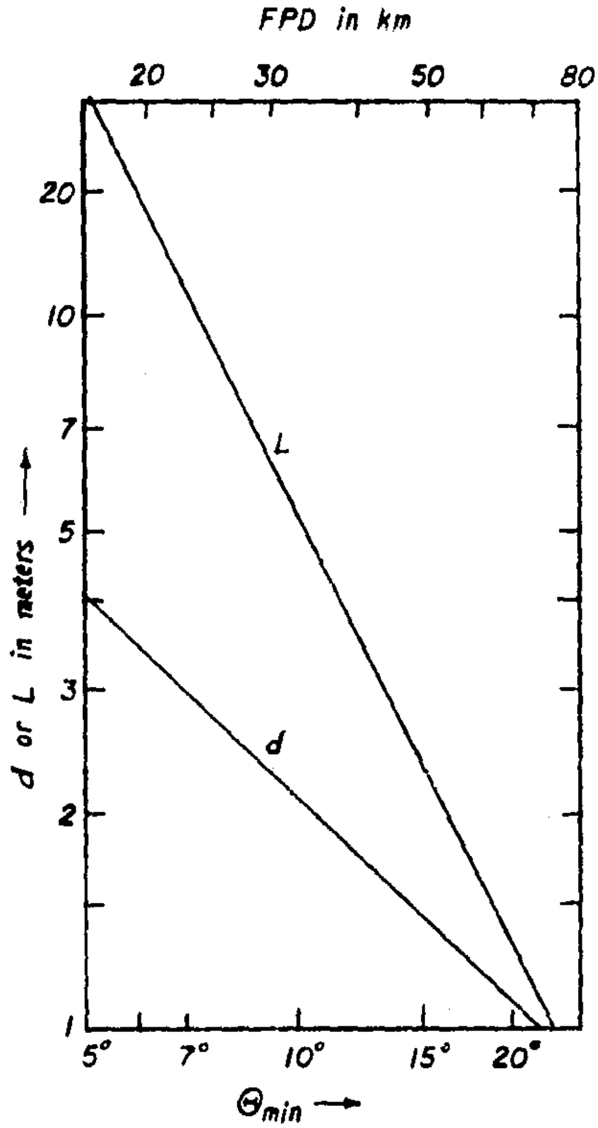


Fig. 2 Diameter and Length of a Minimum Beamwidth Horn

high gain along with low noise temperature [29], [30], [31], [32].

If the horn is of the pyramidal type then the resulting aperture has a somewhat odd shape, bounded by two circular arcs of different radii, and by two non-parallel straight lines, producing a noticeable lack of symmetry. If, however, the horn is conical then the aperture is the projection, in the x, y plane, figure 3, of the intersection of the cone and the paraboloidal surface of the reflector. The intersection is elliptical but its projection, and hence also the aperture, is a circle, as shown by the following analysis.

The equation of the paraboloid in the x, y, z coordinate frame is

$$x^2 + y^2 = 4F\,(z + F). \tag{9}$$

The equation of the cone in the x', y', z' frame is

$$y'^2 + z'^2 = x'^2 \tan^2\theta_\circ \tag{10}$$

where $\theta_\circ$ is the cone's half-angle. Now the x'y'z'frame is obtained by a simple rotation of the x,y,z frame about its y axis through the angle θ_1, as shown in figure 3. The equations of transformation are

$$\left.\begin{aligned} x' &= x \sin\theta_1 - z \cos\theta_1 \\ y' &= y \\ z' &= z \cos\theta_1 + z \sin\theta_1 \end{aligned}\right\} \tag{11}$$

so that the equation of the cone in the x,y,z frame becomes

$$x^2+y^2+z^2 = (x \sin\theta_1 - z \cos\theta_1)^2 \sec^2\theta_\circ\ . \tag{12}$$

To find the intersection of the cone and paraboloid we substitute (9) into (12), giving

$$z + 2F = (x \sin\theta_1 - z \cos\theta_1) \sec\theta_\circ \tag{13}$$

so that (13) and (9) taken together are the equations of the curve of intersection. Eliminating z from these two equations gives the projection of

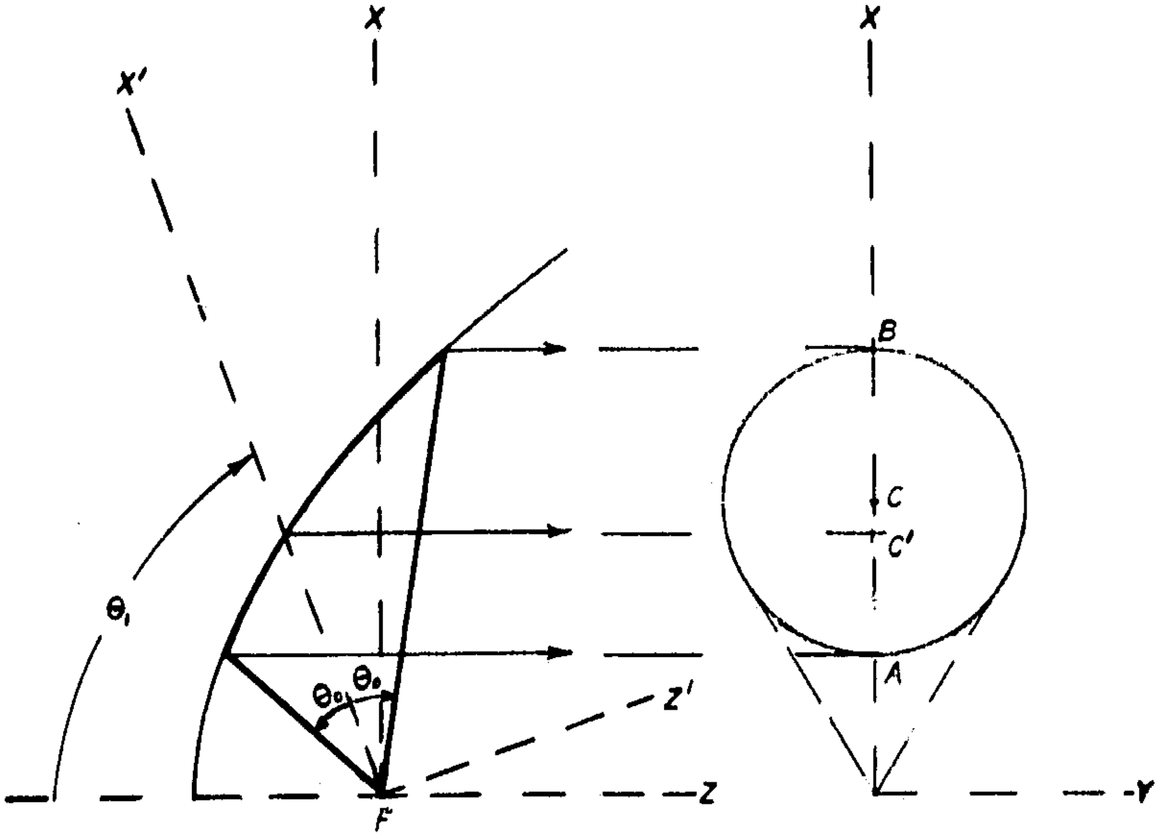


Fig. 3 Geometry of Conical Horn-Reflector

this curve in the x,y plane. We find,

$$x^2 + y^2 - 4F^2 = \frac{4Fx \sin\theta_1 \sec\theta_o - 8F^2}{1 + \cos\theta_1 \sec\theta_o} \qquad (14)$$

which is seen to be the equation of a circle of radius a and center C (x_o,o), where

$$\left.\begin{aligned} a &= \frac{2F \sin\theta_o}{\cos\theta_1 + \cos\theta_o} \\ \text{and}\quad x_o &= \frac{2F \sin\theta_1}{\cos\theta_1 + \cos\theta_o}\ . \end{aligned}\right\} \qquad (15)$$

Although the aperture has thus been shown to be circular, electrical symmetry is nevertheless lacking. The central feed ray, i.e. the cone axis cuts the reflector in a point which does not project into the center of the aperture at C, but into the point C', the electrical center, whose x coordinate is

$$x'_o = \frac{2\ F \sin\theta_1}{1 + \cos\theta_1}\ . \qquad (16)$$

There is an additional dysymmetry introduced into the aperture illumination in the x,z plane by the offset paraboloid. This is due to space taper and is such that, relative to unit power density at the electrical center, C', the power densities at A and B, figure 3, are

$$\left.\begin{aligned} P_A &= \cos^4\left(\frac{\theta_1-\theta_o}{2}\right) \\ P_B &= \cos^4\left(\frac{\theta_1+\theta_o}{2}\right) \end{aligned}\right\}. \qquad (17)$$

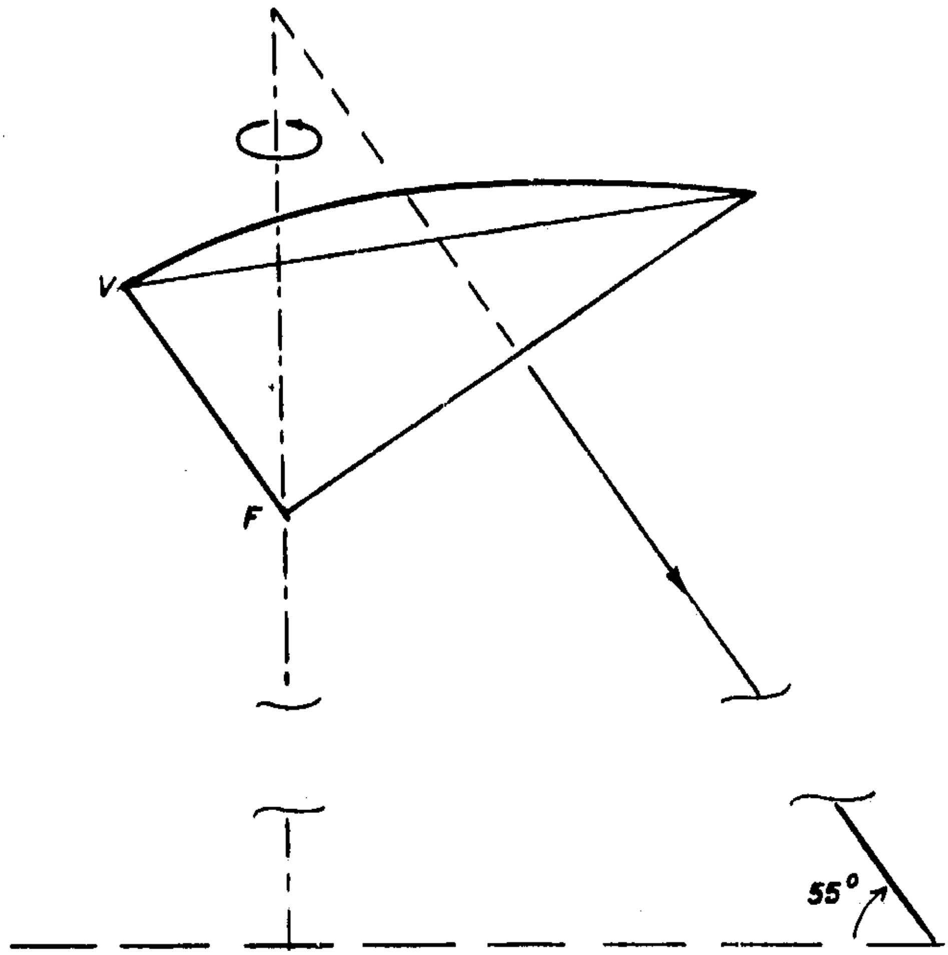


Fig. 4 Conical Scan Offset Reflector

The total space taper is the ratio of these, namely

$$\frac{P_A}{P_B} = \left[\frac{\cos\left(\frac{\theta_1-\theta_o}{2}\right)}{\cos\left(\frac{\theta_1+\theta_o}{2}\right)}\right]^4 . \qquad (18)$$

A typical horn-reflector geometry, [30], is such that $\theta_1 = 90°$ while $\theta_o = 15°$. In this case the space factor given by (18) is 2.88 and causes a 4.6 db dysymmetry in the illumination in the x, z plane.

The above analysis applies not only to the horn-reflector but to other offset reflector systems as well. In addition to the undesirable dysymmetry in aperture illumination suffered by these systems there is also a significant increase in the polarization losses [16], due to the fact that cross-polarized lobes now appear in the principal planes as well as in the intercardinal planes. The offset system proposed by Richter [33], and shown in figure 4, suffers from this effect and has a 6 db unsymmetrical taper in its aperture illumination. Richter proposed to obtain a conical scan (at 55° angle of incidence) by mechanical rotation of the reflector, leaving the feed horn fixed at the focus. This would introduce further complications since the radiated field then becomes a scan-angle-dependent mixture of both vertical and horizontal polarizations.

A type of antenna called the Cassegrain horn-reflector has been described [34], that combines the low spillover characteristics of the horn-reflector with the more compact structure associated with a conventional reflector. It is shown in figure 5. By the use of Cassegrain optics a virtual focus is created at F_1 which would be the apex of the horn in the normal horn-reflector geometry. The real focus, where a feed horn is located, is at F_2 and the virtual focus is created by a hyberboloidal sub-

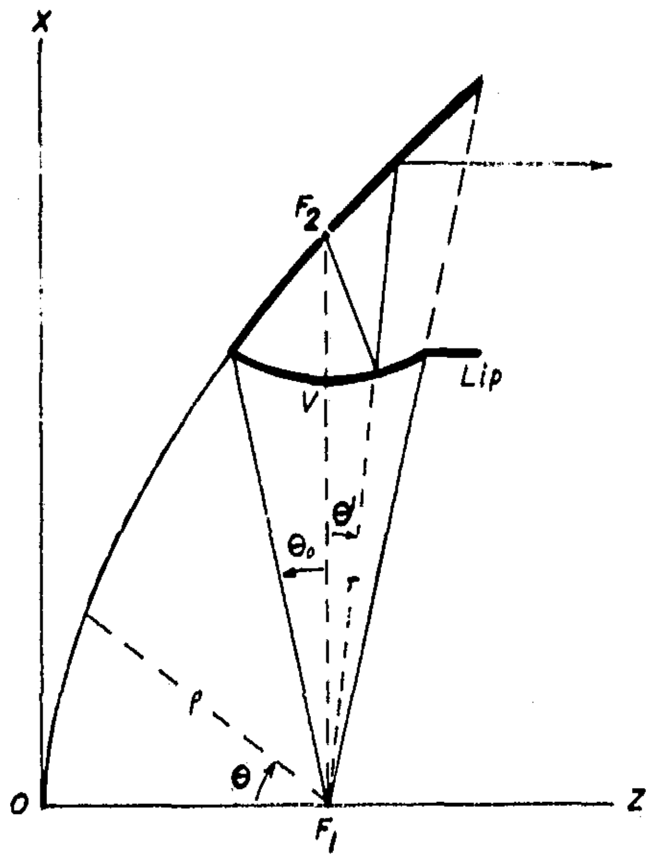


Fig. 5 Cassegrain Horn-Reflector

reflector.

In polar coordinates with pole at F_1 the equation of the parabolic section of the main reflector is

$$\rho = \frac{2F}{1 + \cos\theta} \tag{19}$$

where $F = OF_1$ is the focal length. Referred to the same pole, F_1, the hyperbolic section of the sub-reflector has the equation

$$r = \frac{(e-1)\ f_1}{e \cos\theta' - 1} \tag{20}$$

where $f_1 = VF_1$ is the first focal distance of the hyperbola and e is the eccentricity. The second focal distance, $f_2 = VF_2$, is related to the first by

$$f_2 = \frac{e-1}{e+1} \cdot f_1 \tag{21}$$

whence $$f_1 + f_2 = \frac{2e}{e+1}\ f_1 \quad . \tag{22}$$

Now it is clear that $\rho = f_1 + f_2$ when $\theta = \frac{\pi}{2}$, so that (19) and (22) combined give

$$F = \frac{e}{e+1}\ f_1 \quad . \tag{23}$$

Figure 5 illustrates the most compact configuration, in which it is apparent that $\rho = r$ when $\theta' = \theta_o$ and $\theta = \frac{\pi}{2} - \theta_o$. Equations (19), (20) and (23) then yield

$$\frac{e^2-1}{2e} = \frac{e \cos\theta_o - 1}{1 + \sin\theta_o} \tag{24}$$

which may be regarded as an equation that determines the eccentricity. From (15) the aperture diameter in this case is

$$D = 4F \tan\theta_o \ . \tag{25}$$

Two special cases are shown in figure 6 in which the hyperboloidal sub-reflector has degenerated into the plane mirror PP. When this happens the first and second focal distances are equal and the eccentricity becomes infinite. Equation (24) applies to the compact configuration in figure 6 and we find $\theta_o \simeq 37°$. In this case the aperture diameter is 3F while the space factor, from equation (18), becomes

$$\frac{P_A}{P_B} = \left[\frac{\cos\left(\frac{\pi}{4} - \frac{\theta_o}{2}\right)}{\cos\left(\frac{\pi}{4} + \frac{\theta_o}{2}\right)}\right]^4 = \left[\frac{\cos\frac{\theta_o}{2} + \sin\frac{\theta_o}{2}}{\cos\frac{\theta_o}{2} - \sin\frac{\theta_o}{2}}\right]^4 \tag{26}$$

and is equal to 16, corresponding to a 12 db asymmetrical illumination taper.

All of these horn-reflectors and other offset type systems are seen to suffer from lack of symmetry in aperture illumination and from poor beam efficiency caused by high cross-polarization loss. In every case the horn portion should be corrugated in order to equalize E and H plane beamwidths and to suppress E plane sidelobes. This has an impact on horn-reflector design since it introduces structural complexities. For these reasons none of these types is attractive for ATL radiometry in spite of the fact that, as ground station antennas, they do have low noise temperatures. The cross-polarized lobes point to the cold sky in ground station use, but in a satellite-borne radiometer they would couple to the much warmer surface of the earth, creating large errors for other than small angles of incidence.

3.5 The Periscope Antenna

There is a variant of the Cassegrain horn-reflector that completely does away with the objectionable offset feature, thereby restoring symmetry to the aperture illumination and eliminating the cross polarized lobes in the principal planes. Other desirable features are retained, however, so that the resulting antenna possesses nearly ideal electrical characteristics in a compact configuration. We have already investigated one limiting case of the Cassegrain-horn reflector in which the sub-reflector became a plane mirror with an eccentricity approaching infinity. The new configuration also has its genesis in a limiting case but now the sub-reflector becomes a paraboloid with eccentricity equal to unity.

To see how this comes about we note that the space taper factor in (26) approaches unity (0 db) for small values of the cone angle $\theta_\circ$. At the same time, as $\theta_\circ$ approaches zero, we find from (24) and (25) that

$$e \simeq \frac{1 + \theta_\circ \sqrt{2}}{1 - \theta_\circ} \longrightarrow 1 \tag{27}$$

while $D \simeq 4F\,\theta_\circ$ and approaches the limiting value

$$D \longrightarrow \frac{4f_2}{1 + \sqrt{2}} = 1.66\ f_2 \tag{28}$$

With $e = 1$ the hyperboloidal sub-reflector turns into a paraboloid with focal length f_2, while $f_1 = \infty$. Since F also approaches infinity the original offset paraboloidal reflector becomes a plane mirror inclined at 45° to the axes. This geometrical configuration is shown by the heavy lines in figure 7(a) and it is clear that there is no offset and no dysymmetry in illumination. It is interesting to note that we began with a horn-reflector that was generated by a cone intersecting with a paraboloid of revolution; we arrived at a configuration in which the cone became a circular cylinder while the paraboloid degenerated into a plane. The resulting antenna is not new, having been investigated by the Bell System [35], [36] in 1969 for ground microwave links, and more recently by Japanese workers

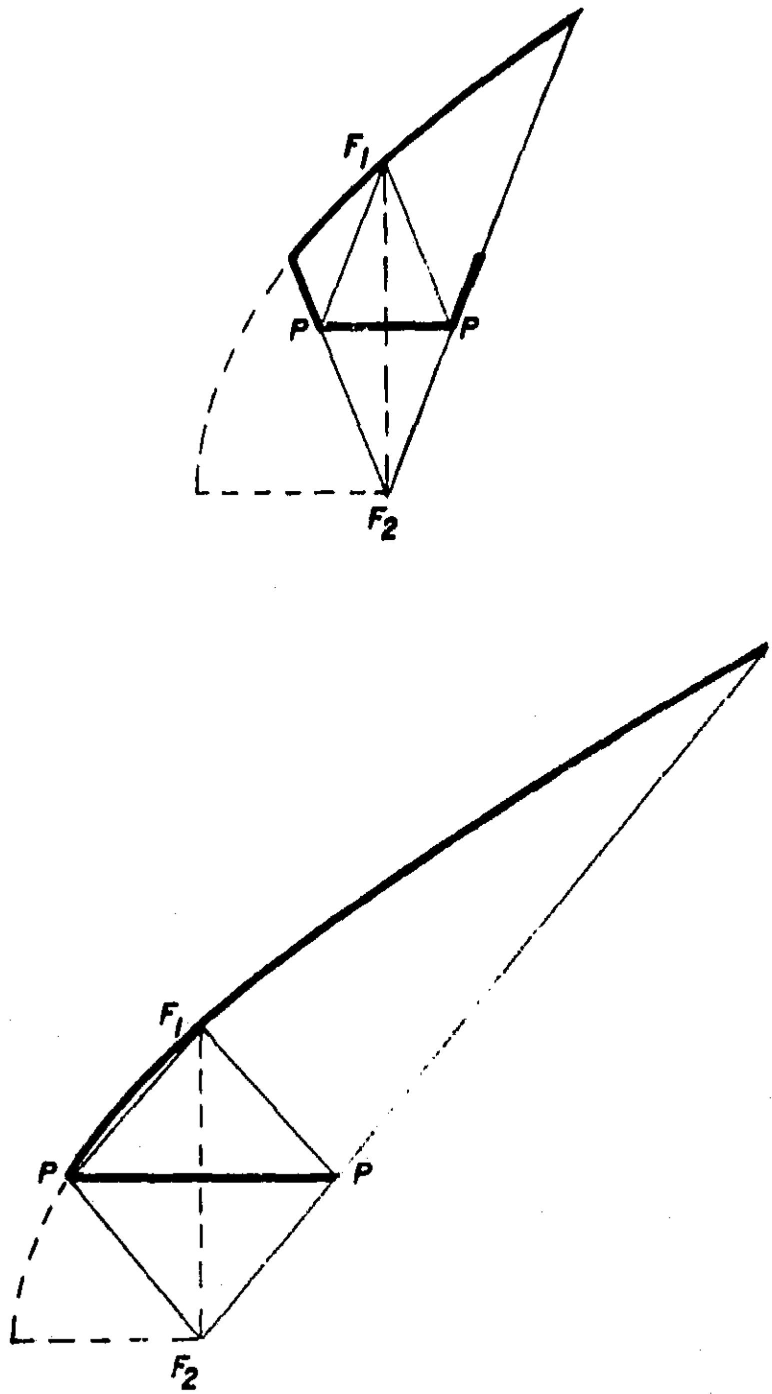
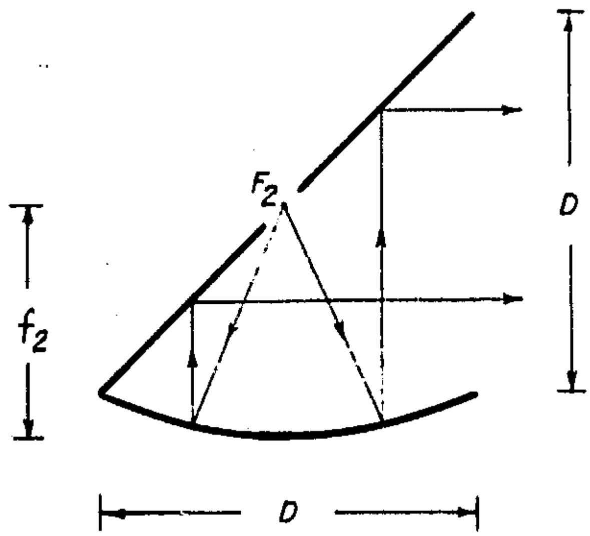


Fig. 6 Limiting Cases of the Cassegrain Horn-Reflector

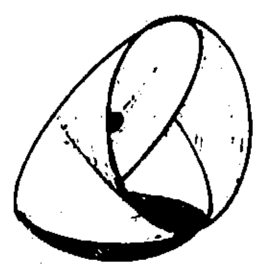
[37], [38] for communication satellite purposes. It has been called the "periscope antenna". Our approach to its design, though somewhat roundabout, serves to make clear how this antenna combines the desirable features of both the horn-reflector and the shallow paraboloid, while avoiding the need for offset geometry.

The sketch in figure 7(b) attempts to show a three-dimensional view and indicates that the antenna is formed by a mitered junction of two orthogonal right circular cylinders. One cylinder is truncated at the aperture; the other is truncated at its intersection with the paraboloidal reflector. The whole structure is thus extremely well "shielded" for most directions that are not normal to the aperture, hence extraneous coupling to external space will be very small. This feature of the periscope antenna was not fully exploited by the Bell System, nor by the Japanese workers referenced above. It will be a valuable asset for our application in reducing spillover.

It is clear from figure 7(a) that the paraboloid subtends an angle of 45° at the focus F_2. Therefore, so far as the plane of the drawing is concerned, any feed radiation at angles slightly greater than 45° will constitute wide angle spillover. However, feed radiation at 90° to the feed axis is in the same direction as the main beam and does not constitute spillover. There are two ways of reducing the small spillover due to feed radiation in the angular region near 45° off the feed axis. The first is to use a horn with a high degree of illumination taper at the edge of the paraboloid. This will impair aperture efficiency, which is of small concern, but it will also require a larger feed, giving rise to increased aperture blocking. The second way to reduce the wide angle spillover is based on



(a) SECTIONAL VIEW



(b) 3D VIEW

Fig. 7 The Periscope Antenna

the use of "blinders" around the aperture [39], [40].

In this case it is possible to add blinders that will re-direct the feed horn spillover rays into the direction of the main beam. Figure 8 shows how this is done by making the blinders conform to the auxiliary paraboloid shown by the dotted lines. The focal length of the auxiliary paraboloid is related to that of the main one by $f' = f_2 \left(\sqrt{2}-1\right)^2 = 0.172 f_2$. The addition of the blinders will create a new aperture, D', somewhat larger than the original aperture D. Although rays arising from the annular ring between D and D' are all properly collimated, the illumination in the ring will not, in general, be in phase with that in the main aperture because there is a constant path difference (equal to D) between the rays in the ring and those in the main aperture. This will reduce the net aperture efficiency but should not affect beam efficiency because its effect is to increase only the near sidelobes while suppressing the far. An analytical treatment is outlined in the section 3.6.

The periscope antenna lends itself quite readily to single-axis mechanical scanning, as is indicated in the three views shown in figure 9. The structure is gimballed so that it is free to rotate about the axis of the paraboloid. An important feature is that the radiometer's RF package can be mounted directly behind the feed horn without causing additional aperture blockage. The plane reflector is used as a bulkhead for exterior mounting of the RF package. The angular extent of the scan will be limited, not so much by the nature of the gimbal, but by the structural sides of the ATL pallet; a range of ± 45° should be achievable.

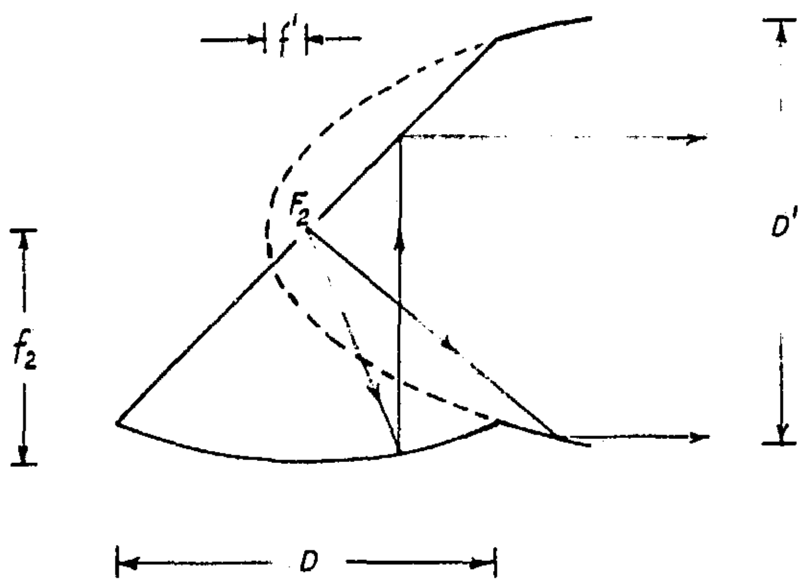


Fig. 8 Periscope Antenna with Blinder

3.6 Radiation Pattern Analysis

Following is an analysis that can be used to predict the radiation pattern of the periscope antenna with blinder, as shown in figure 8. Circular symmetry is assumed for the feed pattern so that there is no ϕ-dependence of the fields. In this case the distant electric field of the antenna is given by

$$g(u) = \int_0^1 F(r)\, J_0(ur)\, r dr \qquad (29)$$

where $u = \frac{\pi D'}{\lambda} \sin\theta$, r is the normalized radial coordinate in the aperture and F(r) describes the radial distribution of the aperture field. To account for a phase error of magnitude δ in the annular ring between D and D' we take

$$F(r) = f(r) \quad , \quad o < r < c$$

$$F(r) = f(r)e^{j\delta} \quad , \quad c < r < 1$$

where $c = D/D'$.

If we neglect the small change in f(r) caused by the change in space taper that occurs at radius c then we have

$$g(u) = \int_0^c f(r)\, J_0\,(ur)\, r dr + e^{j\delta}\int_c^1 f(r)\, J_0(ur)\, r dr. \qquad (30)$$

This can be explicitly evaluated if we assume the usual parabolic amplitude distribution,

$$f(r) = 1 - r^2 \quad . \qquad (31)$$

The result is most conveniently expressed in terms of Lambda functions, defined by

$$\Lambda_n(x) = \frac{2^n n!}{x^n} \quad J_n(x)$$

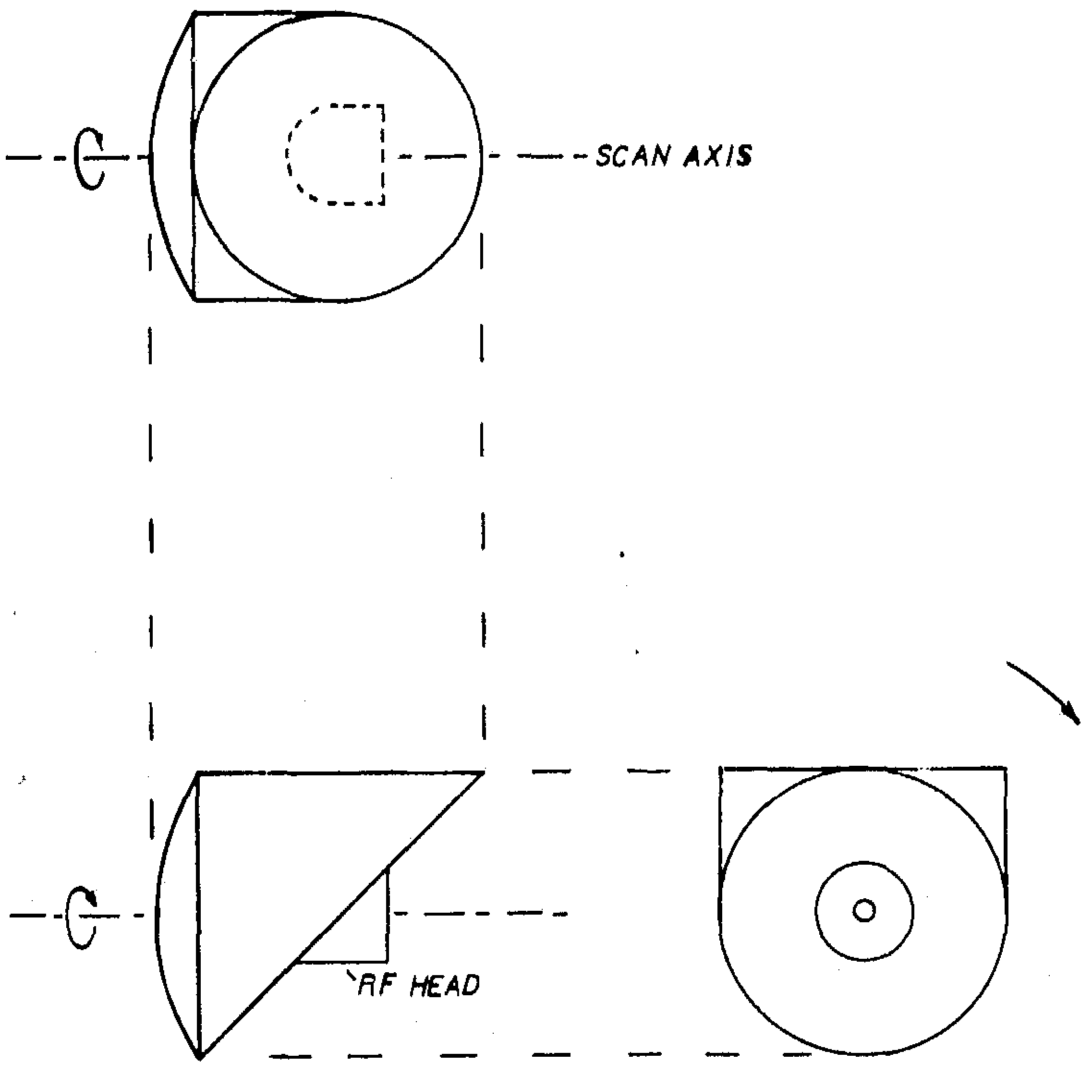


Fig. 9 Periscope with Single-Axis Scan

and we have

$$4g(u) = X + Y\cos\delta + j\,Y\sin\delta \tag{32}$$

where $X = 2c^2 \cdot (1-c^2) \cdot \Lambda_1\,(cu) + c^4\,\Lambda_2\,(cu)$

and $Y = \Lambda_2\,(u) - X$. (33)

The power pattern, denoted by $P(\theta)$, is given by

$$P(\theta) \propto |g\,(u)|^2$$

so that

$$P(\theta) \propto X^2 + Y^2 + 2XY\cos\delta$$

$$\text{or } P(\theta) \propto \left[\Lambda_2\,(u)\right]^2 - 2XY\,(1 - \cos\delta\,) \tag{34}$$

Finally, beam efficiency may be calculated using the definition,

$$\eta\,(\theta) = \frac{\int_0^{\theta} P(\theta)\sin\theta\,d\,\theta}{\int_0^{\pi} P(\theta)\sin\theta\,d\,\theta} \quad . \tag{35}$$

No actual calculations of beam efficiency have been performed, but computations of the power pattern, $P(\theta)$, have been made for a few values of c and for the worst case phase error, viz. $\delta = 180°$. In this case the value c = .54 produces a split main beam with a null at $\theta = 0$. For larger values of c the beam is dimpled at $\theta = 0$ and becomes flat-topped at about c = 0.7. (These cases have been investigated for an entirely different application, namely earth coverage from a high altitude satellite, where gain at edge-of-earth should be higher than at nadir). For the present application the likely value of c is about 0.9 and the pattern for this case is shown by the solid line in figure 10. The dashed line shows the pattern for the main aperture alone. The near side lobe levels are slightly increased by use of the blinder, but the far lobes are suppressed.

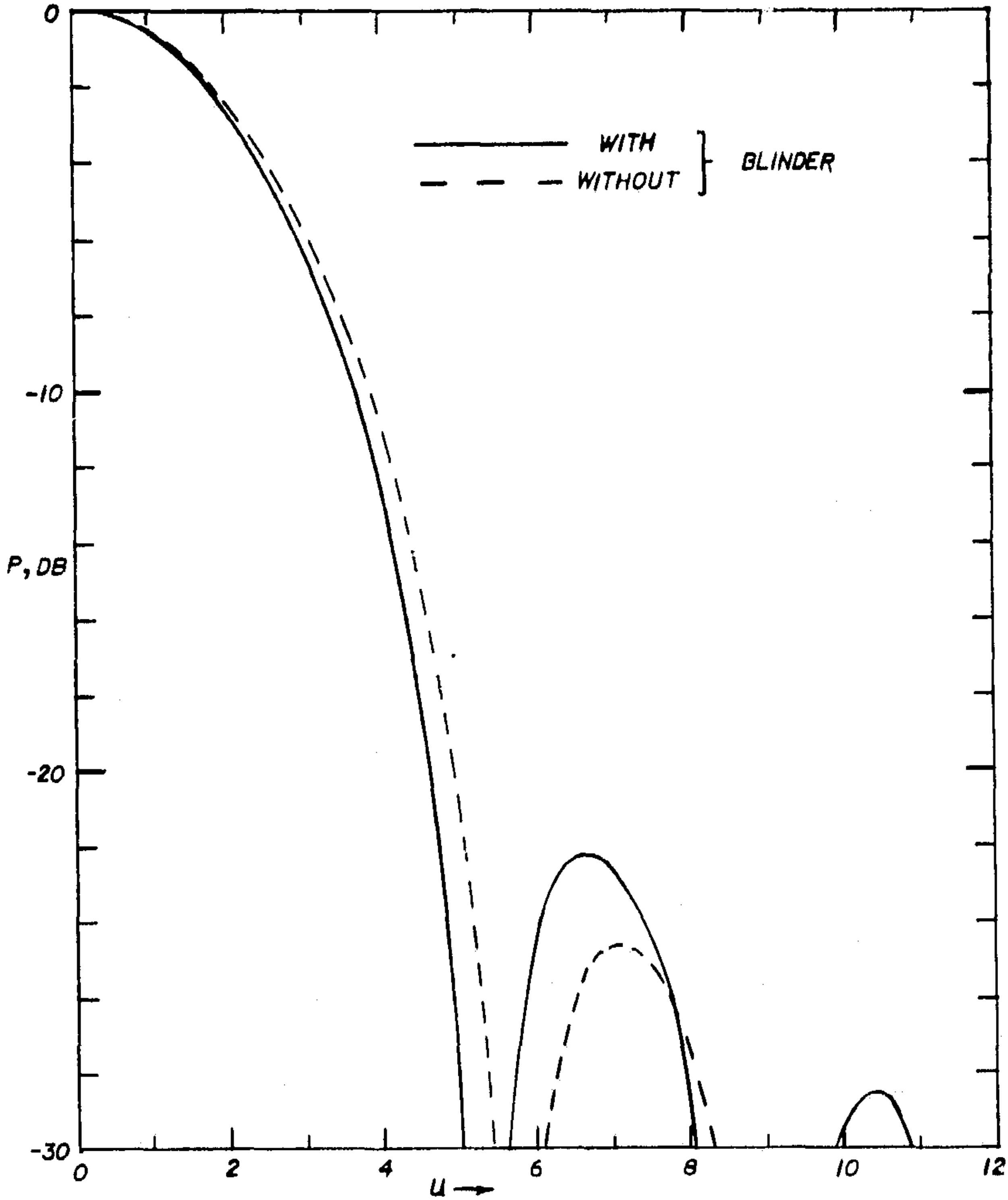


Fig. 10 Calculated Patterns of Periscope Antenna

4.0 PERISCOPE ANTENNA FEEDS

The very desirable electrical characteristics of the periscope antenna can only be realized to the extent permitted by the feed system. The ideal feed for our purpose would have an axially symmetric radiation pattern, the polarization characteristics of a Huyghen's source [41] and be capable of radiating orthogonal polarizations. Low ohmic loss and very wide bandwidth are also pre-requisites. A thorough investigation of possible feed candidates has not been undertaken but preliminary judgment favors use of a corrugated horn.

The paraboloid in the periscope antenna has a focal ratio of 0.603 and subtends an angle of 45° at the focus, giving a space attenuation factor of 1.4 db. The illumination taper is equal to that due to the feed plus the 1.4 db space factor given above. Because a heavy taper is desirable we can specify that the feed pattern should be about 18 db down at 45° off the axis. Such a pattern can be obtained from a corrugated round waveguide having an aperture whose circumference is about 2π wavelengths, according to Knop et al [42]. The overall feed diameter in this case is that of the aperture (2λ) plus twice the corrugation depth, for a total of 2.5λ. We have seen that the size of the ATL pallet will restrict the aperture of the periscope to a diameter of about 3 m, i.e. approximately 14λ at the lowest frequency, 1.43 GHz. The area blocking fraction created by the corrugated feed is thus $(2.5/14)^2 \simeq 3.2\%$ which is acceptable.

There is, however, some doubt that a simple corrugated waveguide feed of this type can operate satisfactorily over a wide band. Since the calculations of Knop, et al, are strictly for $\lambda/4$ tooth depth, their paper [42] sheds no light on this point. A preliminary study of references [21] to [24] indicates that small-flare-angle horns are incapable of wide band

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operation, but that bandwidths in excess of 1.6:1 are possible with wide-flare-angle horns. The latter statement is in agreement with the findings of Kay [28] who developed the scalar feed [43], [44] in which the flare angle is so wide as to cause in excess of π radians phase error in the horn aperture. The scalar feed, of course, represents one of the earliest attempts at horn pattern control using a corrugated surface. For this feed horn the full flare angle of the horn is roughly equal to the full angle subtended by the reflector, i.e. 90° in our case. The horns used by Kay have larger apertures with diameters of about 5λ. In this case aperture blocking would increase to 12-1/2%, causing a significant loss in gain and increase in sidelobe levels. The loss in gain is not especially important, but the increased side lobe level would undoubtedly mean a degradation in beam efficiency which is undesirable.

There are some indications that wide-flare-horns of more modest aperture diameter might be satisfactory. In an article giving empirical design information for corrugated feeds, Buchmeyer [45] states that near octave band performance can be obtained, but fails to substantiate the claim, either in terms of pattern or impedance characteristics. Following his design procedure leads to a horn that is 2λ long with aperture diameter of 2.8λ (hence 3.3λ overall) with quarter-wave corrugations at the lowest frequency. Its total flare angle is 90° and it is said to radiate an axisymmetric pattern that is 15 db down at 45° off the axis. References [46] and [47] contain useful information on wide-flare horn feed design.

It seems clear that the wide-flare horn can produce frequency independent symmetrical patterns over a frequency range of 1.5:1, and possibly more [25], [48]. In this range the horn pattern maintains almost constant beamwidth due to the fact that aperture phase error (which exceeds π radians at the lowest frequency) increases with frequency and causes just enough beam broadening to counteract the effect of the increasing aperture size. We have already discussed this phenomenon in section 3.3. The constancy of the wide-flare horn's beamwidth is usually considered an asset because it means that a reflector antenna can be illuminated with a constant high efficiency over a wide frequency range. The secondary pattern will therefore become narrower and the gain will increase with frequency. This is desirable, of course, in cases where the antenna is directed toward a point source or target. It is not necessarily so in our application in which the target (the ocean) always fills the antenna beam. For radiometric use we could employ a feed (e.g. a small-flare-angle horn) in which the pattern exhibited the usual narrowing with increasing frequency, providing other criteria were met. In this case the secondary pattern and hence the footprint size would remain more nearly constant over the frequency band of operation.

Considerably more study of corrugated horns is needed before these questions can be answered. At the same time we should not neglect the multimode horn. Although a long multimode horn with large aperture is bound to be a narrow band device, it is possible that a short horn could yield a wide bandwidth. The bandwidth limitation comes about because the TE_{11} and TM_{11} (circular) modes propagate with different velocities and so get out of phase in the aperture when the frequency is changed. In a short horn the phase difference remains small over a wider frequency range than in a long horn. Techniques for wideband mode conversion from TE_{11} to TM_{11} have been investigated and described [49], [50].

Another class of feed horn worth investigation is the dielectric horn or dielguide [51]. It has been shown [52] that this kind of horn supports a hybrid HE_{11} mode just as does the corrugated horn, hence its radiation pattern will have the same desirable features, namely axisymmetry and polarization purity. Little information is available on bandwidth, however. A somewhat different dielectric-loaded horn, said to be capable of at least 25% operating bandwidth has been described by Satoh [53]. A dielectric band inside a conical horn is used to convert TE_{11} to TM_{11} mode energy. Because the conversion takes place in the horn and not in the waveguide feeding the horn the modes remain in phase at the aperture over a reasonably wide frequency range.

Finally, Shimizu [54] has described a small, quadruply-ridged feed horn which he claims can feed a reflector over an octave in bandwidth. This is certainly true so far as impedance matching is concerned, but it is not certain that pattern symmetry is achievable over such a wide range. The patterns become narrower with increasing frequency so that the secondary beamwidth would tend to remain constant.

5.0 CONCLUSIONS

We have surveyed the basic generic types of antennas and attempted to assess their suitability for radiometric remote sensing of the earth's surface from the low orbit of the Advanced Technology Satellite. We have concluded that array antennas are unattractive and unsuited to the task. Reflector antennas, including prime-focus fed, Cassegrain and offset types, as well as horn-reflectors, are possible candidates but all have shortcomings that will significantly compromise the accuracy of radiometric observations. The corrugated horn is a strong candidate if adequate bandwidth can be achieved, for its electrical characteristics are ideal. Because of its great physical size, development effort is needed to create a lightweight deployable horn structure having satisfactory dimensional tolerances.

We have traced the evolution of the periscope antenna and concluded that its electrical characteristics are very nearly ideal. Its only shortcoming appears to arise from aperture blocking caused by the feed horn; there is no strut blockage and the radiometer's RF package may be located at the feed location, thereby minimizing ohmic losses without creating aperture blocking. Structurally it has a compact configuration quite compatible with the ATL, without the need for a deployment mechanism. Its salient features are summarized in the following table.

Table 1 Features of the Periscope Antenna

Characteristic	Remarks	Comments
Aperture efficiency	Moderate	Relatively unimportant for radiometric use
Aperture blocking	Due only to the feed; there are no struts	Rather high for a scalar feed; this is the only major shortcoming
Spillover and wide angle radiation	Very low	Assumes heavy illumination taper or use of blinder
Near side lobes	Normal or slightly elevated	Blinder causes slight increase
Beam efficiency	High	Measured to 3 times the half power angle
Ohmic efficiency	Very high	No lossy feed transmission line needed.
Radiation pattern	Depends on feed	Axially symmetric with low side lobes if corrugated feed horn used
Cross-polarization	Very low, due to $F/D \simeq 0.6$, if proper feed is used	There is no cross-polar radiation in the principal planes and only small cross-polar lobes in the intercardinal planes
Dual-polarization capability	Depends only on feed	Scalar feed will give excellent isolation between orthogonal polarizations
Bandwidth	Depends only on feed	Octave bandwidth appears possible; Corrugated feed horn will give 1.6:1
Mechanical configuration	Compact	Any 1.43 GHz antenna for ATL will have a large aperture.
Scan capability	Mechanical rotation of whole antenna	Single axis or double axis, depending upon the gimbal
Compatibility with ATL	Very good	The swept-volume in a scanning mode is not much greater than the static volume

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