United States Patent [19]

Hyde

[11] **3,922,682**

[45] **Nov. 25, 1975**

[54] **ABERRATION CORRECTING SUBREFLECTORS FOR TOROIDAL REFLECTOR ANTENNAS**

[75] Inventor: **Geoffrey Hyde**, Clarksburg, Md.

[73] Assignee: **Communications Satellite Corporation (COMSAT)**, Washington, D.C.

[22] Filed: **May 31, 1974**

[21] Appl. No.: **475,226**

[52] **U.S. Cl.** **343/761**; 343/779; 343/840

[51] **Int. Cl.²** **H01Q 3/12; H01Q 15/16**

[58] **Field of Search** 343/781, 837, 840, 761, 343/779

[56] **References Cited**

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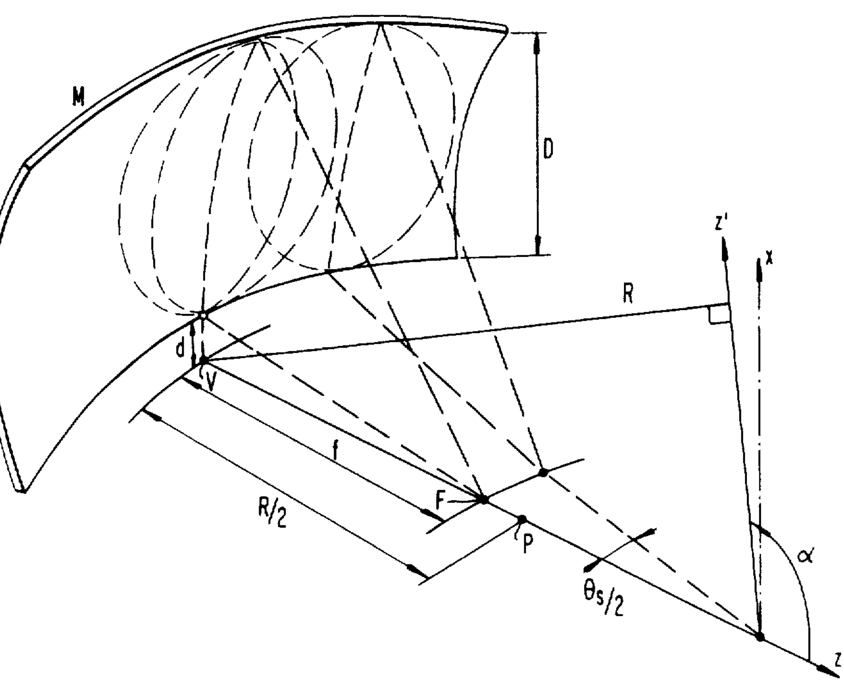
3,737,909	6/1973	Bartlett et al.	343/840
3,828,352	8/1974	Drabowitch et al.	343/837
3,852,763	12/1974	Kreutel et al.	343/840

Primary Examiner—Eli Lieberman
Attorney, Agent, or Firm—Sughrue, Rothwell, Mion, Zinn & Macpeak

[57] **ABSTRACT**

The correction of aberration in toroidal reflector antennas by a novel type of subreflector is disclosed. The specific shape of the subreflector ultimately depends on the geometry of the toroidal reflector. However, in any case, the effect of the subreflector is to achieve a point focus in a system which, without the subreflector, does not focus at a point. Considering the antenna system from a radiation point of view, this is equivalent to turning a non-planar equiphase surface in the aperture into a plane thereby eliminating the phase error about the aperture plane perpendicular to the desired direction of propagation. This is achieved while preserving the wide field of view characteristic of the torus antenna by designing the subreflector so that all pathlengths from a reference plane are constant and equal to a desired reference pathlength. In a practical case, the design of the subreflector is accomplished by developing a heuristic geometric optics model of the focusing properties of the toroidal reflector and using a programmable general purpose digital computer to generate the subreflector shape by numerically computing points on the surface of the subreflector for separate, individual rays intercepted by the toroidal reflector, for a bundle of rays incident from the desired direction. These points may then be used to machine the subreflector surface using well-known numerically controlled milling machines. Of special significance is an optimum antenna configuration using what may be termed a "Cassegorian" subreflector designed according to the principles of the invention having similarities to both Cassegrain and Gregorian subreflectors.

9 Claims, 14 Drawing Figures



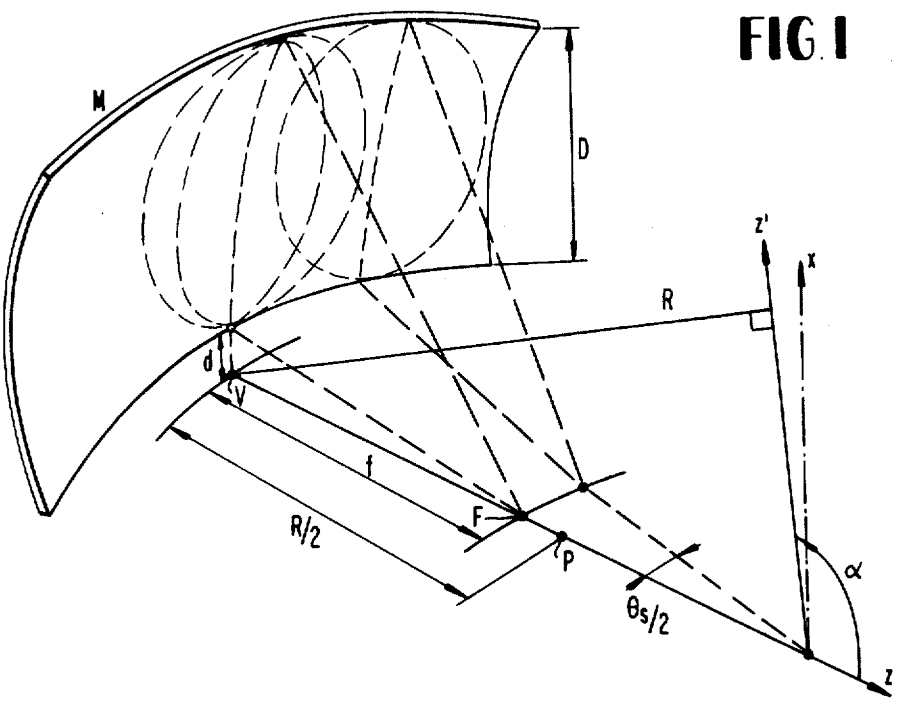


FIG. 1

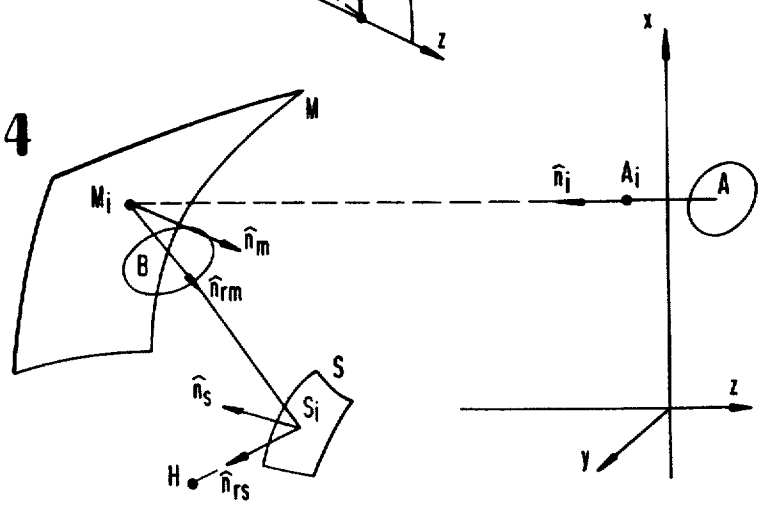


FIG. 4

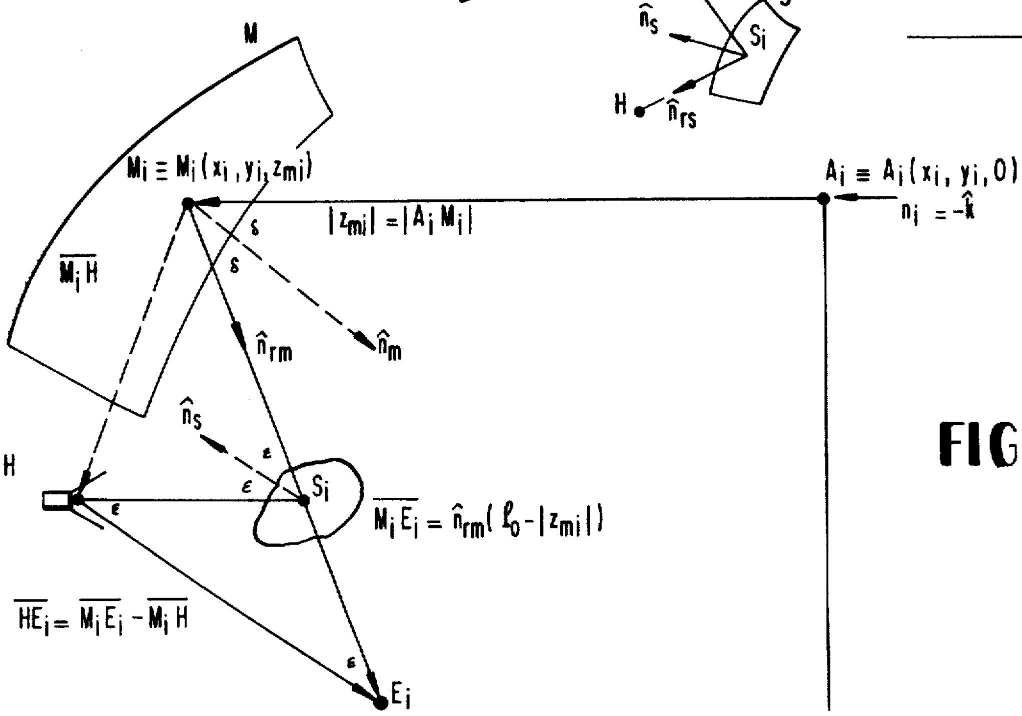
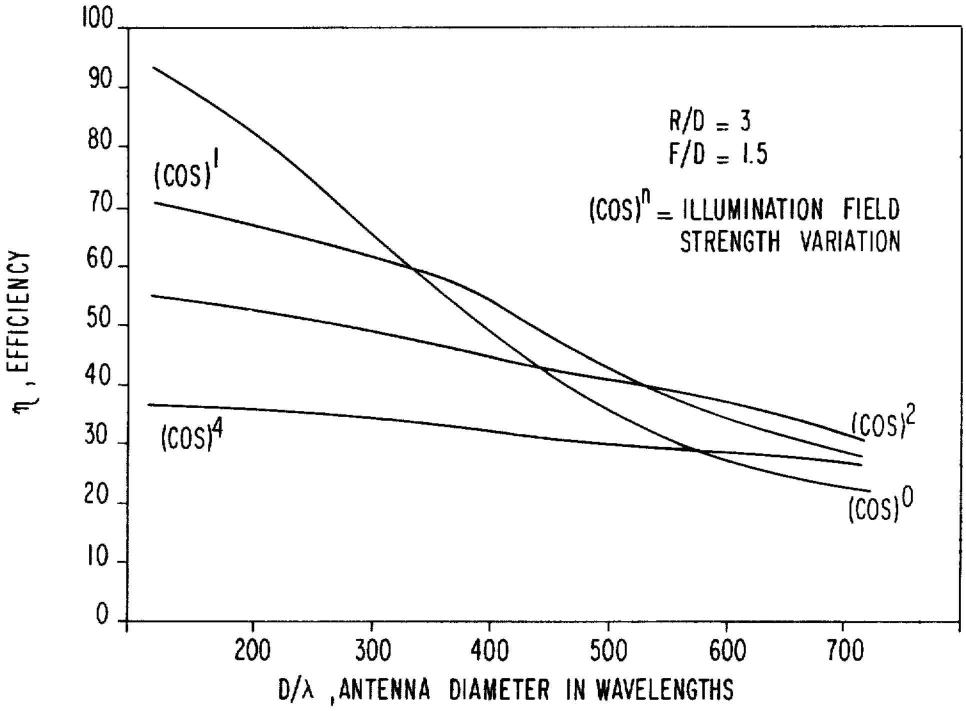


FIG. 5

FIG.2A


100
90
80
70
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40
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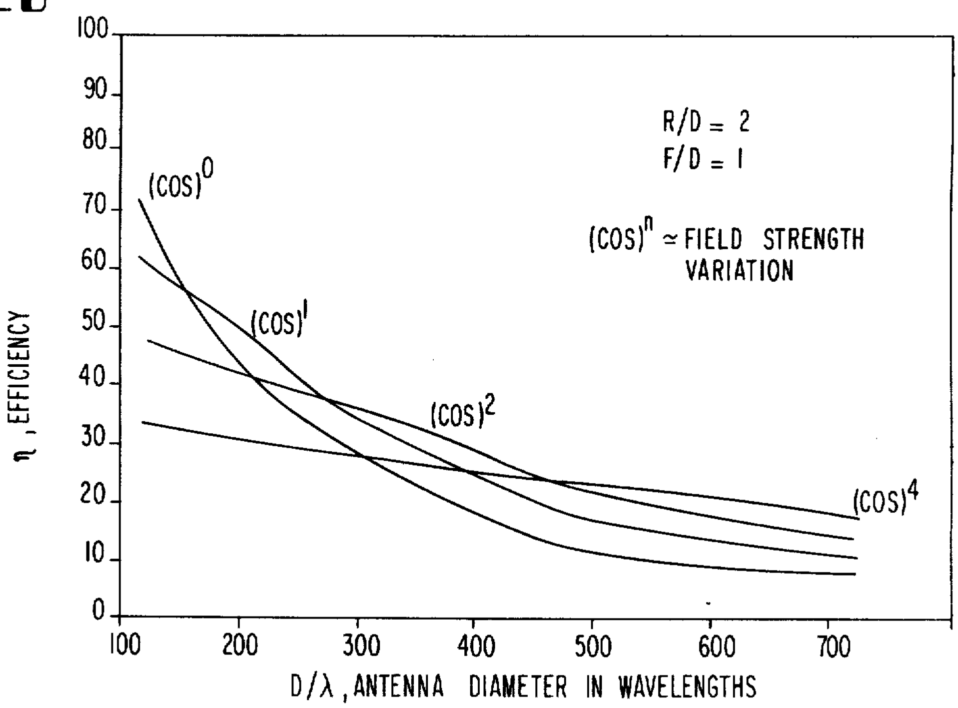
10
0
η, EFFICIENCY
200
300
400
500
600
700
D/λ, ANTENNA DIAMETER IN WAVELENGTHS
R/D = 3
F/D = 1.5
(COS)^n = ILLUMINATION FIELD STRENGTH VARIATION
(COS)^1
(COS)^4
(COS)^2
(COS)^0

FIG.2B


100
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η, EFFICIENCY
100
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500
600
700
D/λ, ANTENNA DIAMETER IN WAVELENGTHS
R/D = 2
F/D = 1
(COS)^n ≃ FIELD STRENGTH VARIATION
(COS)^0
(COS)^1
(COS)^2
(COS)^4

FIG.3A

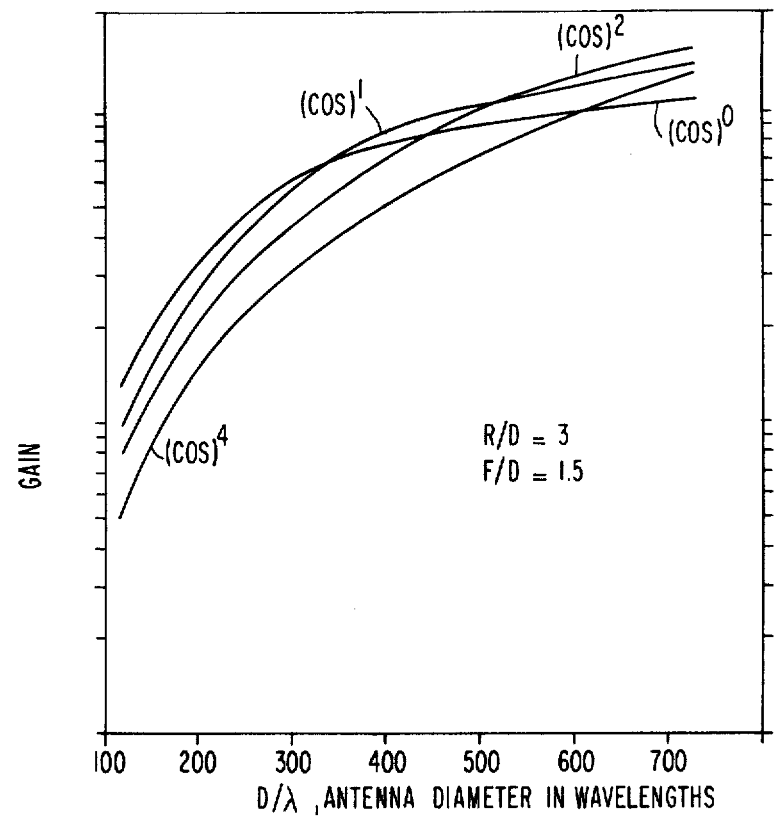
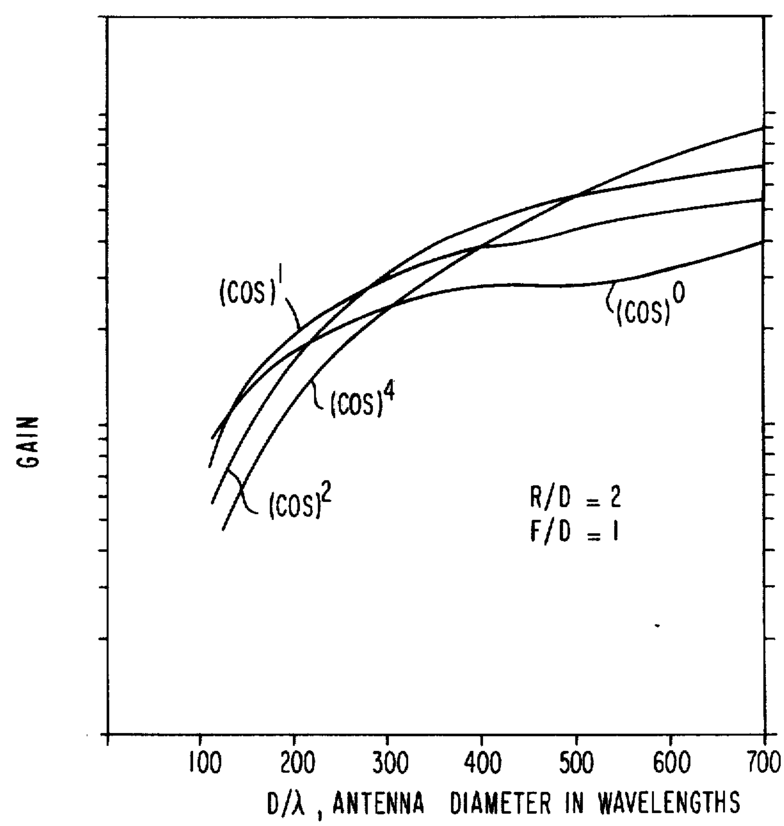

(COS)^2
(COS)^1
(COS)^0
(COS)^4
R/D = 3
F/D = 1.5
GAIN
100
200
300
400
500
600
700
D/λ, ANTENNA DIAMETER IN WAVELENGTHS

FIG.3B


(COS)^1
(COS)^0
(COS)^4
(COS)^2
R/D = 2
F/D = 1
GAIN
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D/λ, ANTENNA DIAMETER IN WAVELENGTHS

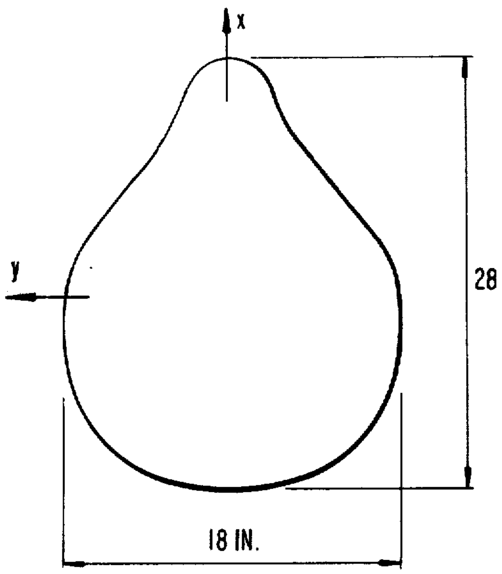


FIG. 6A

FIG. 6C

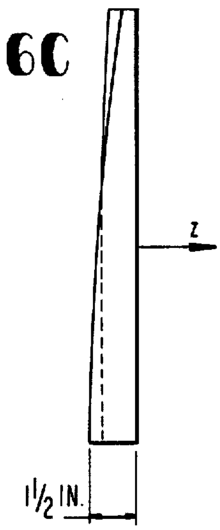


FIG. 6B

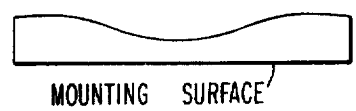
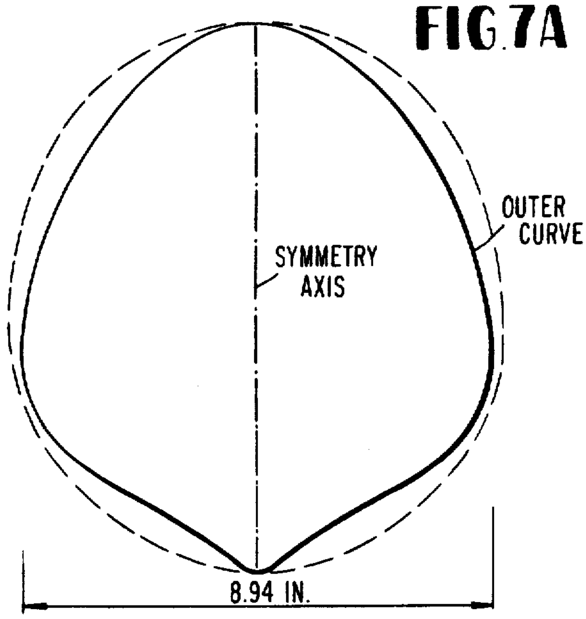


FIG. 7A



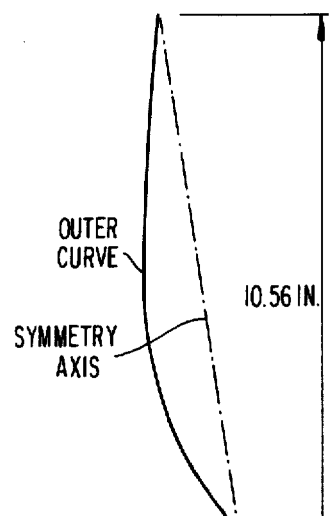


FIG. 7B

FIG. 8A

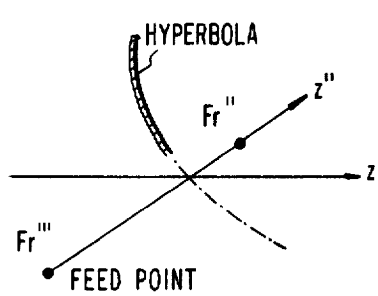
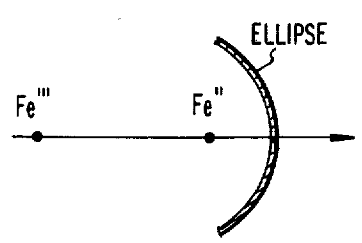


FIG. 8B



ABERRATION CORRECTING SUBREFLECTORS FOR TOROIDAL REFLECTOR ANTENNAS

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention generally relates to toroidal antenna structures and systems, and more particularly to a novel aberration correcting subreflector and design technique useful in both rectangular and non-rectangular toroidal reflector antenna systems.

2. Descriptions of the Prior Art

Simple reflectors useful in a multiple beam environment will, in general, suffer from aberration. That is, a point source cannot be so located to produce a planar wavefront in the reflector aperture perpendicular to the desired beam directions, except for the single exception of the axial beam of the paraboloidal reflector. This aberration is a limitation of the antenna performance.

The problem of aberration is also present in some compound reflectors, such as toroidal reflectors, but because of the complex geometry of toroidal reflectors, a solution of the problem has not before this invention been attempted. A toroidal reflector may be simply defined as a section of a surface of revolution and, typically, the generating curve is a conic section. If the axis of revolution is perpendicular to the axis of the generating curve, then the reflector is a section of a rectangular torus, otherwise it is a section of a non-rectangular torus, otherwise it is a section of a non-rectangular torus. An example of the latter is the subject of U.S. Pat. No. 3,852,763 by Kreutel and Hyde entitled "Torus-Type Antenna Having a Conical Scan Capability".

In order to treat the aberration problem in toroidal antennas, and particularly those having parabolas as generating curves, it is useful to first understand how the toroidal reflector focuses. One approach to this is to consider separately the focusing properties of the generating section and the circular arc about which the generating section is swung, and then to consider the interaction of the two.

A parabolic reflector, as mentioned previously, has perfect focusing properties for axial rays. However, for rays incident slightly non-parallel to the axis, the focus moves in a direction opposite to the deviation from parallel by the incidnet rays to describe a locus of points which define a "best" focus arc. This arc is itself a parabola of focal length one-half that of the parabolic-section of the reflector. As the deviation angle to parallel increases, the focus spreads in a coma-like manner. This is manifested in the far-field pattern by gain loss and by the characteristic coma-lobe on the off-side and a reduced sidelobe on the near side of the off-axis beam of incident rays.

On the other hand, a circular arc provides uniform focusing over a wide angular field, but this desirable result is achieved at the expense of what is known as spherical aberration. The resultant focal region may be characterized as having the possibility that more than one ray passes through a given point. More specifically, in the multiple ray regions, i.e. the region bounded by the marginal rays, the caustic surface and the paraxial focus, more than one ray may pass through a given point. The essential points here are the presence of spherical aberration and the incident angle independence of the focal region distribution. Unlike the parabolic section, which has perfect focusing for rays parallel to the section axis and imperfect focusing for a collimated bundle of rays that are not parallel to the axis, the circular section always has abberration for all directions of the ray bundle. But whereas the aberrations for the parabolic section are a function of the deviation angle, the aberrations arising from a circular section are not a function of direction.

Now by combining the two sections, i.e. the generating parabolic section and the circular section of revolution, a conceptual picture of how the torus focuses may be realized. In such a reflector, the optimum location of the focal point of the parabolic section is located inside the location of the paraxial focus of the circular section. In turn, the optimum feed position turns out to be located just inside the focal point of the parabolic section, with the refocused configuration giving less pathlength variation in the aperture plane than that encountered by putting the feed at the focal point. While this location of optimum feed position minimizes the phase error about an aperture plane perpendicular to the desired direction of propagation, the inherent aberrations of toroidal reflectors severely limits the efficiency of the design of reflectors with electrically larger apertures, i.e. larger D/λ where D is the aperture diameter and λ is the wavelength, measured in the same units.

SUMMARY OF THE INVENTION

It is therefore an object of the present invention to provide an aberration correcting subreflector for toroidal reflector antenna systems and thereby greatly increase the efficiency and the resulting performance of the antenna system for electrically large apertures, while preserving the performance for the smaller apertures.

It is another object of the invention to provide a new feed method for antennas with torus reflectors which corrects incident ray pathlength so that true optical focusing is obtained thereby eliminating aberrations and making the efficiency of such antennas independent of frequency.

The foregoing and other objects of the invention are attained by providing a correcting subreflector which, when illuminated by a feed-horn, reflects energy onto the main toroidal reflector so that a beam is formed to radiate in the desired direction. Alternatively, in reception, incoming rays incident upon the main reflector are reflected onto the subreflector and from it onto the feed-horn, focusing at a point so that the pathlength from a reference plane is equal for all rays. While the specific shape of the correcting subreflector depends on the specific geometry of the main toroidal refelctor, the actual design of the subreflector is achieved by numerical computation of points on the surface of the subreflector for the constraints that (1) all rays focus at a single point, and (2) all pathlengths from a reference plane to the point of focus are constant and equal to a desired reference pathlength.

BRIEF DESCRIPTION OF THE DRAWINGS

The specific nature of the invention, as well as other objects, aspects, uses and advantages thereof, will clearly appear from the following description and the accompanying drawings, in which:

FIG. **1** is a pictorial view illustrating the geometry of a torus antenna;

FIGS. **2A** and **2B** are graphs showing efficiency as a function of antenna diameter in wavelengths with illumination as a parameter for two choices of torus geometry;

FIGS. **3A** and **3B** are graphs showing parabolic torus gain as a function of antenna diameter in wavelengths with illumination as a parameter for the two choices of torus geometry adopted in FIGS. **2A** and **2B**, respectively; FIGS. **2A**, **2B**, **3A**, and **3B** clearly demonstrating the deleterious effects of aberration for electrically larger antennas (larger D/λ);

FIG. **4** illustrates the basic geometric model used to design the surface of the correcting subreflector according to the invention;

FIG. **5** illustrates another geometric model representing the vector equations which define points on the surface of the subreflector according to the invention;

FIGS. **6A**, **6B** and **6C** are, respectively, a plan view and side views of two mutually perpendicular axes of a specific subreflector shape made in accordance with the teaching of the invention;

FIGS. **7A** and **7B** are, respectively, a plan view and a side view of another specific subreflector, herein referred to as a Cassegorian subreflector, made by careful choice of geometric parameters in accordance with the teaching of the invention; and

FIGS. **8A** and **8B** show typical approximate cross-sections of the Cassegorian subreflector shown in FIGS. **7A** and **7B**.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to the drawings, and more particularly to FIG. **1**, there is illustrated the geometry of a typical frontfed toroidal reflector. The specific reflector illustrated is non-rectangular in that $\alpha = 95.5°$, where α is the angle the axis of revolution z' makes with the desired direction of propagation z. This geometry produces a conical scan surface which closely approximates the actual conical surface subtended by an earth station site within the continental and contiguous United States and the geostationary arc as explained in the aforementioned U.S. Pat. No. 3,852,763. Other dimensions useful in defining the specific toroidal reflector illustrated are the offset ratio, $d/D \simeq 0.1$, typically, where d is the vertical distance below the toroidal reflector of a feedhorn and D is the vertical dimension of the toroidal reflector; $3 \leq R/D \leq 2$, where R is the radius of revolution; and $0.48 \leq f/R \leq 0.49$, where f is the focal length of the parabolic generating section. In addition, θ_s is defined as the field-of-view angle at the antenna. The section M through the vertex V, while typically a parabola, may be any other conic section such as a circle, ellipse or hyperbola.

The reflector is formed by rotating the section M about the z' axis. In the specific case illustrated, it should be noted that the axis of the section M is the z axis, which is the desired direction of the beam formed in the region A_o. The optimum projected location of the focal point F of the parabolic section M is located inside the location of the paraxial focus, P. As mentioned previously, the optimum feed position turns out to be located just inside the focal point F, the refocused configuration giving less rms pathlength variation in the aperture plane than that encountered by putting the feed at the focal point.

Because of the circular symmetry, the reflector presents the same shape to, and hence has the same beam forming capability for identical feeds located at all points on the arc described by the rotation of the feed point of the generating curve about the axis of rotation. A single moveable feed or a plurality of selectively energizable feeds located along the feed arc, when illuminating the reflector surface, will form identical beams, the torus of whose axes of beam direction describe the surface of a right circular cone.

The result of this feed positioning is to achieve the best point focus in a system which really does not focus at a point. In the specific example illustrated in FIG. **1**, the desired direction of propagation makes an angle $\alpha = 95.5°$ with the axis of rotation z' so that upon rotation it rules out a very flat right circular cone giving a symmetry to the reflector that yields identical beams in the field of view. The specific purpose of the invention is to turn the equiphase surface mentioned above into a plane while preserving the field of view of the antenna system.

The crux of the problem solved by the invention is that the nonplanar equiphase surface characteristic of the point-fed uncorrected torus is invariant in terms of the physical measurements of the system, while wavelength changes inversely with frequency. Thus, a fixed pathlength departure from the planar condition turns into a phase error that increases with frequency. The consequences of this are shown in FIGS. **2A** and **2B** and FIGS. **3A** and **3B** in terms of efficiency and gain, respectively, as functions of wavelength-normalized antenna diameter D/λ for two choices of R/D. For $D/\lambda < 150$, there is little seen of the effects of aberration, while for $D/\lambda > 300$, it is clear that aberration dominates.

The problem of subreflector correction of pathlength may be simply stated. Given an incoming bundle of rays A, as shown in FIG. **4**, and a reflector M, off which the bundle is reflected, calculate a subreflector S which intercepts the reflected bundle B and reflects it to focus at H. While easy to state, it is by no means clear what the precise limitations under which a physical solution is realizable in all cases. If the condition is imposed that S lie in a region such that no two rays reflected from M intersect at a point in that region, it is clear that the resulting surface S will be physically realizable.

Consider an incoming plane wave characterized by a unit Poynting's vector $\hat{n}_I$, incident on a reflector M, where

$$M \equiv M(x, y, z)$$

where we have chosen our coordinate system such that for a plane wave from a distant source in the desired direction $\hat{n}_I = -\hat{k}$. There is no loss of generality since a simple coordinate rotation of M is all that is required for any other direction. Then the unit normal to $M(x, y, z)$ is given by:

$$\hat{n}_m = \hat{i}\,\frac{\frac{\delta M}{\delta x}}{\left(\sum\limits_{i=x,y,z}\left(\frac{\delta M}{\delta i}\right)^2\right)^{1/2}} + \hat{j}\,\frac{\frac{\delta M}{\delta y}}{\left(\sum\limits_{i=x,y,z}\left(\frac{\delta M}{\delta i}\right)^2\right)^{1/2}} + \hat{k}\,\frac{\frac{\delta M}{\delta z}}{\left(\sum\limits_{i=x,y,z}\left(\frac{\delta M}{\delta i}\right)^2\right)^{1/2}} \quad (1)$$

taking the sign appropriate to the normal on the side of the incident ray. And the reflected vector is given by:

$$\hat{n}_{rm} = \hat{n}_i - 2\hat{n}_m (\hat{n}_i \cdot \hat{n}_m) \qquad (2a)$$

The question now is what is the reflecting surface required to meet the following two conditions:

i. all rays focus at a single point H (x, y, z), and

ii. all pathlengths from a reference plane to H are constant and equal to the desired reference pathlength. This problem can be solved by vector analysis:

From FIG. 4, we may note that

$$\overline{M_iS_i} = C_1\hat{n}_{rm}, \text{ where } C_1 = \text{constant}; \qquad (3)$$

$$\overline{M_iH} = \overline{M_iS_1} + \overline{S_iH}; \qquad (4)$$

$$= C_1\hat{n}_{rm} + C_2\hat{n}_{rs}, \text{ where } C_2 = \text{constant}; \qquad (4a)$$

and finally

$$C_1 + C_2 + |M_iA_i| = l_o, \qquad (5)$$

where l_o is the desired reference pathlength, i.e.

$$C_1 + C_2 = l_o - |M_iA_i|, \text{ and} \qquad (5a)$$

$$\hat{n}_{rs} = \hat{n}_{rm} - 2\hat{n}_s (\hat{n}_s \cdot \hat{n}_{rm}) \qquad (6)$$

From the foregoing, we can make the following observations. Equation (1) tells us we can find the unit normal $\hat{n}_{rm}$ to the surface M. Equation (2) says that if we know this unit normal, and the direction of the incident ray, which is given, we can find the direction of the ray reflected from the surface M, but we do not know its length C_1. Equation (4) tells us that since we know H, the desired focal point, and M_i, the incident point, we know the plane of the two ray segments the first of which is reflected off M at M_i and incident on S at S_i, i.e., $\overline{M_iS_i}$, and the second segment of which is the reflection off S at S_i towards H, i.e., $\overline{S_iH_i}$. An implicit condition is that only one ray is incident on S at each point S_i.

For the incident rays defined by the vector $\hat{n}_i = -\hat{k}$, and the reference plane defined by $z = 0$, then the i^{th} ray pierces the reference plane at $A_i = A_i(x_i, y_i, 0)$ and is incident on the reflector M at $M_i = M_i(x_i, y_i, z_{mi})$, where z_{mi} is the solution of M for $x = x_i$, $y = y_i$, and can therefore be found. The point H is arbitrary and must be given. For our purposes

$$H \equiv H(x_H, y_H, z_H),$$

whence

$$\overline{m_iH} = \hat{i}\,(x_H - x_i) + \hat{j}\,(y_H - y_i) + \hat{k}\,(z_H - z_{mi}),$$

which can readily be determined.

Substituting Equation (6) into Equation (4a),

$$M_iH = (C_1 + C_2)\,\hat{n}_{rm} - 2C_2\hat{n}_s\,(\hat{n}_s \cdot \hat{n}_{rm}).$$

Forming the scalar product $\overline{M_iH} \cdot \hat{n}_{rm}$, and using Equation (5), one obtains successively

$$\hat{n}_{rm} \,.\, \overline{M_iH} = C_1 + C_2 - 2C_2\,(\hat{n}_s \,.\, \hat{n}_{rm})^2, \text{ and}$$

$$C_2 = \frac{1}{2(\hat{n}_s \,.\, \hat{n}_{rm})^2}[l_o - |z_{mi}| - n_{rm} \,.\, \overline{M_i H}], \text{ whence} \qquad (5b)$$

$$\overline{M_iH} = (l_o - |z_{mi}|)\hat{n}_{rm} - \frac{\hat{n}_s(l_o - |z_{mi}| - \hat{n}_{rm} \cdot M_iH)}{\hat{n}_s \cdot \hat{n}_{rm}}$$

Thus,

$$\frac{\hat{n}_s}{\hat{n}_s \cdot \hat{n}_{rm}} = \frac{(l_o - |z_{mi}|)\,\hat{n}_{rm} - \overline{M_iH}}{l_o - |z_{mi}| - \hat{n}_{rm} \cdot \overline{M_iH}} \qquad (7)$$

$$= \hat{i}\,u_s' + v_s' + \hat{k}\,w_s'$$

Then, since $\hat{n}_s$ is a unit vector,

$$(n_s . n_{rm})^2 = (u_s'^2 + v_s'^2 + w_s'^2)^{-1}$$

$$= \frac{(l_o - |z_{mi}| - \hat{n}_{rm} \cdot \overline{M_iH})^2}{(l_o - |z_{mi}|)^2 + |\overline{M_iH}|^2 - 2\,\hat{n}_{rm} \cdot \overline{M_iH}\; l_o - |z_{mi}|} \qquad (8)$$

Finally,

$$\hat{n}_s = \pm \frac{(l_o - |z_{mi}|)\hat{n}_{rm} - \overline{M_iH}}{(l_o - |z_{mi}|)^2 + |\overline{M_iH}|^2 - 2(\hat{n}_{rm} \cdot \overline{M_iH})\,(l_o - |z_{mi}|)^{1/2}} \qquad (7a)$$

and all the vectors in the system can now be found.

Substituting from Equation (8) into Equation (5b), C_2 can be determined. Then, noting that $|M_iA_i| = |z_{mi}|$, C_1 is calculated using Equation (5a), and the point on the subreflector is now completely established.

Returning for a moment to Equation (7), if we examine this equation geometrically as shown in FIG. 5, the simplicity of the scheme is self-evident. If l_o is the reference pathlength, then $l_o - |z_{mi}|$ is the remainder after the ray incident in the aperture plane at A_i strikes the main reflector at M_i. Then $\overline{M_iE_i}$ is a vector of length $l_o - z_{mi}$ in the direction of the reflection, $\hat{n}_{rm}$, of the incident vector, $\hat{n}_i$. Also $\overline{HE_i} = \overline{M_iE_i} - \overline{M_iH}$. Hence,

$$\overline{HE_i} = \hat{n}_{rm}\,(l_o - |z_{mi}|) - \overline{M_iH}.$$

But this is the numerator of Equation (7a), and the denominator is only a constant. Hence, $\overline{HE_i}$ and $\hat{n}_s$ are parallel (or antiparallel). This is immediately verified by the geometry of FIG. 5. $\overline{A_iM_i}$, $\hat{n}_{rm}$ and $\overline{M_iE_i}$ lie in the same plane, by the laws of geometric optics. Similarly, $\overline{M_iS_i}$, $\hat{n}_s$ and $\overline{S_iH}$ lie in the same plane. Further, since

$$l_o = |z_{mi}| + |M_iS_i| + |S_iH|$$

$$= |z_{mi}| + |M_iE_i| = |z_{mi}| + |M_iS_i| + |S_iE_i|,$$

then

$$|S_iH| = |S_iE_i|$$

Hence, the ΔHS_iE_i is isoceles and the equal angles ϵ are equal to the angles of incidence and reflection at S_i. Whence it is seen that the line HE_i is parallel to $\hat{n}_s$.

Further

$$\cos\epsilon = \frac{\overline{HE_i}\;\overline{M_iE_i}}{|HE_i|\;|M_iE_i|}$$

which is calculable, and

$$|S_iH|^2 = \tfrac{1}{2}\,|HE_i|^2 / (1 + \cos 2\epsilon).$$

What the above analysis shows is that the choice of $\hat{n}_i$, the incident wave, M, the main reflector, H, the feed-horn location and l_o, the reference pathlength has given us a deterministic situation for which a point S_i can always be found. It remains only to be certain that one and only one reflected ray can pass through each S_i. This can be accomplished by tracing rays from A into the region of S, either by hand or by computer, and seeing if rays cross before they reach S. Equally effective is to generate S and see if it is a single-layered surface. In practice, it is this latter path which has been followed. More specifically, by suitably programming a general purpose digital computer to perform the numerical computations outlined above, a sufficient number of points S_i on the surface of the subreflector can be determined to accurately define the surface. These points are then used as the inputs to a numerically controlled milling machine to machine the subreflector.

Since the main reflector, M, is the same as that described in the aforementioned U.S. Pat. No. 3,852,753, a single moveable feed assembly consisting of a horn, H, and subreflector S, or a plurality of such feed assemblies located along an arc about the axis of rotation, z', of the main reflector will form identical beams. Moreover, each such feed assembly will provide aberration free beams in scanning.

FIGS. 6A, 6B and 6C show a specific subreflector designed according to the invention for a non-rectangular toroidal antenna system having a 10-foot aperture and dimensional ratios of $f/R \simeq 0.487$ and $R/D \simeq 2$. This subreflector is hyperbolic along the x-axis (the axis of symmetry) and departs from this off the x-axis. In a test at 29.95 GHz, this subreflector improved the gain of the antenna system achieved by conventional means by 2dB, from 54dB to 56dB, and the efficiency from about 28% to about 45% aperture efficiency.

While the improvements realized with the subreflector shown in FIGS. **6A**, **6B** and **6C** are significant, by changing the dimensional parameters of the main toroidal reflector, a more optimum antenna configuration can be realized which achieves an aperture efficiency in excess of 70%. Specifically, for a main toroidal reflector having the dimensional ratio of $f/R \simeq 0.54$, a "Cassegorian" subreflector results for the design procedure according to the invention. Such a subreflector is shown in FIGS. **7A** and **7B**. The name "Cassegorian" was coined because the subreflector has cross-sectional shapes which resemble a subreflector having a hyperbolic section shown in FIG. **8A** and used in Cassegrain systems, and a subreflector having an elliptic section as shown in FIG. **8B** and used in Gregorian systems. Its shape arises due to a careful choice of the parameters f/R, $f/R > 0.5$ (actually $f/R = 0.56$ for the example shown), and the subreflector vertex pathlength such that the vertex lies between F and P. When these parameters and the feed point H are chosen carefully, the resulting subreflector (for a circular aperture of diameter D) is reasonably close to a circle when viewed from H, which is a requirement for efficient feeding.

Because the new feed method according to the invention corrects pathlength so that true optical focusing is obtained, there is not aberration in the antenna system, and the efficiency is independent of frequency. This permits the development of antennas which have high efficiency independent of frequency. For example, a toroidal reflector antenna system can be designed for use at **4, 6, 12, 14, 20** and **30** GHz by use of appropriate feedhorns, without changing the optics of the system.

It will be apparent that the embodiments shown are only exemplary and that various modifications can be made in construction and arrangement within the scope of the invention as defined in the appended claims.

What is claimed is:

1. In a toroidal reflector antenna system including a main reflector having the shape of a surface section of a torus of revolution and a feed-horn assembly positioned to illuminate said main reflector and thereby form beams in the desired directions of propagation, the improvement comprising an aberration correcting subreflector interposed between said main reflector and said feed-horn and forming a feed assembly with said feed-horn, the surface of said subreflector being nonconcentric with said main reflector and so designed that for the aberration correcting surface of said subreflector only one ray is incident on the surface at each point thereon, substantially all rays focus at a single point at said feed-horn and substantially all ray pathlengths from a reference aperture plane to said single point of focus are constant and equal to a predetermined reference pathlength, whereby said system is free of aberration and the efficiency of said system is independent of frequency, said feed assembly further being movable along an arc about the axis of revolution of said main reflector to provide substantially aberration free beams in scanning.

2. The improved antenna system as recited in claim **1** wherein said torus of revolution has a generating curve which is a conic section.

3. The improved antenna system as recited in claim **2** wherein said generating curve is a parabola.

4. The improved antenna system as recited in claim **3** wherein said main reflector is a surface section of a nonrectangular torus, said antenna system having a conical scan capability to scan along the geostationary arc.

5. The improved antenna system as recited in claim **4** wherein the angle between the axis of revolution of said torus and direction of said beam is 95.5°.

6. The improved antenna system as recited in claim **5** wherein said main reflector has the dimensional ratios $f/R \simeq 0.5$ and $R/D \simeq 2$ where f is the focal length of the parabola generating section, R is the radius of revolution, and D is the aperture of said main reflector measured parallel to the axis of revolution and said subreflector is hyperbolic along the axis of symmetry and departs from hyperbolic of the axis of symmetry in such a manner as to preserve the two essential properties of focusing all rays at the desired focal point with the desired pathlength.

7. The improved antenna system as recited in claim **6** wherein the dimensional ratio $f/R < 0.5$.

8. The improved antenna system as recited in claim **6** wherein the dimensional ratio $f/R > 0.5$ and the vertex of the subreflector is chosen to lie between the projection of the paraxial focus P and the focal point F and the feed point is chosen so that the subreflector formed by a circular pencil of rays incident on the aperture D approximates a circle when viewed from the feed point.

9. The improved antenna system as recited in claim **8** wherein said main reflector has the dimensional ratios of $f/R \simeq 0.56$ and $R/D \simeq 2$ where f is the focal length of the parabola generating section, R is the radius of revolution, and D is the length of said main reflector measured parallel to the axis of revolution, and said subreflector has a cross section which resembles an elliptic section along an axis chosen perpendicular to the axis of symmetry.

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