Sept. 18, 1962 K. M. SIEGEL 3,055,005

OMNIDIRECTIONAL RADIO WAVE REFLECTOR IN FORM OF A LUNEBERG LENS

Filed May 2, 1960

FIG. 1

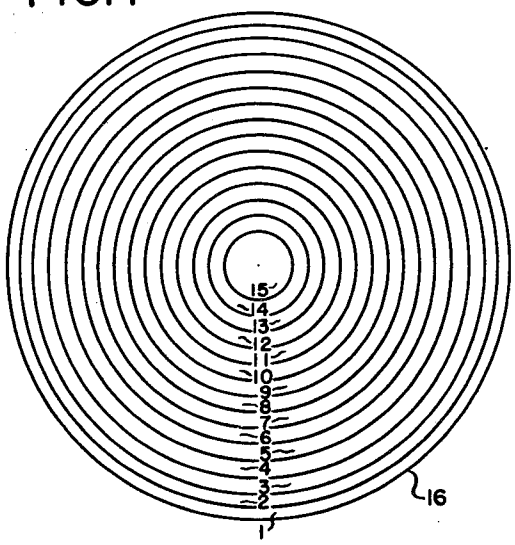



FIG. 2

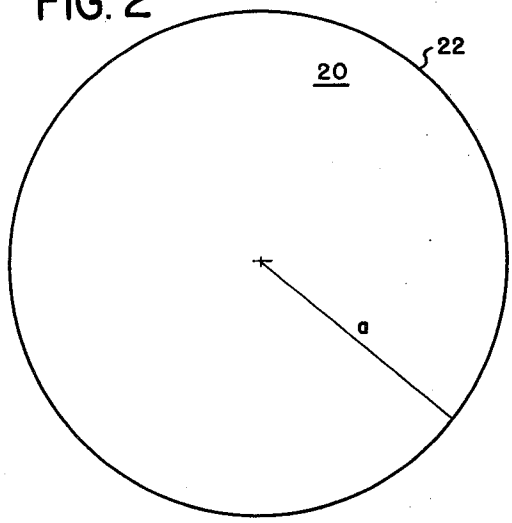



FIG. 3

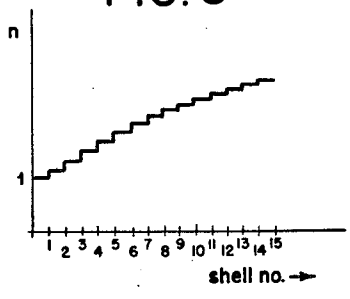



FIG. 4

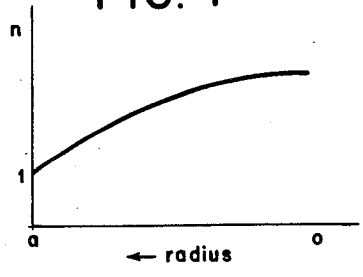
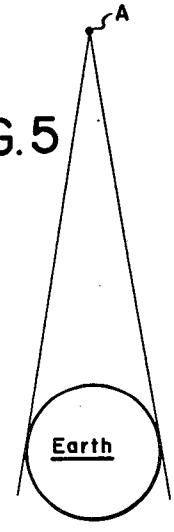



FIG. 5




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# OMNIDIRECTIONAL RADIO WAVE REFLECTOR IN FORM OF A LUNEBERG LENS

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This invention relates to radio communication, and more particularly to an antenna provided for reception and automatic reradiation of electromagnetic wave energy. This invention provides an antenna in the form of a satellite intended to rotate about the earth in an orbit and which will reradiate toward the earth energy radiated from a radio transmitter on the earth and intercepted by the antenna. The antenna of the invention is spherical or substantially spherical in shape, possesses radial symmetry, and has the property of directively reflecting, with partial reflectivity, electromagnetic waves which are incident upon it, its directivity being controlled in accordance with the principles of the invention.

The antenna of the invention comprises a spherical body of material having a uniform partial reflectivity to electromagnetic waves over its surface and in which the index of refraction for electromagnetic waves varies with radial position from a value of unity at or benath the surface to a somewhat higher value at the center. The partial reflectivity to electromagnetic waves may be given to the body by the application to its surface of a coating having limited electrical conductivity.

This variation in the index of refraction imparts to the antenna a focusing property with respect to energy which enters it, and in conjunction with the partially reflecting coating it results in a focussed reflection of electromagnetic wave energy incident on the antenna.

Thus in the case of radiation having plane or nearly plane wave fronts intercepted by the antenna, the antenna provides partial reflection in a substantially conical beam, the aperture of which is controllable in accordance with the invention.

The antenna may be made of cellular foam materials such as polystyrene, the index of refraction being controlled by the incorporation of finely divided metallic particles therein. While the index may vary continuously from the outside to the center of the antenna, it may also vary in a number of discrete steps, the antenna being made up of a plurality of spherical shells each of constant or substantially constant index.

In a preferred embodiment the antenna is made to possess maximum reflectivity over a cone having a half angle of some 8.5°. With the antenna in an orbit parallel to the earth's equator at an altitude of approximately 22,000 miles above the earth, a cone of 17° total angle with the antenna at its apex and with its axis passing from the antenna to the center of the earth will be tangent to the surface of the earth. Radiation from a transmitter on the surface of the earth in the vicinity of the intersection of this axis with the earth will, when intercepted by the antenna, be reflected over that portion of the earth's surface between the circle of tangency and the antenna, and maximum reflectivity over a cone of 17° aperture maximizes the signal returned by the antenna to the earth. A satellite at this altitude will have an orbit time of 24 hours, and will therefore to a first approximation occupy a fixed position with respect to the earth.

It has been proposed heretofore to construct a reflector of electromagnetic waves in the form of a spherical volume of material having an index of refraction $n$ varying from unity at the surface to the square root of two at the center in accordance with the relation

$$n^2=2-\frac{r^2}{a^2} \qquad (1)$$



wherein $r$ is radial position measured from the center of the sphere and $a$ is the radius of the sphere. A plane electromagnetic wave incident on such a device will be focussed to a point on the surface of the sphere opposite that on which the wave is incident, the point of focus being the intersection with the back surface of the sphere of the radius of the sphere which is parallel to the direction of propagation of the wave. If the surface of the sphere is made totally reflecting at this point, the portion of the plane wave front intercepted by the sphere will be reradiated back toward the source as a highly collimated beam. It has also been proposed in such a device to make the index of refraction $n$ vary as a function of radial position $r$ from the center according to the relation

$$n^2=1+\alpha\left(1-\frac{r^2}{a^2}\right) \qquad (2)$$

in which $\alpha$ is a number between zero and unity. If $\alpha$ has such a value, and if the sphere is made totally reflecting over the hemisphere away from the source, the result will be reradiation of a divergent beam, the amount of the divergence varying inversely with the value of $\alpha$.

Both of these proposals of the prior art are however unsuitable for the purpose to which the present invention is addressed because of their lack of radial symmetry. It is undesirable to require that the satellite shall maintain a fixed orientation about its own axes of rotation with respect to the earth.

In accordance with the present invention instead, the reflection is made uniform over the entire surface of the sphere at a value between zero and unity which is preferably at or near one-third, and the index of refraction is made to increase from unity at the surface to a value at the center determined by relation 2, in which $\alpha$ is given a value appropriate to the solid angle of the cone over which maximum reflection is desired.

The invention will now be further described with reference to the accompanying drawings, in which

FIGS. 1 and 2 are sectional views of two antennas according to the invention;

FIGS. 3 and 4 are graphs relating respectively to the antennas of FIGS. 1 and 2; and

FIG. 5 is a diagram, not drawn to scale, illustrating the relation to the earth of an antenna according to one embodiment of the invention.

The antenna of FIG. 1 comprises a plurality of concentric spherical shells 1 to 15 of cellular foam material, for example polystyrene, in which the holes or voids are small compared to the wavelength of the radiation intended to be reflected from the antenna, and into which suitable amounts of finely divided electrically conducting material such as metallic powder has been incorporated. The shells 1 to 15 are of increasing index, from the outermost shell 1 to the innermost shell 15, approximately in accordance with the relation

$$n^2=1+\alpha\left(1-\frac{r^2}{a^2}\right) \qquad (2)$$

in which $n$ is the index of refraction of the material of which the shells are made, $a$ is the radius of the outermost shell, $r$ is the mean radius of the shell in question and $\alpha$ is a coefficient having a value between zero and one, constant for a given antenna. As will be explained presently, a preferred value for the coefficient $\alpha$ is approximately 0.865. The innermost shell 15 may be given an index of refraction $n=\sqrt{1+.865}$ or approximately 1.36, while the outermost shell may have an index of refraction of unitv or slightly more than unity.

The index values for the various shells will be established by suitable choice of materials therefor, and in particular, in the case of shells made of polystyrene foam

or the like, by proper proportioning of the amount of added metallic powder in view of wavelength of the radiation for whose reflection the antenna is to be employed. This wavelength may for example correspond to the so-called $x$-band of frequencies in the vicinity of 10,000 megacycles per second. The addition of metallic powder increases the index of refraction of the cellular plastic foam material. The proportioning of metallic powder to the cellular plastic foam material to achieve desired values of index of refraction at specified frequencies may be carried out according to known methods. See for example the article by K. S. Kelleher at pages 138 to 142 of Electronics for June 1956.

Alternatively, one may start with a material whose index of refraction in the massive state is higher than is desired, and reduce it to the desired value by creating voids therein.

The variation in index with radial position in the antenna of FIG. 1 is illustrated in FIG. 3, where index of refraction is plotted vertically and radial position horizontally, in terms of the shells **1** to **15**, beginning at the left with the outermost shell **1** and proceeding toward the right to the innermost shell **15**.

Of course, the antenna of the invention is not restricted, when made with spherical shells each of substantially uniform index, to the number of fifteen shells shown in the embodiment of FIG. 1. The number of shells may be either greater or smaller.

The outer surface of the antenna of FIG. 1 is provided with a partially reflecting coating **16**, uniform over the entire surface, and providing to that surface a coefficient of power reflection of substantially one-third. The coating **16** may take the form of a paint including a pigment having relatively poor electrical conductivity. The desired value of reflectivity may be obtained by laying down successive coats of such a paint, each of which provides a small increment in reflectivity, until the desired reflectivity is reached.

The antenna of FIG. 1 is shown at point A in FIG. 5 in its relation to the earth. If the antenna rotates about the earth at an altitude of 22,000 miles in a plane parallel to that of the earth's equator, it will occupy a stationary position with respect to the earth, at which it will subtend a cone of about 17°.

The antenna of FIG. 1 may be built to any appropriate size, which should however give to it a radius large in comparison to the wavelength of the radiation to be reflected therefrom. A radius of 50 feet will be ample for radiation in the 3 cm. wavelength range.

The efficacy of the antennas of the invention in reflecting energy incident thereon may be described in terms of their radar cross-section $\sigma$, for example as defined in the radar equation as given at page 21 of Vol. I of the M.I.T. Radiation Laboratory Series, McGraw Hill, 1947. Specifically, the radar cross-section $\sigma$ of the antennas of the invention may be compared to the radar cross-section $\sigma_s$ of a perfectly conducting sphere of the same radius, and to the radar cross section $\sigma_L$ of an antenna of the prior art comprising a sphere of the same radius in which the index conforms to relation 1 (or to relation 2 in which $\alpha=1$) and which has a reflectivity of zero over the hemisphere facing the transmitter and a reflectivity of unity over the hemisphere away from the transmitter.

The antenna of FIG. 1, if constructed to possess for energy of a given wavelength an index of refraction according to relation 2 in which the coefficient $\alpha$ possesses a value of approximately 0.865 and a surface power reflectivity of one-third, will provide for energy of that wavelength incident on it an effective cross-section $\sigma$ related to the effective cross-section $\sigma_s$ of a perfectly conducting sphere of the same outside diameter as a function of the angular separation $\beta$ subtended at the antenna by the transmitting and receiving stations, approximately according to the values given in the following table:

*Table 1*

| $\beta$ | 0° | 2° | 4° | 6° | 8.5° |
|---|---|---|---|---|---|
| $\sigma$ | $28\sigma_s$ | $25\sigma_s$ | $19\sigma_s$ | $12\sigma_s$ | $6.8\sigma_s$ |

FIG. 2 illustrated another form of antenna according to the invention. In this embodiment the antenna comprises a spherical mass **20** of cellular foam material and a partially reflecting coating **22**. The index of refraction $n$ of the mass varies uniformly from approximately unity at the outside to a value of approximately $n=\sqrt{1+\alpha}$ at the center, in accordance with the relation

$$n^2=1+\alpha\left(1-\frac{r^2}{a^2}\right) \tag{2}$$

wherein $a$ is the radius of the sphere, $r$ is radial position measured from the center of the sphere, and $\alpha$ is the coefficient of value between zero and unity, preferably in the vicinity of 0.865. The coating **22** may be similar to the coating **16** in the embodiment of FIG. 1. The variation in index with radial position in the embodiment of FIG. 2 is shown graphically in FIG. 4.

The antenna of the invention preferably possesses a reflectivity or power reflection coefficient of one-third because, for radiation of wavelengths small compared to the outer diameter of the antenna, that value of reflection coefficient maximizes the effective cross-section of the antenna to radiation from the transmitter as seen at the receiver.

For a power reflection coefficient R and a power transmission coefficient $T=1-R$, the cross-section of the antenna of the invention as to radiation back-scattered in the direction of the transmitter is:

$$\sigma=TRT\sigma_L+(1-T)\sigma_s \tag{3}$$

assuming the antenna to conform to relation 2 with $\alpha=1$.

The term $TRT\sigma_L$ in expression 3 represents that portion of the energy received upon the antenna of the invention which penetrates the spherical mass of the antenna, is partially reflected on the side thereof away from the transmitter, and partially transmitted back toward the transmitter through the face of the antenna toward the receiver. The term $(1-T)\sigma_s$ represents that part which is reflected upon striking the side of the antenna toward the receiver.

Maximizing the expression 3 with respect to T gives for T the value

$$T=\frac{1}{3}(1\pm\sqrt{1-(3\sigma_s/\sigma_L)}) \tag{4}$$

For $a\gg\lambda$, $\sigma_s$ has the value $\pi a^2$ and $\sigma_L$ has the value

$$\frac{4\pi^3a^4}{\lambda^2}$$

Hence,

$$T=\frac{1}{3}\left(1+\sqrt{1-\frac{3\lambda^2}{4\pi^2a^2}}\right)$$

When, as is desirable, $a\gg\lambda$, $T\sim 2/3$. Applying a value $T=2/3$ to Equation 3 gives

$$\sigma=\frac{4}{27}\sigma_L+\frac{1}{3}\pi a^2 \tag{5}$$

Relation 5 may also be written in slightly modified form to describe the radar cross-section $\sigma(\beta)$ of the antenna of the invention for non-zero values of the angle $\beta$ between the transmitter and receiver. $\sigma(\beta)$ may be set forth in terms of the radar cross-section $\sigma_L(\beta)$ at the same angle $\beta$ of a reflector of the prior art having the form of a sphere of the same radius in which index varies according to relation 2 with $\alpha<1$ and having zero reflectivity over the hemisphere facing the transmitter and unit

reflectivity over the hemisphere away from the transmitter. The value of $\sigma(\beta)$ is then given by

$$\sigma(\beta)=\frac{4}{27}\sigma_L(\beta)+\frac{1}{3}\pi a^2 \quad (6)$$

Normalizing Equation 6 to the radar cross-section $\sigma_s=\pi a^2$ of a perfectly conducting sphere of radius $a\gg\lambda$, which cross-section is uniform for all values of $\beta$ from 0 on to at least 90° (so that the last term on the right-hand side of Equation 6 is the same as the last term on the right-hand side of Equation 5), gives

$$\frac{\sigma(\beta)}{\pi a^2}=\frac{4}{27}\frac{\sigma_L(\beta)}{\pi a^2}+\frac{1}{3} \quad (7)$$

The quantity

$$\frac{\sigma_L(\beta)}{\pi a^2}$$

is given by the relation

$$\frac{\sigma_L(\beta)}{\pi a^2}=\frac{(1-\alpha^2)^2}{(1+\alpha^2-2\alpha\cos\beta)^2} \quad (8)$$

The value of Equation 8 can be computed for various values of the parameter $\alpha$ and for various values of the angle $\beta$. Representative values are given in the accompanying table:

*Table 2*

$\sigma_L(\beta)/\pi a^2$ vs. $\beta$

| $\alpha$ \ $\beta$ | 0 | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| .519 | 10 | 9.9 | 9.8 | 9.5 | 9.2 | 8.8 | 8.3 | 7.8 | 7.3 | 6.7 | 6.2 |
| .634 | 20 | 19.6 | 19 | 18 | 16.8 | 15.2 | 13.8 | 12.4 | 10.8 | 9.2 | 8.0 |
| .691 | 30 | 29.1 | 27.2 | 25.2 | 23.4 | 20.1 | 17.4 | 15 | 12.6 | 10.2 | 8.4 |
| .752 | 50 | 46.5 | 44 | 38.5 | 32 | 26.5 | 21.3 | 16.8 | 13 | 10.5 | 8.8 |
| .818 | 100 | 92 | 78 | 61 | 46 | 32.5 | 23 | 16.2 | 11 | 8 | 5.8 |
| .865 | 190 | 167 | 125 | 81.7 | 51.3 | 32.3 | 19 | 12.9 | 8.6 | 5.9 | 4.3 |
| .929 | 756 | 476 | 197 | 83.2 | 35.5 | 16.6 | 9.1 | 5.0 | 3.0 | 2.0 | 1.5 |
| .960 | 2,400 | 802 | 156 | 41.9 | 14.9 | 6.5 | 3.2 | 1.9 | 1.1 | .67 | .45 |

In view of Equation 7, the values of Table 2 multiplied by

$$\frac{4}{27}$$

will give the approximate value of the radar cross-section of the antenna of the invention, for various values of $\alpha$ and $\beta$, as multiples of the radar cross-section $\pi a^2$ of a perfectly conducting sphere of the same radius. A value of $\alpha$ of 0.865 is seen from Table 2 to give the most nearly uniform distribution of energy out to angles $\beta$ of the order of 8°. This value of $\alpha$ moreover gives the highest absolute value to the ratio

$$\frac{\sigma_L(\beta)}{\pi a^2}$$

for a maximum $\beta$ of approximately 8°.

Even for $\alpha=1$, the invention provides an antenna which is rotationally symmetric and which provides an enormously higher radar cross-section for back scattering to the transmitter (i.e. at $\beta=0$) than a perfectly conducting sphere which is the rotationally symmetric antenna of the prior art.

In the non-rotationally symmetric reflector of the prior art having an index conforming to relation 1, zero reflectivity over the hemisphere adjacent the transmitter and unit reflectivity over the other hemisphere, the radar cross-section for back scattering in the direction of the transmitter, which may conveniently be called $\sigma_{L1}(0)$ is

$$\sigma_{L1}(0)=\frac{4\pi^3a^4}{\lambda^2}$$

Hence relation 6 takes the form

$$\sigma_{\alpha=1}=\frac{16}{27}\frac{\pi a^2\pi^2a^2}{\lambda^2}+\frac{1}{3}\pi a^2$$



or

$$\frac{\sigma_{\alpha=1}}{\sigma_s}=\frac{16}{27}\frac{\pi^2a^2}{\lambda^2}+\frac{1}{3}$$

If $a$ equals 50 feet and $\lambda$ equals 0.1 foot, the ratio

$$\frac{\sigma_{\alpha=1}}{\sigma_s}$$

has a value of the order of $10^7$.

I claim:

1. An antenna comprising a substantially spherical mass of material having an index of refraction for electromagnetic waves varying between unity at the surface and a maximum of the square root of two at the center, and a substantially uniform partially reflecting coating for electromagnetic waves over said mass, said coating being of spherical shape and enclosing said mass and having a power reflectivity substantially less than unity.

2. An antenna comprising a substantially spherical mass of material having an index of refraction $n$ for electromagnetic waves varying substantially according to the relation:

$$n=\sqrt{1+\alpha\left(1-\frac{r^2}{a^2}\right)}$$

wherein $a$ is the radius of said mass, $r$ is radial position within said mass measured from the center thereof, and $\alpha$ is a constant having a value between zero and unity, said antenna having a uniform partially reflecting coating for electromagnetic waves over the surface thereof, said coating being of spherical shape and enclosing said mass and having a power reflectivity substantially less than unity.

3. An antenna according to claim 2 in which the power reflectivity of said coating is substantially one-third.

4. An antenna according to claim 2 in which said constant $\alpha$ has substantially the value 0.865.

5. An antenna according to claim 2 in which the power reflectivity of said coating is substantially one-third and in which the constant $\alpha$ has a value of substantially 0.865.

6. An antenna comprising a substantially spherical mass of material having for high frequency electromagnetic waves of a selected frequency an index of refraction varying between substantially unity at the surface of said mass and substantially $\sqrt{1+\alpha}$ at the center of said mass, $\alpha$ being a constant having a value between zero and unity, and a substantially uniform partially reflecting coating for waves of said frequency over the surface of said mass, said coating being of spherical shape and enclosing said mass and having for waves of said frequency a power reflectivity substantially less than unity, said antenna possessing radial symmetry and the radius of said mass being large compared to the wavelength in free space of electromagnetic energy of said selected frequency.

7. An antenna comprising a plurality of concentric spherical shells of material, each of said shells having a distinct index of refraction for electromagnetic waves, and a uniform partially reflecting coating for electromagnetic waves over the entire surface of the outermost of said shells, the power reflectivity of said coating being substantially less than unity, the indices of refraction of said shells increasing progressively from the outermost to the innermost.

8. An antenna comprising a plurality of concentric spherical shells of material, each of said shells having a distinct index of refraction for electromagnetic waves, and a uniform partially reflecting coating over the entire surface of the outermost of said shells, the power reflectivity of said coating being substantially less than unity, the outermost of said shells having an index of refraction of substantially unity, others of said shells having progressively higher indices of refraction toward the

center, the innermost of said shells having an index of refraction not substantially exceeding 1.414.

9. An antenna according to claim 8 in which the index of refraction of the innermost of said shells is substantially 1.36 and in which the power reflectivity of said coating is substantially one-third.



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