SPIRAL ANTENNAS

Spiral antennas are so named because of their shape. Often flat, antenna arms of thin conducting sheet material are defined by spiral curves. Two widely used shapes are related to the spiral curves shown in Figs. 1 and 2. The spacing between turns of an Archimedean spiral is constant, but in the logarithmic spiral the spacing grows with the distance from the origin. An arm of an Archimedean spiral antenna has the spiral curve as centerline and the arm has constant width. An arm of a logarithmic spiral (log-spiral) antenna has edges defined by two logarithmic spiral curves that differ by rotation around the origin. Hence, the arm width of a log-spiral antenna also increases with distance from the origin. Usually, two or four arms comprise an antenna.

The antenna arms cannot follow the spiral curves in the regions close to or far from the origin. The truncation of the conductors near the origin provides terminals for connection to transmission lines or cables. Truncation at the other end, which defines the length of the arms, is dictated by practical matters, such as cost, weight, and the available space. The positions of two arms to form a planar Archimedean spiral antenna are shown in Fig. 3. The second arm is identical to the first, but rotated by 180°. Figure 4 shows a two-arm log-spiral antenna. Note that the small and large limits of this structure are defined by lines, but could also be defined by concentric circles of small and large radii centered at the origin.

Planar spirals can be made by cutting the desired shapes from thin sheets of good-conducting metal, such as copper or aluminum. However, a better way is to use photolithographic techniques like those used to make printed circuits. Thin sheets of metal-clad microwave substrate (dielectric) material are commercially available in rather large sizes. The shapes of the spiral antenna arms are drawn on paper using computer software like that used in preparing Figs. 3 and 4. The artwork is used to make a photographic negative. The image

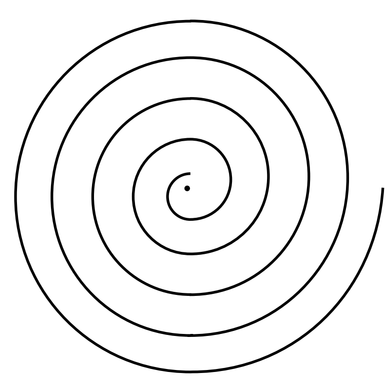

Figure 1. Segment of an Archimedean spiral curve. The dot in the center is the origin.

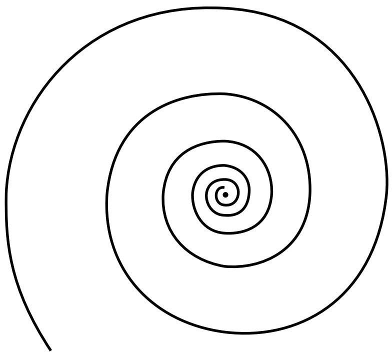

Figure 2. Segment of a logarithmic spiral curve. The dot in the center is the origin.

of the drawing is then used to expose photo-resist on the metal-clad substrate. The excess metal is etched away, leaving the antenna arms in the desired shape, supported by the thin layer of dielectric.

Many spiral antennas conform to the surface of a cone rather than a plane. Infrequently, spiral antennas conform to some surface other than a plane or a cone. The construction of nonplanar antennas is somewhat more complicated but can be accomplished with proper modification of the photolithographic method. In the case of conical spirals flat artwork is prepared and used to fabricate a planar set of conductors on flat, but flexible, substrate. The substrate is then formed into a conical shape and the conductors are soldered together along the seam.

Most spiral antennas can radiate or receive at any frequency within a very wide band, so wide that it is characterized by the ratio of the upper to the lower limit (e.g. 20:1). The lowest frequency of the operating band is determined by the distance from the origin to the far truncation, the maximum extent of the arms. The highest frequency is determined by the distance from the origin to the near truncation, the size of the terminal region.

Transmitting planar spirals in free space radiate the same amount of power on each side of the plane containing the spiral arms. Receiving planar spirals in free space receive equally well on both sides of the plane. The radiation pattern of a planar spiral is generally rather broad, encompassing much of the angular space above and below the plane of the

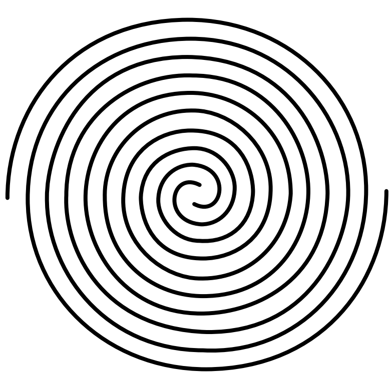

Figure 3. A two-arm, balanced Archimedean spiral antenna. The inner ends are the input terminals.

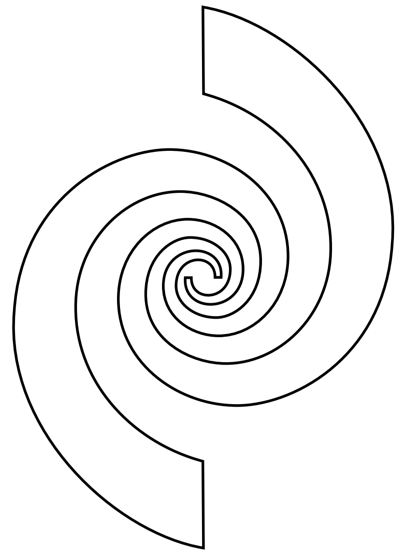

Figure 4. A two-arm, balanced logarithmic spiral antenna. The outlined edges could be the boundaries of thin metal arms, or of a slot in a thin metal sheet.

spiral. However, conical spirals are usually designed to radiate mostly in one hemisphere. Depending upon the choice of the parameters of the spiral curve, the radiation beam of a conical spiral antenna can be made quite broad or rather narrow.

In most of the radiation beam of spiral antennas the polarization is circular, or nearly so. The sense of the polarization is determined by the direction of rotation in which the spiral expands. Pointing the thumb in the direction of propagation of the wave radiated by the spiral with the fingers parallel to the spiral (in the direction of the spiral wrap), the hand used indicates the sense of polarization following the standards of the Institute of Electrical and Electronics Engineers. (Physicists often use the opposite designation.) Planar spirals radiate one sense in one hemisphere and the opposite sense in the other hemisphere. The spiral of Fig. 3 radiates right-hand sense in the space above the antenna; left-hand sense in the space below. Spirals with more than two arms must be excited with an arm-to-arm phase progression that agrees with the sense of the polarization as determined by the direction of wrap of the spiral. Spiral antennas are sometimes used even in narrowband applications because of their polarization properties.

One of the first applications of a spiral antenna was on a navigation satellite. Many other satellite applications have occurred since then. Circular polarization is preferred over linear polarization for waves that penetrate the ionosphere where the plane of linear polarization undergoes rotation. Conical spiral antennas are used as feeds for reflector antennas. The University of Illinois radio telescope used a linear array of conical spirals as a slow-speed scanning feed for a parabolic cylinder reflector (1). The direction of the beam of such an array can be changed by rotating the antenna elements. This follows from the circular polarization of the spiral antennas, because the phase of the radiated field is directly related to the angle of rotation. The broadband capability of spiral antennas is utilized in direction finding, surveillance, and electronic warfare systems (2–5).

SPIRAL ANTENNA GEOMETRY

The defining equation for a planar Archimedean spiral is

$$\rho = \pm k\phi \tag{1}$$

where ρ is the distance from the origin to a point on the spiral, ϕ is the angle measured from a reference axis in the counterclockwise direction, and k is a parameter that determines how tightly the spiral is wrapped. The sign of k determines the direction of wrap. The spacing between the turns of an Archimedean spiral is given by $2\pi|k|$. If Eq. (1) is used to define the centerline of one arm of an antenna, then the centerline of the other arm of a balanced, symmetric antenna would be given by

$$\rho = k(\phi - \pi) \tag{2}$$

Input terminals are provided by starting the spiral, not at $\rho = 0$ or $\phi = 0$, but at some other value of either ρ or ϕ. The structure is truncated at the large end by defining a maximum value of either ρ or ϕ. The antenna of Fig. 3 was drawn by using Eq. (1) with $k = 0.01$, $\phi_{\min} = \pi/2$ and $\phi_{\max} = 10\pi$ and Eq. (2) with $k = 0.01$, $\phi_{\min} = 3\pi/2$ and $\phi_{\max} = 11\pi$.

The equation for the logarithmic spiral curve of Fig. 2 is

$$\rho = e^{a\phi} \tag{3}$$

where ρ and ϕ are as defined above, e is the base of Napierian logarithms, and a is a parameter. Since

$$\frac{d\rho}{d\phi} = ae^{a\phi} = a\rho \tag{4}$$

the parameter a is given by

$$a = \frac{1}{\rho}\frac{d\rho}{d\phi} \tag{5}$$

which shows a to govern the rate at which the distance from the origin increases as ϕ increases. Hence, a is called the spiral-rate constant. Negative values of a give spirals that approach the origin as ϕ increases, said to be wrapped in the direction opposite to those with positive a.

An incremental change in ϕ produces an incremental change in ρ as shown in Fig. 5. The hypotenuse of the differential triangle becomes tangent to the curve in the limit as $\Delta\phi \to 0$.

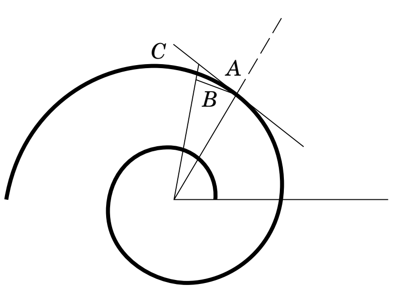

Figure 5. Construction showing the angle, A, between an extended radius and the tangent to a logarithmic spiral curve. $A = \alpha$, $B = \rho\,\Delta\phi$, $C = \Delta\rho$.

$$\lim \frac{\Delta\rho}{\rho\Delta\phi} = \frac{1}{\rho}\frac{d\rho}{d\phi} = a = \cot\alpha \tag{6}$$

Hence, the angle α between the radial line and the tangent is another measure of the spiral rate. Spirals with α near 90° are said to be *tightly wrapped,* but those with small values of α are *loosely wrapped.* For a given logarithmic spiral, the angle α is fixed, leading to the alternative name, *equiangular spiral.*

Suppose that the scale is changed on a log-spiral curve, say by multiplying the radial coordinate by a constant, $K < 1$.

$$\rho_2 = Ke^{a\phi} \tag{7}$$

The same spiral would be given by

$$\rho_2 = e^{a(\phi + \frac{1}{a}\ln K)} \tag{8}$$

which is the equation for the original spiral rotated through the angle

$$\delta = -\frac{1}{a}\ln K \tag{9}$$

clockwise being considered the positive direction of rotation. Hence, a change in the scale of a log-spiral curve is equivalent to a rotation.

Two log-spiral curves separated by rotation by some angle δ form the edges of one arm of a log-spiral antenna. Either δ or K can be used as the arm-width parameter, because they are related by Eq. (9). A third edge for the arm can be defined either by $\pi = d/2$ or by $\phi = \phi_1$; a fourth edge, either by $\rho = D/2$ or by $\phi = \phi_2$. For a symmetrical, balanced antenna the second arm is obtained by rotating the first by 180°. One of the arms of the log-spiral antenna of Fig. 4 was defined by

$$\rho_1 = e^{0.25\phi}$$
$$\rho_2 = e^{0.25(\phi - \pi/2)}$$
$$\phi_1 = -3\pi$$
$$\phi_2 = 0.5\pi$$

and the other one, by

$$\rho_3 = e^{0.25(\phi - \pi)}$$
$$\rho_4 = e^{0.25(\phi - 3\pi/2)}$$
$$\phi_3 = -2\pi$$
$$\phi_4 = \frac{3\pi}{2}$$

Frequently, nonplanar spiral antennas are needed. Conical spirals are widely used because of their unique performance. Antennas for fast moving vehicles are often required to be conformal with the surrounding surface. The geometry of a nonplanar spiral antenna is usually derived from that of a

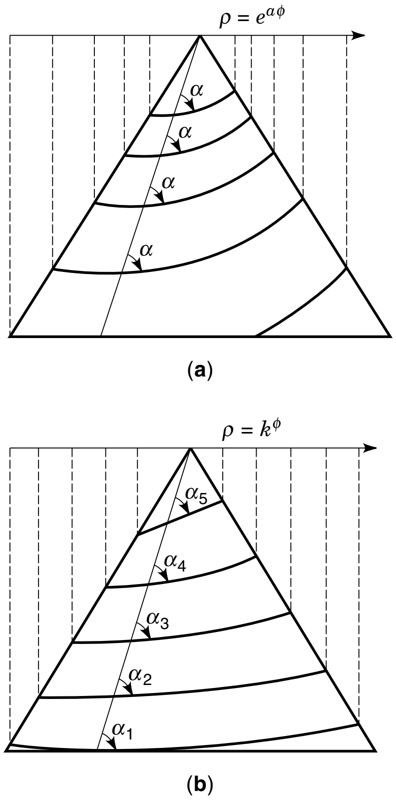

Figure 6. Projection of log-spiral and Archimedean spiral curves in a plane onto the surfaces of cones. Note that the angle, α, between a radius and the tangent to the spiral curves is constant for the log-spiral, but is not constant for the Archimedean spiral. After J. D. Dyson and P. E. Mayes, New circularly polarized frequency-independent antennas with conical beams or omnidirectional patterns. *IRE Trans. Antennas Propag.,* **AP-9:** 4C, 1961.

planar spiral antenna by orthogonal projection. Figure 6 shows how the procedure would work graphically, however, analytic expressions can be used to compute points on the space curves needed to outline the antenna. If the cone is defined by $\phi = \pi - \theta_0$, then the equations for the edges of one conical log-spiral arm are

$$\rho_1 = e^{(a \sin\theta_0)\phi}$$
$$\rho_2 = e^{(a \sin\theta_0)(\phi-\delta)} = K\rho_1$$

As with the planar log-spiral antennas, rotation of both edges of one arm will define the edges of a second arm of a balanced antenna. The angle α between the radius vector and the tangent to any edge of the conical log-spiral antenna remains constant for any cone angle θ_0.

HISTORY OF DEVELOPMENT

Experiments with Archimedean spiral antennas were begun in 1953 by E. M. Turner at Wright Air Development Center, Dayton, Ohio (6). The problem of limited antenna bandwidth was hampering the development of broadband homing, direction-finding and other electronic systems of interest to the U.S. Air Force. The Research Laboratory of Electronics at Massachusetts Institute of Technology (MIT) was awarded a contract to develop a theory for the Archimedean spiral antenna and much development work was done at the Naval Research Laboratory, Diamond Ordnance Fuze Laboratories, and elsewhere. Other contracts went to the Antenna Laboratory of the University of Illinois at Urbana-Champaign (UIUC) to study the general problem of greatly increasing antenna bandwidth.

In September of 1954, V. H. Rumsey came to the UIUC Antenna Laboratory from Ohio State to assume the position of director. It was well known that the performance of an antenna was determined by its size in wavelengths. Rumsey had already tested some preliminary ideas about antennas that were described, insofar as possible, by angles rather than lengths. He also recalled that Mushiake had pointed out that a self-complementary antenna would have a constant input impedance, independent of frequency (7). Little practical use had been made of this principle because all self-complementary shapes extend to infinity. It occurred to Rumsey that an unbounded logarithmic (equiangular) spiral could be specified completely by a single angle and it could be used to define a self-complementary antenna (8). A two-arm, log-spiral antenna is said to be self-complementary when the arm edges are spirals that are 90° apart (as are those in Fig. 4). The space between arms is then congruent to the arms, the condition to be self-complementary.

But could a physical antenna, necessarily a truncated version of the ideal, be made to operate like the infinite one, even over a finite band? He suggested to John Dyson, a graduate student in the Antenna Laboratory, that self-complementary antennas using log-spirals as boundaries should be investigated as potential broadband antennas.

It was not readily apparent how to isolate the performance of the spiral-shaped antenna from the effects of the cable that must be attached to connect the antenna to transmitters or receivers for testing. By making the spiral arms as a slots in a large ground plane, rather than a thin conducting sheet, the cable could be affixed to the ground plane where it would cause minimum perturbation of the field. So the *terminals* of the spiral slots were extended directly toward one another to meet at the origin, the shield of the feed cable was soldered to the area between the spiral slots up to one side of the slot near the origin, and the center conductor was attached on the other side of the slot. In some instances, a dummy cable was soldered in a symmetrical location to improve the balance of the feed region and the symmetry of the radiation patterns. This feed provides a simple conversion from the unbalanced cable to the balanced antenna, the function of devices called baluns.

Dyson demonstrated that planar log-spiral slot antennas in the shape shown in Fig. 4 (with the terminals connected by continuation of the slot) could indeed be made to have impedance and pattern characteristics that changed very little over bandwidths greater than 10:1. Dyson later studied planar sheet log-spirals and conical log-spirals and gave design and application information (9).

THEORY OF OPERATION

As with other antennas, the distribution of current produced by applying a source of radio frequency power to the terminals is the key to understanding the performance of spiral antennas. Although powerful computer methods are available and have been used to find the current distributions on spiral antennas with conducting arms (10,11), the computed results serve primarily to reinforce intuitive concepts and measurements that were used in the original development of spiral antennas.

Consider the Archimedean spiral shown in Fig. 3. A balanced source at the input would produce currents at the terminals which differ in phase by 180°. Because currents tend to travel along thin wires with a constant speed determined by the surrounding medium, the phase difference at any two points that are diametrically opposite one another will remain at 180°. However, it is the relative phase of the currents in adjacent arms of the spiral that is important to understanding the radiation phenomenon. Near the input terminals the distance the current must travel from one terminal until it draws near the current from the out-of-phase terminal is small compared to the wavelength. So the adjacent currents near the input are approximately out of phase. Out-of-phase currents act in a manner similar to currents in a two-wire transmission line, producing little radiation.

At some distance away from the input of an Archimedean spiral antenna there will be a half-turn that is approximately one-half wavelength in length. In this region consider the currents at points A and B that are diametrically opposed on the spiral. As always, these currents will be out of phase. But between point A and a point C on the same spiral arm, where points B and C are located side-by-side on adjacent turns, the current will undergo 180° shift in phase. The condition of zero phase difference at points B and C is conducive to radiation. It is satisfied exactly only at points B and C, but it is satisfied approximately over a band that may constitute several turns of the spiral antenna. The input power is thus guided by the spiral arms from the input terminals to a radiation band that has a circumference approximately equal to the wavelength of the input signal. In the radiation band the currents change in phase by approximately 360° each time they propagate around the quasicircular path. The analysis of such a current distribution leads to a rather broad beam of circularly polarized fields in both the upper and lower hemispheres (12).

The power that is delivered to the input terminals of an Archimedean spiral antenna begins to propagate along the spiral arms as though they were conductors of a two-wire transmission line. As the relative phase of the currents in adjacent conductors begins to change from 180° toward zero degrees, the spiral begins to radiate. The radiation per unit length of the spiral arms will become maximum at the region where the phase difference goes to zero. However, radiation will continue beyond the maximum point. For best performance, it is desirable for almost all of the input power to be radiated before the relative phase of the currents in adjacent conductors approaches 180° once more. If the maximum circumference of the spiral is no greater than one wavelength at the lowest frequency of operation, leftover power will be refected from the truncated ends of the spiral arms. Because the reflected power travels through the radiation zone in the opposite direction to the incident power, the radiation will be polarized in the opposite sense. This will be detrimental to the axial ratio of the antenna. Furthermore, any reflected power that reaches the input terminals will cause a variation in the input impedance as frequency changes.

If the antenna circumference is large enough, additional radiation zones will be present. The phenomenon described above will occur again near any region where the circumference is an odd integer multiple of the wavelength. Because the amplitude and phase of the radiation fields depend upon the order of the radiation zone, simultaneous radiation from more than one zone is generally detrimental to the radiation pattern.

The current distribution on log-spiral antennas is not so easily determined or understood, particularly for the planar case. A combination of numerical techniques, approximate analytical techniques, and experimental measurements have been used. Some of the experimental results are presented in the next section and the numerical methods are discussed briefly in the last section.

EXPERIMENTAL DATA

Planar Log-Spiral Antennas

In the early investigation by J. D. Dyson, the radiation patterns of more than forty log-spiral slot antennas with $0.2 \leq a \leq 1.2$ and $0.375 \leq K \leq 0.97$ were measured (13). Each antenna shape was cut from a 35.5-cm square metal plate and a feed cable was affixed in the area between the slots. The metal plate was then inserted into a like-sized hole near the center of a ground plane 3.66-m square. A movable boom could be swung across the space above the ground plane to measure the θ variable cut in a hemispherical coordinate system with the polar axis normal to the ground plane. The plate containing the slot antenna could also be rotated about the normal so that the elevation cuts could be made at any value of ϕ. Or a ϕ variable cut could be measured, while the boom was held fixed at a given θ location. Typical measured patterns of both the θ and ϕ components of the electric field are shown in Figs. 7 and 8. The patterns at 595 and 12,000 MHz show the effects of truncation at the large and small ends, respectively. Across the band between these frequency limits, a bandwidth of 20:1, the patterns are very much the same.

On loosely wrapped log-spirals, the beamwidths in orthogonal planes are not equal. Then it can be observed that the pattern rotates with changes in frequency. Thus, the pattern repeats periodically with the logarithm of the frequency. Log-spiral antennas are special cases of logarithmically periodic (log-periodic) antennas. Antennas with tightly wound arms and those with wide arms have more uniform patterns that suffer smaller variations in beamwidth. Antennas with negligible variation in patterns and impedance over bandwidths determined solely by the truncation dimensions are called frequency-independent antennas.

Measurements of fields near the antenna arms indicate a rapid decay (up to 20 dB per wavelength) with displacement from the feedpoint. As frequency increases, so does the decay. The portion of the antenna having appreciable near field is almost constant when measured in wavelengths. The decay in near fields makes possible the truncation at a finite distance from the origin while retaining the radiation characteristics of a structure of infinite size. The large-end truncation effect is negligible as long as the arm length is equal to or greater than approximately one wavelength. Because of the spiral shape, this arm length can be contained within a circular area of diameter equal to or less than one-half wave-

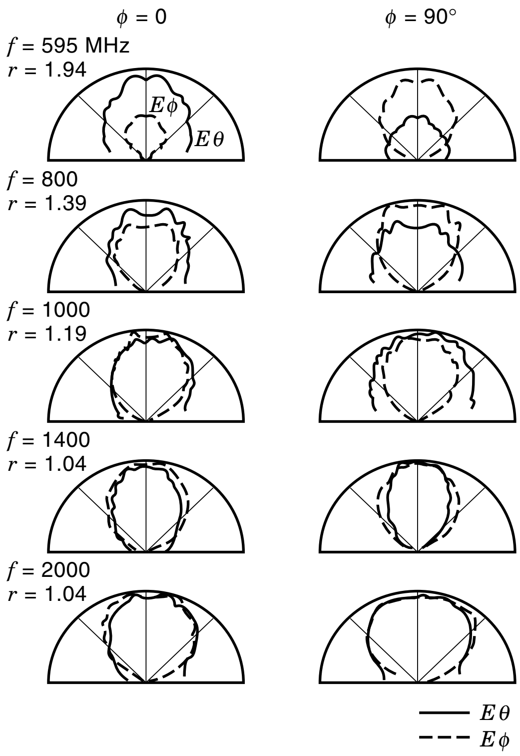

Figure 7. Measured radiation patterns of a two-arm, balanced, log-spiral antenna, r = axial ratio. (After J. D. Dyson, The equiangular spiral antenna. *IRE Trans. Antennas Propag.,* **AP-7:** 2C, 1959.

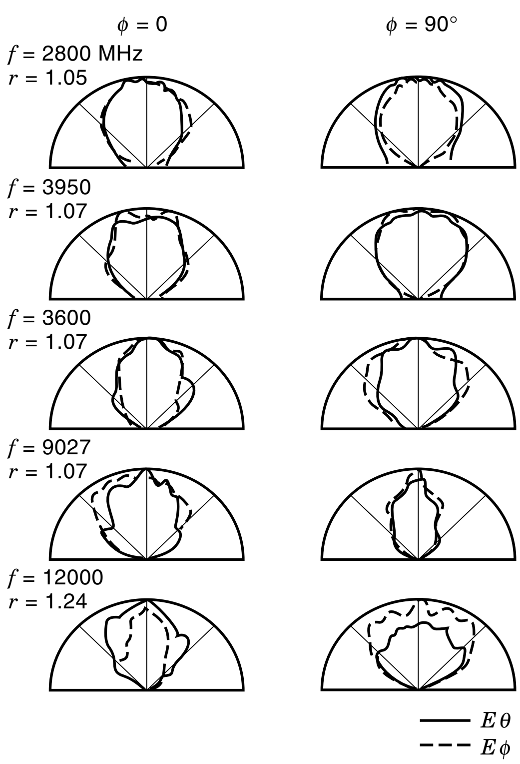

Figure 8. Measured radiation patterns of a two-arm, balanced, log-spiral antenna, r = axial ratio. After J. D. Dyson, The equiangular spiral antenna. *IRE Trans. Antennas Propag.,* **AP-7;** 2C, 1959.

length. Planar log-spirals that are truncated at the large end in a circle operate to a lower frequency for a given maximum diameter than those that are truncated in lines as in Fig. 4.

Once the operating frequency is higher than the required minimum, the input impedance is observed to change little until the frequency is high enough that the feed region becomes an appreciable part of the operating wavelength. The average value of the impedance of a balanced log-spiral antenna is predominantly resistive. For a slot version, the average input impedance varies, depending primarily upon the width of the slot, from 180 Ω for wide slots (K = 0.5) to 60 Ω for narrow ones (K = 0.9). The efficiency of planar log-spiral antennas, whether slots in a metal plane or metal arms in free space, was measured to be approximately 98 %, as long as the arm length was equal to or greater than one wavelength.

Conical Log-Spiral Antennas

A very interesting and useful phenomenon occurs when the arms of a log-spiral antenna are developed on the surface of a cone, as shown in Fig. 9, particularly a cone with small apex angle ($2\theta_0$). As the apex angle decreases, the radiation becomes confined more and more to the half-space in the direction the tip of the cone is pointing. The measured patterns displayed in Fig. 10 show that, when $\theta_0 \leq 15°$, the front-to-back ratio is very high. This unidirectional pattern is needed for many applications and is the principal contributing factor to the popularity of conical log-spiral antennas.

The conical log-spiral can be fed by bonding the feed cable to one arm in a manner similar to the feed of the planar log-

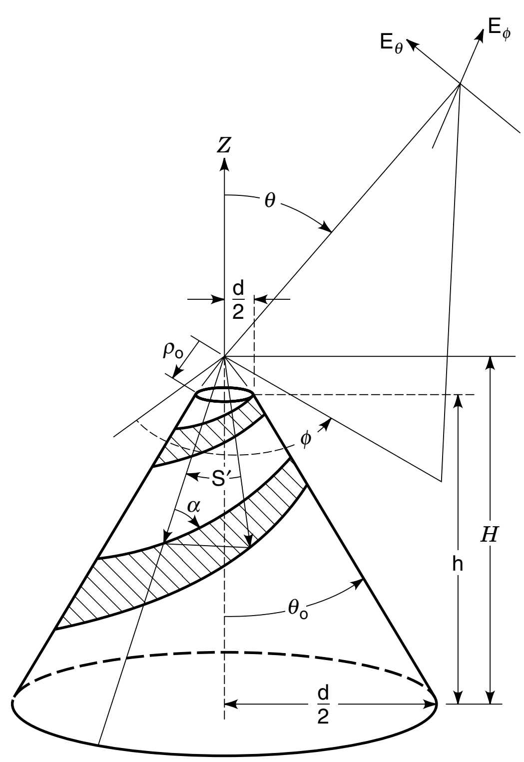

Figure 9. Parameters of a conical log-spiral antenna and the coordinates used to describe radiation patterns. After J. D. Dyson, The characteristics and design of the conical log-spiral antenna, *IEEE Trans. Antennas Propag.,* **AP-13:** 7C, 1965.

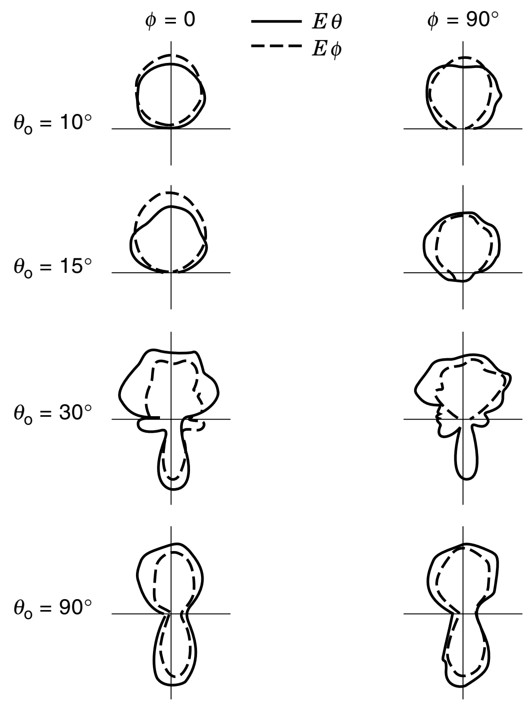

Figure 10. Radiation patterns of a conical log-spiral antenna showing increasing front-to-back ratio with decreasing cone angle, θ_0. After J. D. Dyson, The unidirectional equiangular spiral antenna. *IRE Trans. Antennas Propag.,* **AP-7:** 4C, 1959.

spirals. However, because the cable so used may be much longer than for the planar antennas, cable loss may be unacceptably high, particularly at frequencies above 1 GHz. It is possible to bring a feed line along the interior axis of the cone with minor effect on the performance of the antenna. A single-feed cable can be used with a broadband balun at the feed point, or twin cables can be excited with 180° phase difference by a hybrid network located at the base of the cone.

Since the arms of a conical log-spiral appear to be wrapped more tightly than those of the corresponding planar antenna, the radiation patterns are more nearly rotationally symmetric. Even though the pattern rotates with frequency, the variation in beamwidth is hardly noticeable. A conical log-spiral with $\theta_0 = 10°$ and $\alpha = 73°$ was observed to have half-power beamwidths of 70° for electric field polarized in the θ direction and 90° for electric field polarized in the ϕ direction. The result is radiation that is very nearly circularly polarized over much of the beam.

Much of the behavior of the radiation pattern can be understood in light of knowledge of the near field. Figure 11 shows measured amplitude and phase of the magnetic field close to one arm of conical log-spirals that differ only in angle of wrap, α. For the tightly wrapped case ($\alpha = 80°$) the near field displays a single dominant peak beyond which occurs a precipitous drop. The measured phase is smooth and indicative of the phase progression of a wave traveling toward the feedpoint (i.e., radiation in the backfire direction). Most of the radiation takes place in the vicinity of the peak of the near field, the so-called *active region.* The radiation in the backfire direction results in the rapid decay in the near field. When the active region is relatively small, encompassing only a few turns of the spiral, most of the radiation is phased for backfire. As frequency changes, the active region moves, maintaining constant size in wavelength measure.

When the antenna is wrapped more loosely ($\alpha = 60°$), the active region is broader and includes turns that are phased away from backfire toward broadside. This accounts for the broader beams. This effect becomes even more pronounced as the wrap is loosened further ($\alpha = 45°$). Fluctuation in the near-field amplitude in Fig. 11 is caused by the probe passing close to conductors of the spiral. The dashed lines show smoothed data more indicative of the behavior of the near field along the arm rather than that along a radial line.

The plots of phase versus displacement in Fig. 11 illustrate how the phasing is affected by the increasing length of conductor in each successive turn of the log-spiral. Appreciable slope is seen in the active region for $\alpha = 80°$. As the slope in the active region decreases, more turns are included in the active region and some of these turns are phased in directions slightly removed from backfire. The bandwidths of antennas with wide active regions are smaller for a given physical size than those of antennas with more limited active regions.

Apparently because of the effective small wrap angle of conical log-spiral antennas, the pattern performance does not depend greatly upon the width of the arms. In fact, for moderate bandwidths it is possible to eliminate the flat conductors altogether if a dummy cable is used on the second arm as recommended to preserve the symmetry.

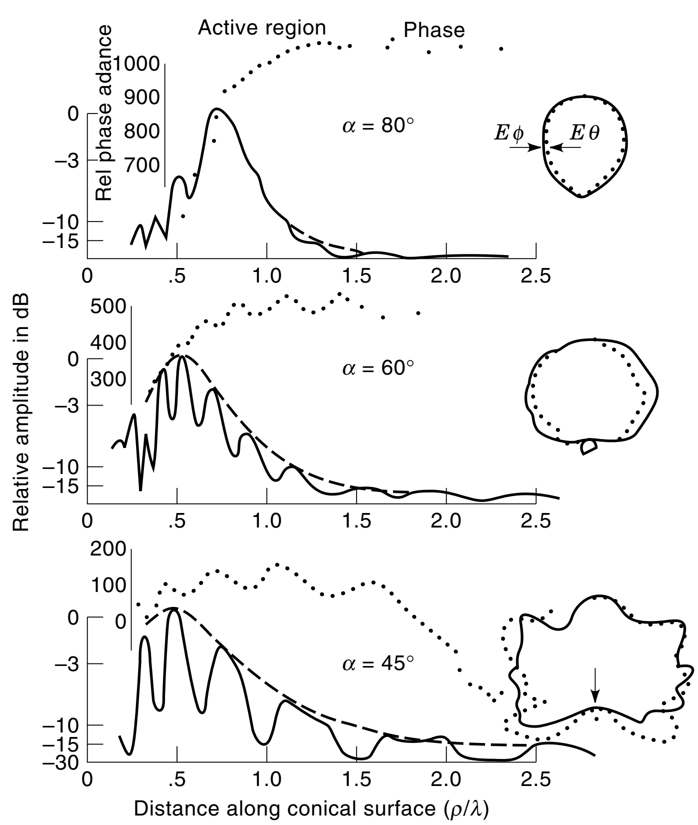

Figure 11. Relative amplitude and phase of magnetic fields (currents) measured along the surface of conical log-spiral antennas ($2\theta_0 = 15°$, $\delta = 90°$) and corresponding radiation patterns. After J. D. Dyson, The characteristics and design of the conical log-spiral antenna. *IEEE Trans. Antennas Propag.,* **AP-13:** 7C, 1965.

Several parameters are required to describe a single conical log-spiral antenna. The pattern shape is most dependent upon the apex angle, $2\theta_0$, of the cone. However, the arm width, δ, and the wrap angle, α, can also have an effect. Radiation patterns for several values of $2\theta_0$, δ, and α are shown in Fig. 12. As to be expected, tightly wrapped antennas have the smoothest, most symmetrical patterns for a wider range of $2\theta_0$ and δ. However, the front-to-back ratio is best for the smallest apex angle, $2\theta_0 = 15°$. Antennas with arm widths given by $\delta = 90°$ have patterns superior to those with either wider or narrower arms. Infinite planar spiral structures with $\delta = 90°$ are self-complementary. Although the argument for constancy of impedance applies only to such planar cases, evidently there are other advantages to be gained by applying the self-complementary condition.

The measured input impedance does not change much over the frequency band of good patterns, a span of 20 : 1 or more in frequency is possible. Table 1 gives data for the mean impedance and SWR as a function of the cone angle, θ_0.

Table 1. Measured Input Impedance of Balanced Conical Log-Spiral Antennas ($K = 0.925$, $L = 150$ cm, $a = 0.303 \sin \theta_0$, $\alpha = 73°$)

θ_0	Approx. mean impedance (Ω)	Max. SWR[a]
10°	129	1.9
15°	147	1.9
30°	153	1.95
90°	164	2.1

[a]Referred to the mean impedance.
Source: J. D. Dyson, The unidirectional spiral antenna, IRE Trans. Antennas Propag, **AP-7**: 4C, 1959.

Multiarm Log-Spiral Antennas

Although most log-spiral antennas in use today have two arms, that is by no means a requirement. The needs of certain applications can be better met with an antenna having more than two arms. Log-spiral antennas with only one arm can be fed against ground, but the performance is unsuitable for most applications (14,15). Two-arm log-spirals are conventionally fed with 180 degree phase difference between the arms at the input. As the number of arms increases, other possibilities arise, as shown in Fig. 13. Some of these are simply related to the azimuthal (ϕ dependent) solutions of Maxwell's equations, $\exp(\pm jm\phi)$, where m is an integer to ensure single-valued fields. The conventional feed for two-arm spirals can produce fields having only odd integer values of m, because a rotation of 180° is in agreement with a phase change of 180°. However, measurements of the fields radiated from conventionally fed two-arm spirals find that contributions from values of m greater than one are negligibly small. Hence, it might be expected that a field which varies as $\exp(\pm j2\phi)$ could be produced by feeding a four-arm spiral as shown in Fig. 13(c). Recalling that the sense of polarization is determined by the direction of wrap, trying to excite a multiarm spiral in the wrong sense leads to poor performance. The excitation of Fig. 13(c) applies equally well to $m = \pm 2$, but the direction of wrap determines the sense of the polarization. The purity of the phase law as given by $\exp(\pm jm\phi)$ is demonstrated by the measured phase of the

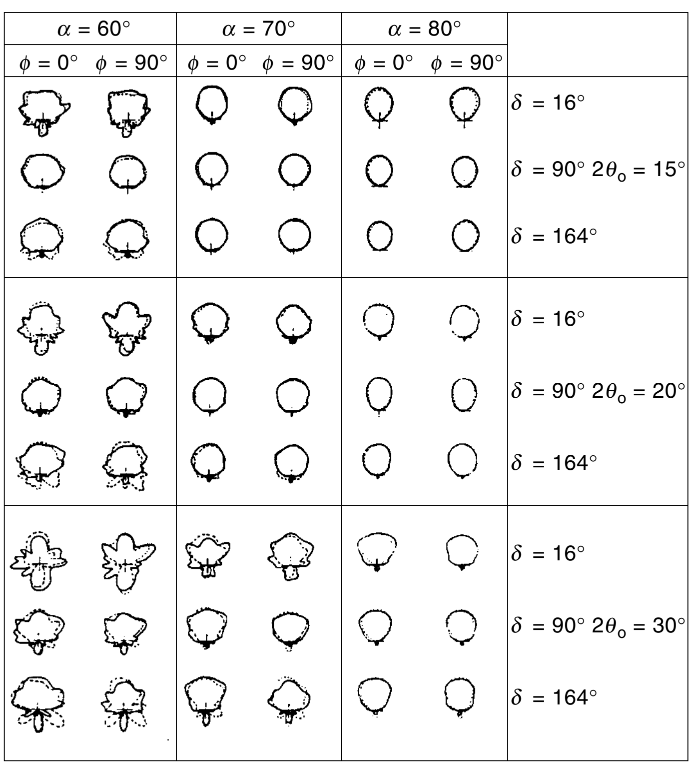

Figure 12. Typical radiation patterns indicating changes in shape with cone angle, θ_0, spiral angle, α, and angular arm width, δ. After J. D. Dyson, The characteristics and design of the conical log-spiral antenna. *IEEE Trans. Antennas Propag.,* **AP-13:** 7C, 1965.

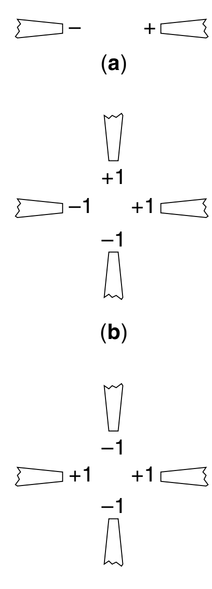

Figure 13. Possible simple excitations of multiarm antennas. After J. D. Dyson and P. E. Mayes, New circularly polarized frequency-independent antennas with conical beams or omnidirectional patterns. *IRE Trans. Antennas Propag.,* **AP-9:** 4C, 1961.

fields radiated by two-arm and four-arm spirals shown in Fig. 14.

Maxwell's equations show that any solution of the form $\exp(\pm jm\phi)$, with integer m differing from unity, has a null along the polar axis (a *conical* beam). Figure 15 shows elevation-plane patterns for four-arm conical log-spirals fed in the manner of Fig. 13(c). Note that the angle of the peak of the conical beam can be controlled by changing the angle of wrap parameter, α. Using $\alpha = 45°$ produces a circularly polarized field that has an omnidirectional pattern in the azimuthal ($\theta = 90°$) plane. Recalling that the angle of wrap of the logarithmic spiral is constant, whereas that of the Archimedean spiral is not, it can be expected that consequences of this difference in geometry would be displayed in the radiation characteristics of these two types of spirals. A widening of the beamwidth of the two-arm Archimedean spiral is hard to observe for planar antennas, but becomes more apparent for conical versions. For four-arm spirals excited to produce conical beams, the difference in radiation patterns is evident, as shown in Fig. 16. Thus, it is possible by using a four-arm conical Archimedean spiral to obtain a beam that scans toward the horizon as frequency increases. If this frequency-scanning behavior is not desirable, then a logarithmic spiral should be used.

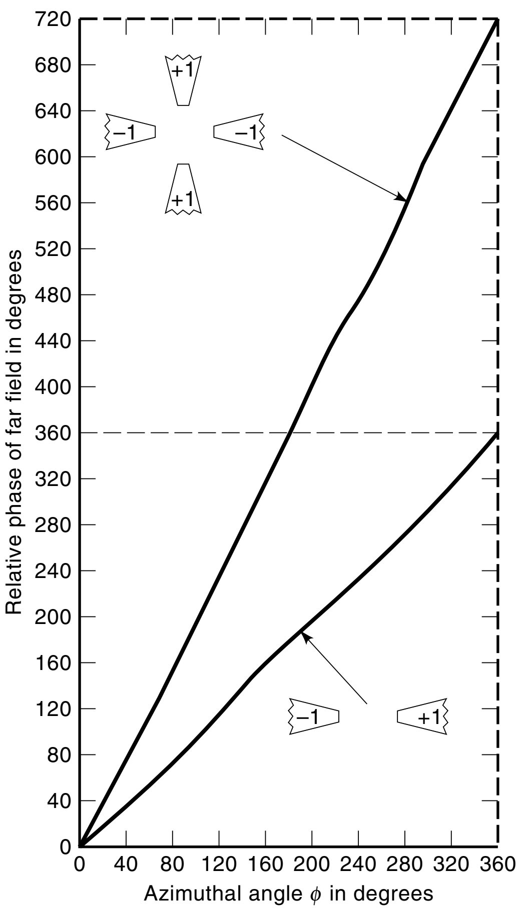

Figure 14. Phase of radiated field measured in the $\theta = 90°$ plane as a function of the azimuth angle, ϕ, for two antennas with $\alpha = 45°$. After J. D. Dyson and P. E. Mayes, New circularly polarized frequency-independent antennas with conical beams or omnidirectional patterns. *IRE Trans. Antennas Propag.,* **AP-9:** 4C, 1961.

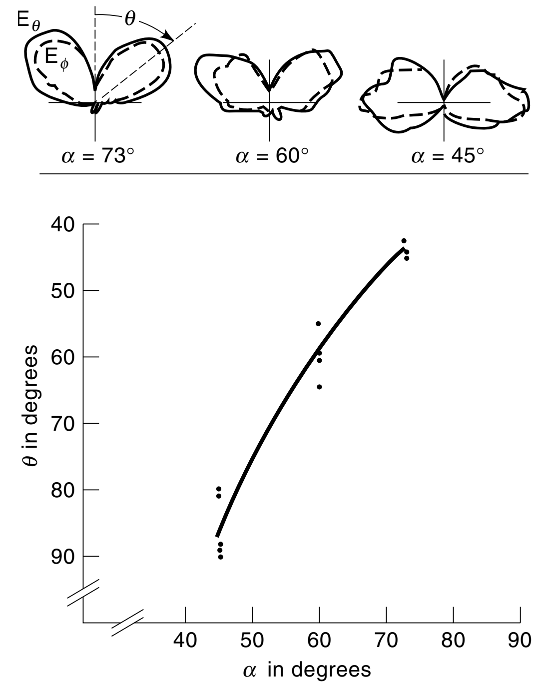

Figure 15. Typical radiation patterns and orientation of the conical beam as a function of the spiral angle, α ($7.5° \leq \theta_0 \leq 10°$). After J. D. Dyson and P. E. Mayes, New circularly polarized frequency-independent antennas with conical beams or omnidirectional patterns. *IRE Trans. Antennas Propag.,* **AP-9:** 4C, 1961.

RECENT AND FUTURE WORK

Planar spiral antennas in free space find little application because of the equal radiation on both sides of the plane. If the application will allow 3 to 4 dB loss, the power radiated from

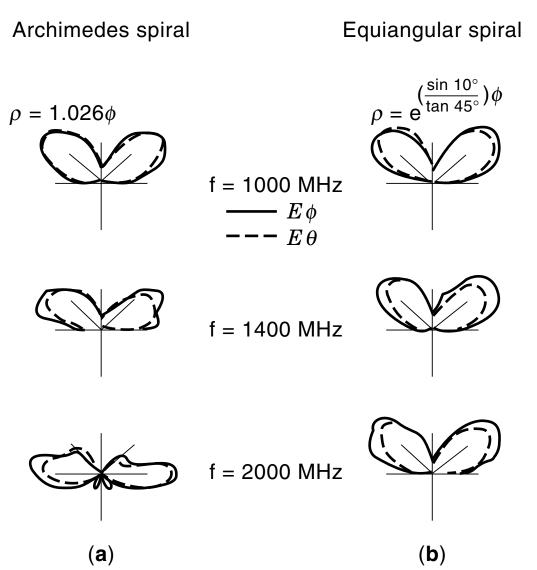

Figure 16. Radiation patterns of symmetrical, four-arm (a) Archimedean and (b) equiangular spiral antennas; $\theta_0 = 10°$, $D = 29.5$ cm, $d = 4.5$ cm, ($\phi = 90°$, θ variable). After J. D. Dyson and P. E. Mayes, New circularly polarized frequency-independent antennas with conical beams or omnidirectional patterns. *IRE Trans. Antennas Propag.,* **AP-9:** 4C, 1961.

one side can be absorbed. This is often accomplished by placing a conducting cavity on one side of a planar spiral and introducing resistance cards, lossy foam, or some other absorbing material into the cavity. Sometimes the losses can be avoided if the band to be covered is sufficiently narrow and some degradation in performance can be permitted.

Some recent publications have indicated that spiral antennas can operate well when placed parallel to a closely spaced conducting ground plane (16). The effect of the close ground is to reduce the rate of decay of the currents on metal spiral arms. Hence, it may be necessary to absorb the power that is left at the truncation to prevent large reflected power from degrading the pattern and impedance. A ring of absorber around the outer rim of a spiral antenna may dissipate less power than an absorbing cavity and provide thereby increased gain.

An alternative to the peripheral absorber ring is a vertical resistance card that spans the space between the spiral arms and the ground plane and follows along an edge or the centerline of the spiral. This method has the potential to control the rate of decay of the currents so that negligible current remains to be reflected at the truncation. Although computer simulations have shown the card-loaded spirals over close ground to work well, the construction of such an antenna is difficult and the measured performance is not as good as predicted (15).

The electromagnetic boundary-value problem presented by a log-spiral antenna has, so far, proved intractable. Analytic results have been obtained for anisotropic conducting sheets with spiral lines of conductivity (17,18), but this model is somewhat divergent from the practical case. The availability of high-speed digital computers has made it possible to solve discretized versions of integral equations for practical log-spiral geometries. The conducting arms of a spiral antenna are divided into many small areas (patches). The current on each patch is represented by some (basis) function with an unknown complex-valued coefficient. Expressing the field in terms of these coefficients enables one to convert the integral equation into a set of linear algebraic equations that can be solved with standard techniques. The digital computer is capable of solving such systems of equations that involve thousands of unknowns. The coefficients so determined can be used with the basis functions to calculate an approximate current distribution on the antenna. The calculation of the radiated fields, polarization and patterns, from the approximate currents is straightforward. An approximate value for the input impedance can be determined from the value of the current at the input terminals. Additional information about applying these *method of moments* techniques to spiral antennas can be found elsewhere (19,20).

Finding the currents on multiarm spirals, particularly those used with closely spaced ground planes or cavities (with or without absorber) and intended for use over very wide bands, can tax the capability of even the fastest supercomputer. One way to reduce the number of unknowns on many spiral antennas is to make use of the discrete rotational symmetry, the fact that each arm is an exact duplicate of the others and the separations between adjacent arms are the same. Further work in numerical analysis will likely yield faster algorithms for computing the electromagnetic fields produced by various distributions of currents and this will reduce the computer time needed to solve problems with large numbers of unknowns. Alternative methods for evaluating the input impedance may prove to be more accurate than the value obtained directly from just the approximate current at the input terminals.

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