Oct. 7, 1969 H. A. ROSEN Re. 26,680
APPARATUS PROVIDING A ROTATING DIRECTIVE ANTENNA
FIELD PATTERN ASSOCIATED WITH A SPINNING BODY
Original Filed Sept. 28, 1961 4 Sheets-Sheet 1

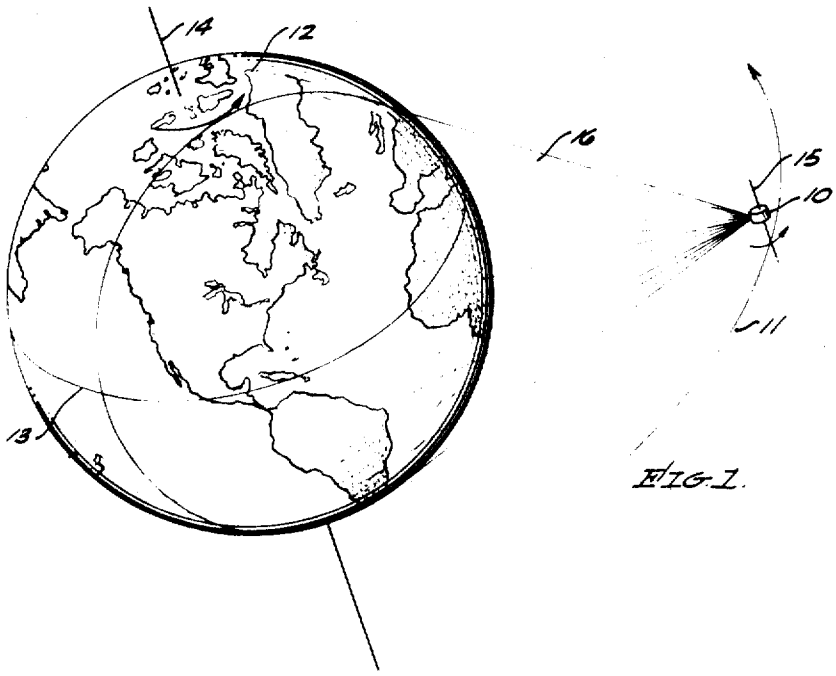


FIG. 1.

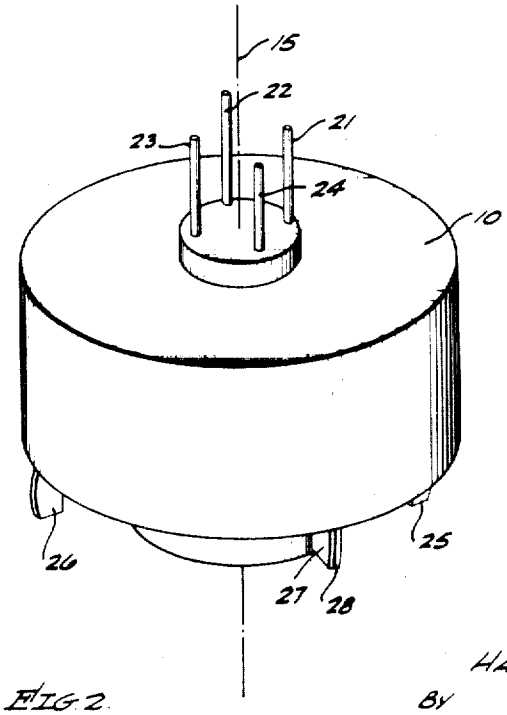


FIG. 2.

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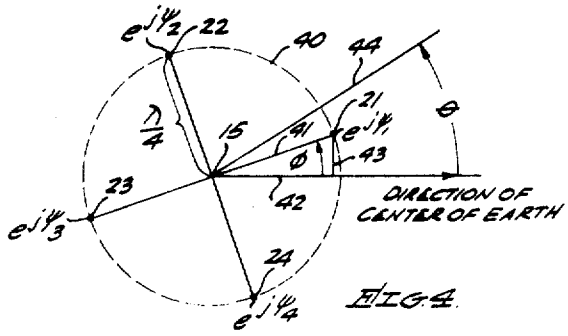


FIG. 4.

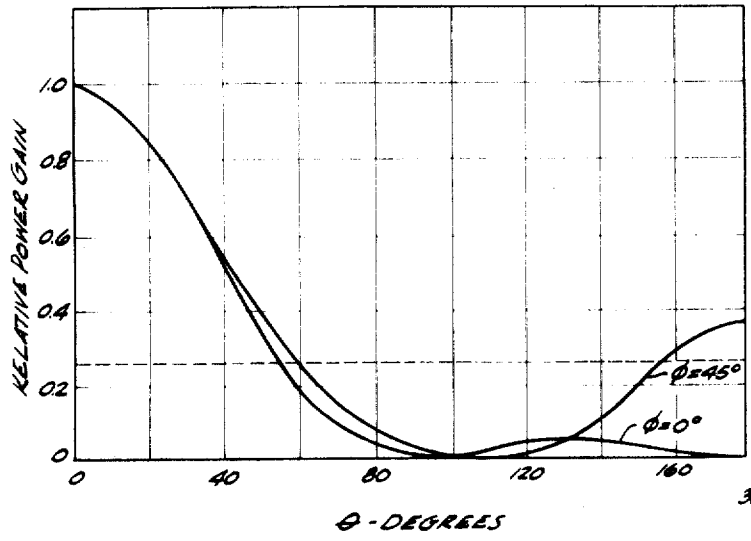


FIG. 5.

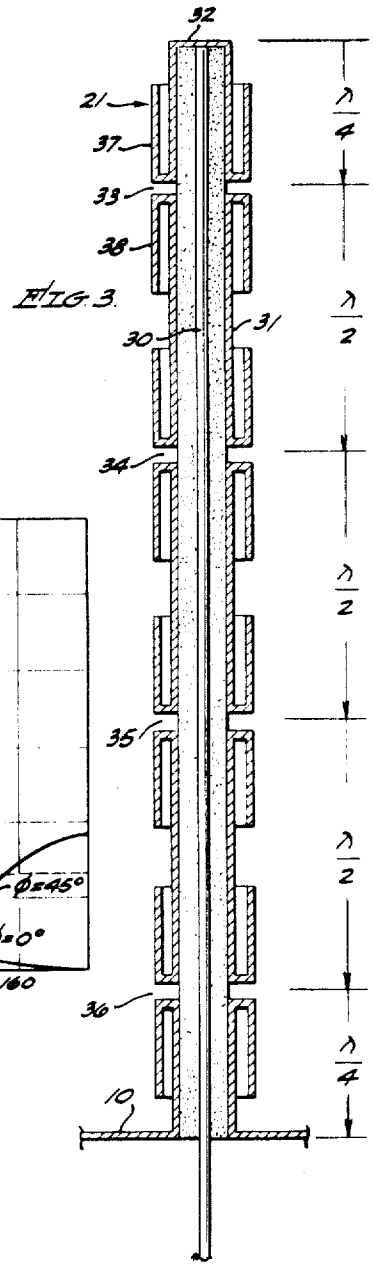


FIG. 3.

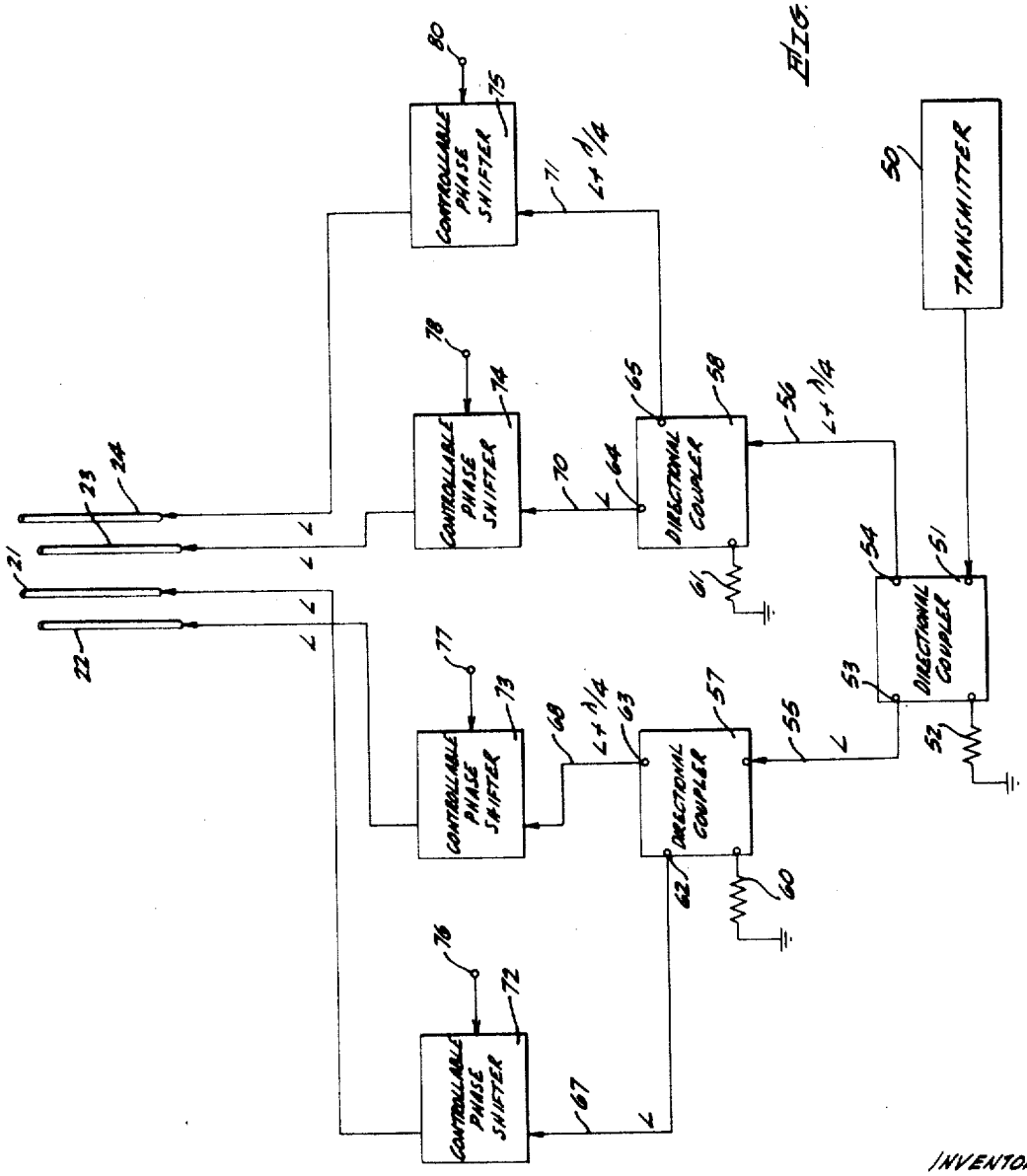
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Original Filed Sept. 28, 1961 4 Sheets-Sheet 3

FIG. 6.



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Oct. 7, 1969 H. A. ROSEN Re. 26,680

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Original Filed Sept. 28, 1961 4 Sheets-Sheet 4

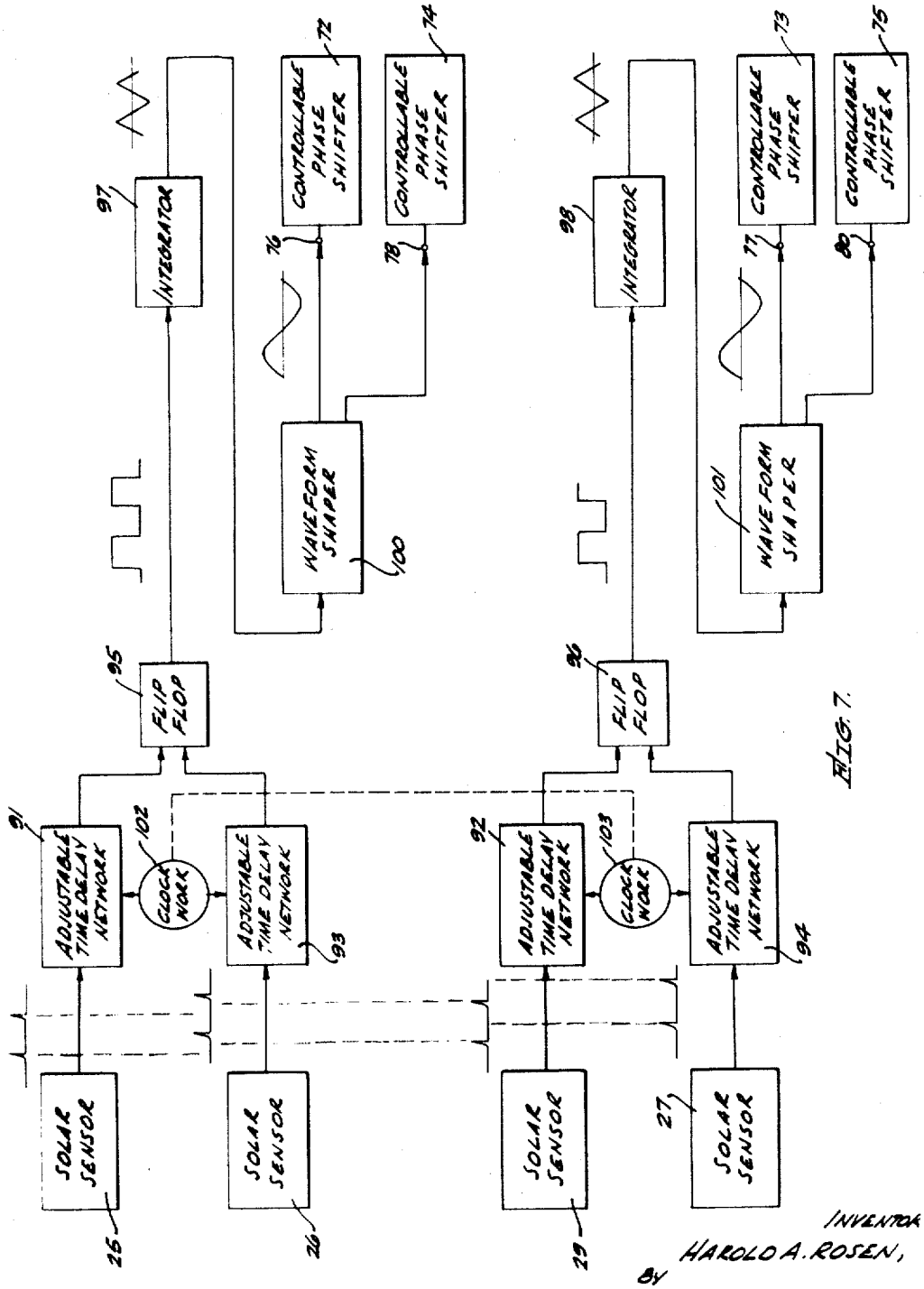


FIG. 7.

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United States Patent Office

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26,680

APPARATUS PROVIDING A ROTATING DIRECTIVE ANTENNA FIELD PATTERN ASSOCIATED WITH A SPINNING BODY

Harold A. Rosen, Santa Monica, Calif., assignor to Hughes Aircraft Company, Culver City, Calif., a corporation of Delaware

Original No. 3,133,282, dated May 12, 1964, Ser. No. 141,527, Sept. 28, 1961. Application for reissue Apr. 8, 1966, Ser. No. 547,058

Int. Cl. H04b 7/00

U.S. Cl. 343—100 9 Claims

Matter enclosed in heavy brackets [ ] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue.

ABSTRACT OF THE DISCLOSURE

Apparatus for producing a rotatable directional antenna pattern is disclosed. The apparatus employs an antenna array comprising a plurality of longitudinal rod-like elements disposed symmetrically about a central axis. Each element is a collinear slot array of the coaxial type. The elements are connected to a source of radio frequency energy by directional couplers and electrically controllable phase shifters. The control signals for the phase shifters are derived from pulses from light-sensitive cells. The desired control waveforms are produced from the pulses by appropriate circuits.

This invention relates to directive radio antenna systems and, more particularly, to apparatus for producing a [rotating] *rotatable* directive antenna field pattern *for a radiating system. Such a field pattern may be* associated with a spinning body, the field pattern rotating counter to the spin of the body and at the same angular velocity, thereby de-spinning the pattern.

In a space vehicle such as a communication satellite, for example, it is desirable that any radio antenna thereon be highly directive so that the most effective use may be made of the limited amounts of radio energy available for transmission. One type of antenna system for space vehicles utilizes an antenna having a directive field pattern that is mounted on a movable member whose orientation is automatically varied relative to the space vehicle in order to maintain the antenna field pattern constantly directed in the desired direction. Alternatively, the attitude of the vehicle itself may be automatically controlled, the orientation of the antenna remaining constant, or the attitude of both may be automatically controlled. Any of these expedients requires a large and heavy electro-mechanical control system to automatically control the orientation of the antenna or the vehicle.

To eliminate the necessity for complex automatic orientation systems in a communication satellite orbiting the earth, the satellite may be caused to spin about an axis as it traverses its orbit to provide orientation stability, with the spin axis perpendicular to a line from the earth to the satellite. A directive antenna may then be used to provide a uniform circular antenna field pattern about the spin axis that is narrow in width about a plane extending through the center of the satellite perpendicular to the spin axis. Some portion of this pancake-like antenna pattern is always directed toward the earth as the satellite spins on its axis. Although this arrangement provides a gain improvement of eight decibels over an omidirectional field pattern, it is inefficient in that not all of the radiated energy is directed toward the earth. The most efficient antenna is one producing a pencil-like beam or lobe of narrow width that is directed to the earth. Such an antenna provides a gain improvement of approximately 18 decibels.

To provide a pencil-like directive antenna field pattern in a fixed direction from a spinning body, the antenna pattern must rotate counter to the spin of the body and at the same angular velocity. Although antenna systems providing rotating field patterns have been in existence for use in radio beacons, direction finding equipment and the like, this apparatus is unsuitable for use in space vehicles for several reasons. The antenna field patterns produced thereby are usually not of the highly directive pencil-beam type. The apparatus is large and heavy, usually utilizing large rotating structures such as apertured masks or cages, large rotating antenna elements or the like. The prior art apparatus is not adapted for use on a spinning body, there being no provisions for counter rotation of the field pattern at the same angular velocity thereof.

Accordingly, it is an object of the present invention to provide [a predetermined] *improved apparatus producing rotatable* antenna directivity from a [radio] *radiating* system [on a spinning body].

Another object of the invention is the provision of apparatus for increasing antenna power gain from a spinning communication satellite.

[Yet another] *Another* object of the present invention is to provide apparatus for improving the antenna gain and directivity from *rotatable beam radiating* [radio] equipment [on a spinning body] that is simple and light in weight.

A further object of the invention is the provision of *improved* electrical means providing a [rotating] *rotatable* directive antenna field pattern [associated with a spinning body] *for a radiating system.*

A still further object of the present invention is to provide circuit means for causing a rotating antenna field pattern associated with a spinning body to rotate counter to the spin thereof and at the same angular velocity thereof, thereby de-spinning the pattern.

In accordance with these and other objects of the invention, *in the illustrated embodiment thereof* a body adapted to spin about an axis is provided with an antenna array, the relative disposition and excitation phase of the various elements thereof being such that a narrow beam type of field pattern is formed perpendicular to the spin axis of the body. The excitation phase is periodically modulated or varied by electrically controlled phase shifters to cause the beam to rotate counter to the spin of the body and at the same angular velocity thereof. The rotation of the antenna field pattern is synchronized with the spin of the body by a control circuit to maintain the antenna field pattern pointing in a desired direction.

The following specification and the accompanying drawings describe and illustrate an exemplification of the present invention. Consideraton of the specification and drawings will provide a complete understanding of the invention including the novel features and objects thereof. Like reference characters are used to designate like parts throughout the figures of the drawings.

FIG. 1 is a perspective view of the earth and an orbiting satellite associated therewith and illustrating a directive antenna field pattern of the type contemplated by this invention;

FIG. 2 is a perspective view of a space vehicle suitable for communication uses and illustrating an antenna array constructed in accordance with the present invention and associated solar sensors;

FIG. 3 is a cross sectional elevational view of a single antenna element in accordance with the present invention;

FIG. 4 is a plan view of an antenna system in accordance with the present invention illustrating the phase relationship of the several elements thereof;

FIG. 5 is a graph of relative power gain as a a function of excitation phase angle between the antenna elements of FIG. 4;

FIG. 6 is a schematic circuit diagram of the interconnection of the antenna system of the present invention; and,

FIG. 7 is a schematic circuit diagram of a synchronizing system for use with the antenna system of the present invention.

Referring now to FIG. 1, there is illustrated a space vehicle, such as a satellite **10**, traversing an orbit **11** about the earth **12**. The staellite **10** is in the equatorial plane of the earth, that is, a plane passing through the equator **13** also passes through the orbit **11** of the satellite **10**. The satellite **10** travels in the same direction as the earth **12** does in rotating about its axis **14** and also travels at the same angular velocity thereof. Thus, the satellite **10** rotates with the earth **12** to remain stationary over a single geographic area thereof. Such an orbit **11** is commonly referred to as being of the synchronous, stationary, or 24-hour type. Although described with reference to a stationary orbit, the invention is also applicable to satellites in other orbits. The satellite **10** also spins about a spin axis **15** as it traverses the orbit **11** in order to provide attitude stabilization thereof. The spin axis **15** of the satellite **10** is parallel to the earth's rotational axis **14**. For other than equatorial orbits, the spin axis is aligned normal to the orbital plane. Methods of placing the satellite **10** into its orbit **11** are known and form no part of the present invention. Furthermore, methods of spinning the satellite **10** about its spin axis **15** and orienting the spin axis **15** parallel to the earth's axis **14** are also known and form no part of the present invention. For example, the spin of the satellite **10** may be residual spin imparted by the launching vehicle and the spin axis **15** may be oriented parallel to the earth's axis **14** by precession caused by applying a moment to the satellite **10** in a predetermined direction.

FIG. 1 also illustrates an antenna field pattern **16** or beam which is optically conical and extends from the satellite **10** to the earth **12** with the apex of the conical pattern **16** being at the satellite **10**. The field pattern **16** intersects a large area on the surface of the earth **12**. FIG. 1 is solely representative and is not to scale, the relative size of the satellite **10** to that of the earth **12** and the distances therebetween being disproportionate for convenience. Accordingly, although the included angle of the conical field pattern **16** is represented as being rather large in FIG. 1, the actual angle is relatively small, being approximately 17.3 degrees. The satellite **10** is at an altitude of 22,300 miles above the earth **12** and, at this distance the provision of an extremely directive antenna field pattern **16** is of great importance. As mentioned hereinbefore, the gain of the pencil beam antenna pattern **16**, which it just encompasses the earth **12** from an altiude of 22,300 miles, is approximately 18 decibels.

FIG. 2 illustrates an array of four antenna elements **21–24** disposed on the satellite **10** for forming a narrow pencil beam field pattern **16**. Many other different types of antenna arrangements will also form a directive antenna field pattern suitable for use in accordance with the present invention and the embodiment herein shown and described is by way of example only. The satellite **10**, of the present example, is generally cylindrical about the spin axis **15**. The antenna elements **21–24**, which will be described in more detail hereafter, are longitudinal, rod-like members and project parallel to the spin axis **15** from one of the flat surfaces of the satellite **10**. The antenna elements **21–24** are identical and are disposed symmetrically about the spin axis **15** of the satellite **10** at an appreciable fraction of a wavelength therefrom. A satisfactory radial spacing between the antenna elements **21–24** and the spin axis **15** is one-quarter wavelength, for example, although other spacings may be used. In the present example, the antenna is designed for operation in the vicinity of 2000 megacycles at which frequency the wavelength involved is approximately 6 inches. In the present embodiment of the invention, four antenna elements **21–24** are provided, although any number from a minimum of two may be utilized. The gain improvement is in general proportional to the number of elements, however, if a greater number of elements are symmetrically located at the same radial distance from the spin axis **15** as provided for the lesser number of elements, the spacing between the elements will be less and there will be an increase of interaction or mutual coupling between them that will adversely affect the radiation impedance to some extent so that the optimum gain improvement factor may not be achieved.

A first solar sensor **25**, associated with the first antenna element **21**, projects from the flat surface of the satellite **10** that is opposite the flat surface from which the antenna elements **21–24** project. The solar sensor **25** is a generally elongated, flat assembly that is aligned with and intersected by a plane passing through the spin axis **15** and the associated antenna element **21**. A second solar sensor **29** (not shown in FIG. 2) is associated with the second antenna element **22** and is angularly displaced around the circumference of the satellite **10** from the first solar sensor **25** to lie in a plane passing through the spin axis **15** and the second antenna element **22**. Similarly, third and fourth solar sensors **26** and **27** also project from the flat surface of the satellite **10** at the circumference thereof and are aligned with the third and fourth antenna elements **23** and **24**, respectively. Each of the solar sensors is provided with a longitudinal, slit-like opening **28** that is aligned with the plane passing through the respective antenna element. Within each of the solar sensors are sensing elements (not shown) such as cadmium sulfide or silicon cells that produce an electrical voltage in response to sunlight passing through the opening **28**.

The construction of the first antenna element **21** is illustrated in FIG. 3 and is typical of the remaining elements **22–24**. The antenna element **21** is a collinear slot array of the coaxial type and comprises a coaxial transmission line having an inner conductor **30** and an outer conductor **31**. The transmission line is provided with a short-circuiting member **32** at the distal end and is provided with four circumferential openings or slots **33–36** in the outer conductor **31**. The slots **33–36** are spaced one-half a free space wavelength apart and the end slots **33** and **36** are one-quarter wavelength away from the ends of the antenna element **21**. The surface of the satellite **10** is conductive and forms a ground plane for the antenna system. The slots **33–36** are excited with an in-phase relationship to obtain a broadside field pattern, that is, a circular pattern perpendicular to the axis of the antenna element **21**. To accomplish this, the electrical distance between the slots **33–36** has been made equal to a whole wavelength by folding the outer conductor **31** adjacent the slots **33–36**, as at portions **37** and **38** adjacent the distal slot **33**, to obtain the necessary phase shift. Alternatively, this may be accomplished, if desired, by utilizing a material having a dielectric constant of 4 within the coaxial transmission line. Such a material is titanium dioxide loaded with iron particles, for example.

FIG. 4 is a plan view of the antenna array showing the relative location of the elements **21–24** and is for the purpose of identifying symbols to be used in subsequent analysis. The antenna elements **21–24** are located on a circle **40** having a radius equal to one-quarter wavelength and are symmetrically displaced from each other. Taking the amplitude as unity, the radiated field from the first antenna element **21** is expressed vectorially in exponential form as $e^{j\psi_1}$. The field from the second antenna element **22** is $e^{j\psi_2}$; for the third antenna element **23**, e^{ψ_3}; for the fourth antenna element **24**, $e^{j\psi_4}$. The

phase angle ψ indicates the time phase of the excitation potential applied to the related antenna element. The angle φ or spin angle is the angle between a radial line **41** from the spin axis **15** to the first antenna element **21** and a line **42** from the spin axis **15** in the direction of the center of the earth and varies as the satellite **10** spins about the axis **15**. The field pattern of the antenna is at a maximum along the line **42** to the center of the earth. A perpendicular line **43** from the line **42** to the earth passing through the first antenna element **21** forms a right triangle having the radial line **41** for a hypotenuse, the earth line **42** for an adjacent side, and the perpendicular line **43** for an opposite side. The angle φ is an angle between the line **42** in the direction of the center of the earth and a line **44** in which the antenna field pattern is less than maximum.

In order that the far field (the field at a distance at which the [anntenna] *antenna* array appears to be a point source) contributed by each of the antenna elements **21–24** have an in-phase relationship in the direction of the earth, the excitation phase angles ψ are assigned values that account for the different space delays (differences in path length along the line **42** to the earth) of the individual elements **21–24**. The excitation phase angle for the first antenna element **21** may be found by considering the right triangle associated therewith. The amount of space delay of the first antenna element **21**, or the component of the difference in path length from the center of the array at the spin axis **15** along the line **42** to the earth, by

$$\text{trigonometry}=\text{hypotenuse } d\chi \cos\varphi$$

The hypotenuse is one-quarter wavelength which corresponds to a phase shift of $\pi/2$ radians. Accordingly, the space delay of the

$$\text{first antenna element } \mathbf{21}=-\psi/2\cos\varphi$$

The first element **21** is closer to theearth than the reference point (the spin axis **15**), hence its delay is negative. Hence, the excitation phase angle for the first element **21**, $\psi_1=-\pi/2\cos\varphi$. The sign convention used here for excitation phase angle is minus for phase lag and plus for phase lead. Inasmuch as the antenna elements **21–24** are angularly separated by 90° or $\pi/2$ radians, the excitation phase angles of the remaining elements **22–24** are found by trigonometry to be for the

Second element **22**, $\psi_2=-\pi/2\cos(\varphi+\pi/2)$
Third element **23**, $\psi_3=-\pi/2\cos(\varphi+\pi)$
Fourth element **24**, $\psi_4=-\pi/2\cos(\varphi+3\pi/2)$.

Stated generally for the four element array of the present example, the excitation phase angle of each of the elements **21–24** is

$$\psi_i=-\frac{\pi}{2}\cos\left[\phi+(i-1)\frac{\pi}{2}\right]$$

where i is the number of the particular one of the four antenna elements **21–24** being considered. Thus, to provide an antenna field pattern that is at a maximum along a line **42** in the direction of the center of the earth as the satellite **10** spins about its spin axis **15**, the excitation potential applied to each of the antenna elements **21–24** varies sinusoidally in phase between the limits of ±90°. Hence, a total phase shift of 180° must be variably provided for each of the antenna elements **21–24**. Furthermore, there is a 90° phase difference between the rate of change of phase between adjacent ones of the antenna elements **21–24**. That is, when the phase of the excitation potential applied to the first antenna element **21** is passing through 0° going toward 90°, the phase of excitation potential applied to the second antenna element **22** is passing through —90° going toward 0°, the phase of the third element **23** is passing through 0° going toward —90°, and the phase of the fourth element **24** is passing through +90° going toward 0°.

Still further, the excitation phase angles must be periodically varied in accordance with the variations in the spin angle φ and is sinusoidal in the present example. Slight variations from sinusoidal modulation may be desirable to reduce the incidental spin modulation of the gain in the direction of the earth.

To show the gain improvement factor of the antenna array, the radiation field along the line **44** at an angle θ to the line **42** in the direction of the earth is considered. The normalized far field in the equatorial plane may be shown to be equal to

$$E=e^{-j\frac{\pi}{2}}[\cos\phi-\cos(\theta-\phi)]+e^{-j\frac{\pi}{2}}[\cos\phi-\cos)\theta-\phi)]+$$
$$e^{-j\frac{\pi}{2}}[\sin\phi+\sin(\theta-\phi)]+e^{-j\frac{\pi}{2}}[\sin\phi+\sin(\theta-\phi)]$$

This may be reduced to

$$E=2\cos\left\{\frac{\pi}{2}[\cos\phi-\cos(\theta-\phi)]\right\}+$$
$$2\cos\left\{\frac{\pi}{2}[\sin\phi+\sin\theta-\phi)]\right\}$$

FIG. 5 is a graph of the relative power gain

$$\left(\frac{E}{4}\right)^2$$

of the antenna array as a function of θ for 2 values of φ and represents the field pattern of the antenna array. It will be seen from FIG. 5 that the radiated field in the direction of the earth ($\theta=0°$) is at a maximum (normalized to unity). The field decreases to approximately zero in the direction at right angles to the direction of the earth ($\theta=90°$). However, minor side lobes are present, the most pronounced being in the direction opposite to the direction of the earth at that point in the spin cycle when the satellite spin angle $\varphi=45°$. For comparative purposes, the straight horizontal broken line in FIG. 5 indicates the field of a directive antenna having a uniform circular, pancake-like pattern.

From the graph of FIG. 5, the power gain improvement factor of the array may be computed. When $\varphi=0$ the improvement factor of the pencil beam is 6 decibels over the 8 decibel gain of a flat circular pattern, or a total of 14 decibels gain over an omnidirectional pattern. When $\varphi=45°$, the present array is only 5 decibels greater than the gain of a circular pattern. This one decibel reduction of the improvement factor as the satellite **10** spins shows the deleterious effect of the close spacing of the antenna elements **21–24**. However, the attained gain of 13–14 decibels of the present antenna array compares favorable with the 18 decibels optimum which corresponds to full earth coverage by a pencil beam.

The interconnection of the antenna element **21–24** with a radio transmitter **50** is shown in FIG. 6. The transmitter **50** is connected to a power divider which may be a unitary device or made up of several microwave bridge networks known as hybrid networks. In the present example, the transmitter **50** is connected to one terminal of a first directional coupler **51** having a second terminal terminated in its characteristic impedance by a resistive impedance element **52**. The construction and operation of the directional coupler **51** is well known in the art. When the directional coupler **51** is connected as described, the signal energy appears at two terminals **53** and **54** at equal power levels but the signal at one terminal **53** lags the signal at the other terminal **54** by 90°. Each of these terminals **53** and **54** is individually connected by transmission lines **55** and **56** to one terminal of second and third directional couplers **57** and **58**, respectively. The transmission line **56** interconnecting the first and third directional couplers **51** and **58** is one-quarter wavelength longer than the other transmission line **55** to compensate for the 90° phase difference of the signals between the terminals **53** and **54** of the first directional coupler **51**. Hence, the signals applied to the second and

third directional couplers **57** and **58** have an in-phase relationship as well as being equal in magnitude.

The second and third directional couplers **57** and **58** each have a terminal terminated in the characteristic impedance by resistive elements **60** and **61**. The signal energy appears at two terminals **62** and **63** of the second directional coupler **57** equal in magnitude but the signal at one terminal **62** lags the signal at the other terminal **63** by 90°. Similarly, the signal energy appears at two terminals **64** and **65** of the third directional coupler **58** equal in magnitude but the signal at one terminal **64** lags the signal at the other terminal **65** by 90°. These terminals **62–65** of the second and third directional couplers **57** and **58** are each individually connected by transmission lines **67**, **68**, **70** and **71** to a different one of four controllable phase shifters **72–75**. The lengths of the first and third transmission lines **67** and **70** are equal and the second and fourth transmission lines **68** and **71** are one-quarter wavelength longer to compensate for the phase difference of the signals at the terminals **62–65** of the second and third directional couplers **57** and **58**. Hence, the signals applied to the phase shifters **72–75** have an in-phase relationship as well as being equal in magnitude. The directional couplers **51**, **57** and **58** may be of the flat-strip transmission line type described on pages **78–80** of the book "Handbook of Tri-Plate Microwave Components," published in 1956 by Sanders Associates, Inc., Nashua, New Hampshire.

The controllable phase shifters **72–75** serve to modulate the phase of the signals to be applied to the antenna elements **21–24** to cause the beam or field pattern to rotate and provide a phase shift of ±90°. The phase shifters **72–75** comprise ferrite phase modulators utilizing a varying magnetic field to control the phase shift through a ferrite element. Other types of phase shifting devices may also be used, such as rotating half-wave plates, rotating capacitors, and varactor diode phase modulator. The latter device utilizes a semiconductor diode having a capacitance that varies with an applied control potential. An electro-mechanical type of phase shifter that may be used is described on pages 333–335 of the book "Principles and Applications of Waveguide Transmission" by George C. Southworth, published in 1950 by D. Van Nostrand Co., Inc., although the all-electronic type is more convenient. The control signals for the controllable phase shifters **72–75** are applied to control signal terminals **76**, **77**, **78** and **80**. Each of the controllable phase shifters **72–75** is individually connected to a different one of the four antenna elements **21–24** by transmission lines of equal length. The first phase shifter **72** is connected to the first antenna element **21**, the second phase shifter **73** is connected to the second antenna element **22**, and the third and fourth phase shifters **74** and **75** are connected to the third and fourth antenna elements **23** and **24**, respectively.

The phase shifters **72–75** are controlled by the synchronizing circuit schematically illustrated in FIG. 7. This circuit provides control voltages for each of the phase shifters **72–75** which produce relative phase shift between the antenna elements **21–24** necessary to cause the formation of a narrow beam field pattern and also sinusoidally varies the control voltages to cause the beam to rotate.

The four solar sensors **25**, **26**, **27** and **29** on the exterior of the satellite **10** are each electrically connected to a different one of four adjustable time delay networks **91–94**. Each of the solar sensors **25**, **26**, **27** and **29** supplies an electrical pulse to the associated one of the delay networks **91–94** each time the satellite **10** rotates one complete revolution about the spin axis **15**. The first solar sensor **25** associated with the first antenna element **21** is connected to the first delay network **91**, the second solar sensor **29** associated with the second antenna element **22** is connected to the second delay network **92**, and the third and fourth solar sensors **26** and **27** associated with the third and fourth antenna elements **23** and **24**, respectively, are connected to the third and fourth delay networks **93** and **94**, respectively. The adjustable delay networks **91–94** comprise resistance-capacitance circuits having mechanically variable impedance elements.

The first and third delay networks **91** and **93** are connected to a first bistable multivibrator circuit or flip flop **95** at the set and reset terminals thereof, respectively, and the second and fourth delay networks **92** and **94** are connected to the set and reset terminals of a second flip flop **96**. The pulses from the solar sensors **25**, **26**, **27** and **29** are applied by the delay networks **91–94** to the flip flops **95** and **96**, thereby causing the flip flops **95** and **96** to change state. The first and third solar sensors **25** and **26** are on diametrically opposed sides of the satellite **10** and alternately produce pulses each 180° of rotation thereof, resulting in a square wave being developed by the first flip flop **95**. The second and fourth solar sensors **29** and **27** are also on diametrically opposed sides of the satellite **10**, resulting in a square wave also being developed by the second flip flop **96**, but displaced 90° from the square wave produced by the first flip flop **95**.

Each of the flip flops **95** and **96** is individually connected to a different one of two integrators **97** and **98** that integrate the square waves to form triangular waves. The integrators **97** and **98** are each individually connected to a different one of two waveform shapers **100** and **101** that form the triangular waves into sine waves having a 90° relative phase difference. The waveform shapers **100** and **101** provide push-pull output signals, that is, the output signals appear at two terminals with equal amplitude but opposite in phase, or with a polarity inversion. The first wave form shaper **100** is connected to the control signal terminals **76** and **78** of the first and third controllable phase shifters **72** and **74**. The sine wave control voltage applied to the third phase shifter **74** is inverted in polarity to provide 180° phase difference between the control signals applied to the first and third phase shifters **72** and **74**. The second waveform shaper **101** is connected to the control signal terminals **77** and **80** of the second and fourth controllable phase shifters **73** and **75**. The sine wave control voltage applied to the fourth phase shifter **75** is inverted in polarity to provide 180° phase difference between the control signals applied to the second and fourth phase shifters **73** and **75**. Due to the 90° phase difference between the sine wave from the first waveform shaper **100** and the sine wave from the second waveform shaper **101** and due to the application of the sine waves with opposite polarity to the third and fourth controllable phase shifters **74** and **75**, the control signals applied to the four phase shifters **72–75** have a fixed relative phase difference of 90°. That is, if the phase of the control signal applied to the first phase shifter **72** is taken as the reference phase or 0°, then the phase of the control signal at the second phase shifter **73** is 90°, at the third phase shifter **74** it is 180°, and at the fourth phase shifter **75** it is 270°. This produces the required relative phase variation of the radio signal applied to the antenna elements **21–24** to form the antenna field pattern into a narrow beam and to cause the field pattern to rotate in a direction counter to the spin of the satellite **10** and at the same angular velocity. This causes the beam to point in a fixed direction, namely, in the direction of the earth.

Inasmuch as the direction of the beam from the antenna array is determined in the present example by the direction of the sun, two clockwork mechanisms **102** and **103** are provided that compensate for movement of the earth with respect to the sun in order to maintain the antenna beam directed towards the earth. The clockwork mechanisms **102** and **103** are mechanically coupled together and are coupled to the mechanically variable impedance elements in the adjustable time delay networks **91–94** to progressively vary the phase shift of the pulses produced by the solar sensors **25**, **26**, **27** and **29**. The clockwork mechanisms **102** and **103** shift the solar phase reference pulses 360° per day or for each revolution of

the satellite around the earth. A clock accuracy of one part in 20,000 causes a beam aiming error of only 6° per year. This synchronizing arrangement may be corrected at relatively infrequent intervals by radio control signals from the earth, if desired. As an alternative to the clockwork mechanisms **102** and **103**, synchronizing of the phase modulation with the spin cycle of the satellite to maintain the gain maximum point of the antenna array in the direction of the earth may be accomplished wholly by radio control from the ground. In this case, synchronizing signals would be transmitted to the satellite.

There has been described a directional antenna system for use with a spinning body wherein an antenna field pattern is maintained in a fixed direction. Although the present invention has been described with reference to use in a space vehicle such as a satellite, the invention is not limited thereto. The invention would also have significant utility in a radio beacon or, in radio direction finding apparatus. Furthermore, the invention may be utilized on a spinning body located in environments other than space.

Having thus described the invention and the present embodiments thereof, it is desired to emphasize the fact that many other modifications may be resorted to in a manner limited only by a just interpretation of the following claims.

What is claimed is:

1. A communication satellite comprising:

(*a*) a body adapted to spin about an axis;

(*b*) a plurality of antenna elements disposed symmetrically about said axis;

(*c*) controllable phase shifting means;

(*d*) circuit means coupled to said antenna elements through said controllable phase shifting means;

(*e*) means for developing synchronizing signals;

(*f*) and control means coupled to said last-named means and responsive to said synchronizing signals for developing control signals, said control means being coupled to said controllable phase shifting means for applying said control signals thereto.

2. In a communication satellite orbiting the earth and spinning about an axis, apparatus for directing an antenna radiation pattern toward the earth despite the spinning of the satellite by forming the radiation pattern into a narrow beam and couner rotating the beam in synchronism with the spin of the satellite, said apparatus comprising:

(*a*) a body adapted to spin about an axis;

(*b*) a plurality of longitudinal radiating elements mounted to and extending from said body parallel to said axis, said elements being symmetrically disposed about said axis, each of said elements being an array of radiators of the type which radiates in a direction perpendicular to said axis, said elements being spaced at least one-quarter wavelength away from said axis;

(*c*) a radio transmitter;

(*d*) a plurality of controllable phase shifters, each individually coupling one of said elements to said radio transmitter;

(*e*) a phase control circuit coupled to said phase shifters for controlling the phase shift thereof, said phase control circuit controlling the phase shift of said phase shifters in a manner such that radiation from said elements is formed into a beam, said phase control circuit varying the phase shift of said phase shifters such that said beam rotates around said axis counter to the spin of said body;

(*f*) and a synchronizing circuit responsive to solar radiation and coupled to said phase shift control circuit for synchronizing the rotation of said beam with the spin of said body.

3. Apparatus for producing a rotating directive antenna field pattern associated wtih a spinning body, the field pattern rotating counter to the spin of the body and at the same angular velocity comprising:

(*a*) a body adapted to spin about an axis;

(*b*) a plurality of antenna elements disposed on said body and equally spaced about said axis, the individual radiation field pattern of each of said antenna elements being substantially circular in a plane transverse to said axis;

(*c*) a radio transmitter associated with said body and producing a radio signal;

(*d*) means including a plurality of controllable phase shifters each coupling said transmitter to a different one of said antenna elements for varying the phase of said radio signal in response to applied control signals;

(*e*) means providing electrical pulses synchronized with the spin of said body about said spin axis;

(*f*) means coupled to said last-named means for developing in response to said pulses a plurality of sinusoidally varying control signals having a predetermined phase displacement therebetween;

(*g*) said control signals being applied to said controllable phase shifters;

(*h*) said phase shifters providing in response to said control signals a predetermined phase shift to said radio signal applied to different ones of said antenna elements and producing a sinusoidal phase variation of said phase shift causing the individual field patterns of said antenna elements to combine into a narrow directive antenna pattern rotating counter to the spin of said body and at the same angular velocity.

4. Apparatus for producing a rotating directive antenna field pattern associated with a spinning body, the field pattern rotating counter to the spin of the body and at the same angular velocity comprising:

(*a*) a body adapted to traverse an orbit around the earth and adapted to spin about an axis;

(*b*) a plurality of longitudinally extending antenna elements projecting from a surface of said body parallel to said axis and equally disposed therearound, the individual radiation field pattern of each of said antenna elements being substantially circular in a plane transverse to said axis;

(*c*) a radio transmitter associated with said body and producing a radio signal;

(*d*) means including a plurality of controllable phase shifters each coupling said transmitter to a different one of said antenna elements for varying the phase of said radio signal in response to applied control signals;

(*e*) means providing electrical pulses in response to for each revolution of said body around the earth; axis while traversing said orbit;

(*f*) adjustable time delay means coupled to said last-named means for delaying said pulses by selected amounts;

(*g*) a clockwork mechanism operatively coupled to said adjustable time delay means for producing a delay of said pulses progressively increasing to 360° for each revolution of said body around the earth;

(*h*) means coupled to said time delay means for developing a square wave in response to said pulses;

(*i*) and waveform shaping means coupled to said last-named means for forming said square wave into a plurality of sinusoidally varying control signals having a predetermined phase displacement therebetween;

(*j*) said control signals being applied to said controllable phase shifters;

(*k*) said phase shifters providing in response to said control signals predetermined sinusoidally varying phase shifts to said radio signal applied to different ones of said antenna elements causing the individual field pattern of said antenna elements to combine into a narrow directive antenna pattern rotating

counter to the spin of said body and at the same angular velocity.

5. Apparatus for producing a rotating directive antenna field patterns of said antenna elements to combine pattern rotating counter to the spin of the body and at the same angular velocity comprising:

(*a*) a body adapted to traverse an orbit around the earth and adapted to spin about an axis;

(*b*) four longitudinally extending, collinear slot, coaxial antenna elements projecting from a surface of said body parallel to said axis and equally disposed therearound, the individual radiation field pattern of each of said antenna elements being substantially circular in a plane transverse to said axis;

(*c*) a radio transmitter associated with said body and producing a radio signal;

(*d*) a plurality of directional couplers coupled to said transmitter by transmission lines of predetermined length to provide four in-phase radio signals of equal amplitude;

(*e*) four controllable phase shifters each coupling said directional couplers to a different one of said antenna elements by transmission lines of a predetermined length for varying the phase of said four radio signals in response to applied control signals;

(*f*) four solar sensors fixed to said body and disposed symmetrically about said spin axis [;], said solar sensors each having a longitudinal aperture slit opening outwardly of said body for admitting solar radiation to a radiant energy detector disposed therewithin, each of said solar sensors being associated with a different one of said antenna elements and having said aperture slit aligned in a plane passing through said spin axis and the associated one of said antenna elements, said solar sensors producing an electrical pulse in response to solar radiation admitted by said aperture slits as said body spins about said spin axis while traversing said orbit;

(*g*) four adjustable time delay networks coupled to said solar sensors for delaying said pulses by selected amounts;

(*h*) clockwork mechanism operatively coupled to said adjustable time delay networks for producing a delay of said pulses progressively increasing to 360° for each revolution of said body around the earth;

(*i*) a pair of bistable multivibrators, each being individually coupled to a different, diametrically oppositely disposed pair of said solar sensors, said bistable multivibrators each developing a square wave in response to said pulses, said square waves being relatively displaced in time of occurrence by 90°;

(*j*) a pair of integrators each coupled to a different one of said multivibrators for forming said square waves into triangular waves;

(*k*) and a pair of waveform shapers each being coupled to a different one of said integrators for forming said triangular waves into first and second sinusoidal control signals having a 90° phase displacement therebetween;

(*l*) said first control signal being applied to the pair of said controllable phase shifters associated with a diametrically oppositely disposed pair of said antenna elements and said second control signal being applied to the remaining pair of said controllable phase shifters, each of said control signals being applied with opposite polarity to the associated pair of said phase shifters;

(*m*) said phase shifters providing in response to said control signals sinusoidally varying phase shifts of said four radio signals causing the individual field patterns of said antenna elements to combine into a narrow directive antenna pattern rotating counter to the spin of said body and at the same angular velocity.

6. Apparatus for producing a rotatable directive antenna field pattern from an antenna array of the type having a plurality of substantially omnidirectional antenna elements arranged symmetrically about an axis whereby each element receives radiation from the others comprising:

(a) a support;

(b) a plurality of antenna elements disposed on said support substantially symmetrically about an axis, said antenna elements having individual characteristic radiation field patterns substantially circular in a plane transverse to said axis;

(c) a source of a radio frequency signal;

(d) means including a plurality of electrically controllable electrical phase shifters, each of said phase shifters continuously and simultaneously coupling said source to an individual one of said antenna elements for varying the phase of the radio frequency signal fed thereto by varying an electrical parameter of said phase shifters while all portions thereof remain stationary, said means also including unidirectional transmission means having energy dissipation means;

(e) an electrical control means for applying electrical control signals to said phase shifters and adapted to effect relative phase shifts of the radio frequency signals fed to said antenna elements so that the radiated signals from said antenna elements form a directive antenna field pattern, said control means being operable to vary said electrical control signals to effect rotation of said field pattern relative to said axis in a plane substantially transverse thereto.

7. Apparatus for producting a rotatable directive antenna field pattern from an antenna array of the type having a plurality of substantially omnidirectional antenna elements arranged symmetrically about an axis whereby each element receives radiation from the others comprising:

(a) a support;

(b) a plurality of antenna elements disposed on said support substantially in parallel, equally spaced relation about a central axis, said antenna elements having individual characteristic radiation field patterns substantially circular in a plane transverse to said axis;

(c) a source of radio frequency signal;

(d) power splitting means including unidirectional transmission means having energy dissipation means;

(e) a plurality of electrically controllable electrical phase shifters for varying the phase of a radio frequency signal by varying an electrical parameter of said phase shifters while all portions thereof remain stationary;

(f) means continuously and simultaneously connecting each of said antenna elements to said radio frequency signal source through said power splitting means and phase shifters;

(g) an electrical control means for applying electrical control signals to said phase shifters and adapted to effect relative phase shifts of the radio frequency signals applied to said antenna elements so that the signals radiated from said elements form a directive pattern at substantially a right angle to said axis, said control means being operable to vary said electrical control signals to effect angular movement of said directive pattern relative to said axis in a plane substantially transverse thereto.

8. The apparatus in claim 6 in which said control means includes:

(a) means for generating a series of pulses;

(b) *means for forming sinusoidal signals from said pulses;*

(c) *and means controlling said phase shifters in accordance with said sinusoidal signals to effect said rotation of said directive antenna field pattern at a speed determined by the frequency of generation of said pulses.*

9. The apparatus defined in claim 7 in which said control means includes:

(a) *means for generating a series of pulses;*

(b) *means for forming sinusoidal signals from said pulses;*

(c) *and means for varying said control signals in accordance with said sinusoidal signals to effect said angular movement of said directive pattern at a speed determined by the frequency of generation of said pulses.*

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