

TECHNICAL FEATURE

Resonant Quadrifilar Helix Design

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C. C. Kilgus received the B.S. in electrical engineering from Drexel Institute of Technology in 1964 and the M.S.E. degree from Johns Hopkins University in 1968. He is presently at Johns Hopkins University as a candidate for the Ph.D. degree. In 1964 he joined the Applied Physics Laboratory of the Johns Hopkins University and is now a member of the Senior Staff and Project Supervisor of the Satellite R.F. System Design project. Mr. Kilgus is a member of Tau Beta Pi, Eta Kappa Nu and I.E.E.E.

Feeding the elements of the fractional-turn, four element helix in antiphase produces a resonant, circularly polarized antenna with a cardioid shaped radiation pattern. Beamwidths from 90° to 240° , high front-to-back ratios and good circular polarization are simultaneously obtainable by the proper choice of the helical parameters. This paper presents an intuitive analysis linking the helix with the loop dipole antenna. Helix radiation patterns are calculated using this analogy and compared with measured data. Measured beamwidth, back-to-front ratio and axial ratio data are included. Applications of the helix as a satellite antenna and as a ground station antenna, and some practical design details are described.

Circularly polarized antennas with broad beamwidths ($>90^\circ$) have application in space communication links as both non-tracking ground antennas and as stabilized-satellite antennas. Unfortunately, most of the available antennas with broad beamwidth and circular polarization (for example the conical spiral, traveling-wave bifilar helix, or turnstile with reflectors) are cumbersome mechanically at VHF and low UHF.

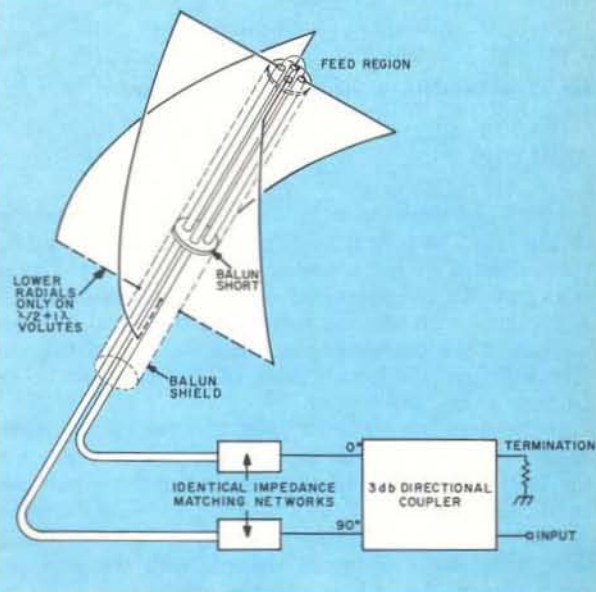
This paper describes a new and more compact antenna, the resonant, fractional-turn, quadrifilar helix with anti-phase feed (called the "volute" in this paper).

Volutes with elements $\lambda/4$, $\lambda/2$, $3\lambda/4$ and 1λ long have been studied. (For convenience, the volute with elements $\lambda/4$ long will be referred to as the " $\lambda/4$ volute".)

These four types of volute are fed in the same fashion (Fig. 1). One end of each element is bent to the center feed point, the opposite end is open circuited ($\lambda/4$ and $3\lambda/4$ volute) or bent to the center and short circuited ($\lambda/2$ and 1λ volute). At the feed point opposite elements are fed in antiphase, producing two independent bifilar helices. Each bifilar helix radiates a circularly polarized, toroid-shaped pattern with the null perpendicular to the helical axis. Feeding these two bifilar helices in phase quadrature produces a cardioid-shaped radiation pattern with circular polarization over the front hemisphere.

In the "analysis" section of the paper a physical argument is presented relating the $\lambda/2$ volute to two orthogonal loop-dipole antennas. The radiation patterns calculated by this equivalence are compared with measured patterns. An earlier paper¹ presented exact integral expressions for the $\lambda/2$ volute radiation pattern shape. Solutions obtained by computer-aided integration were presented and compared with measured data.

The "application" section of this paper includes experimental beamwidth, axial ratio, back-front ratio and radiation pattern data, and details of mechanical construction.



1/4 TURN VOLUTE WITH FOLDED BALUNS
FIGURE 1

Fig. 1 — $1/4$ turn volute with folded baluns.

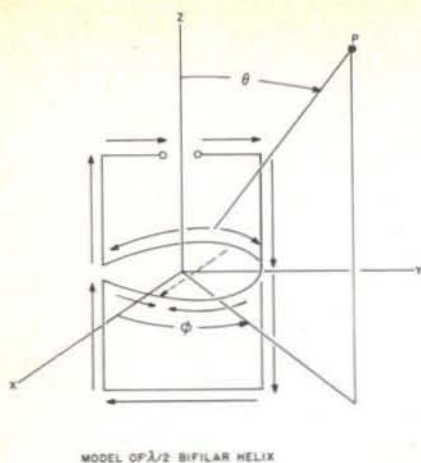


Fig. 2a — Model of $\lambda/2$ bifilar helix.

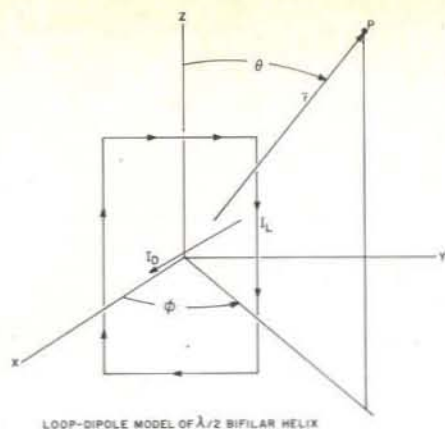


Fig. 2b — Loop-dipole model of $\lambda/2$ bifilar helix.

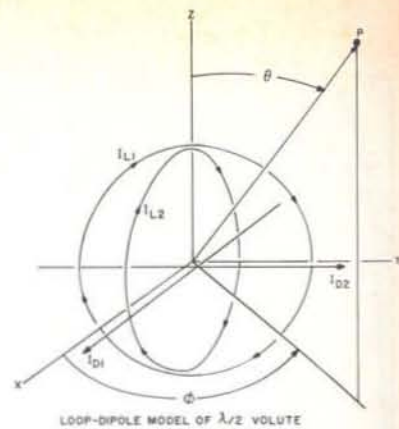


Fig. 2c — Loop-dipole model of $\lambda/2$ volute.

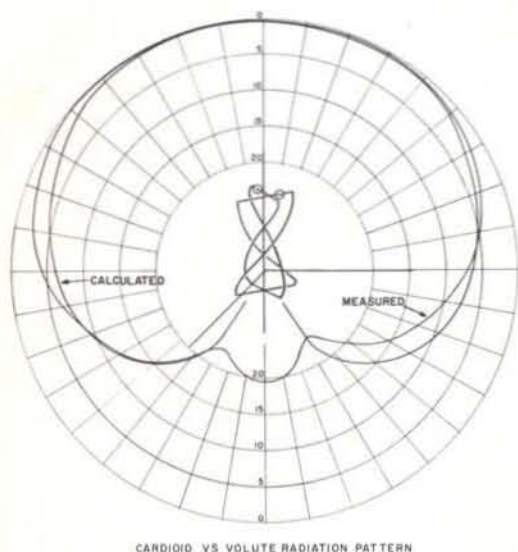


Fig. 3 — Cardioid vs. volute radiation pattern.

ANALYSIS

A simplified model of a $\lambda/2$ turn bifilar helix is sketched in Fig. 2a. The helical parts of the elements have been approximated by linear and semi-circular pieces. The arrows indicate the measured current distribution of the $\lambda/2$ volute; with maxima at the feed and distal ends and minima at the centers of the elements. The dotted current indicates the vector sum of the currents in the circle.

If the wires are removed (Fig. 2b) the current distribution is similar to that of a loop-dipole antenna with the loop in the plane of the radials and the dipole perpendicular to the plane.

The circularly polarized radiation pattern of the $\lambda/2$ turn bifilar helix is toroid shaped, with the null perpendicular to the radials and the helical axis. This experimentally measured similarity with the radiation pattern of the loop-dipole antenna supports the validity of the current model.

Extending this argument, two orthogonal loop dipole antennas (Fig. 2c) fed in phase quadrature provide a model of the $\lambda/2$ volute.

From this model expressions for the volute radiation pattern can be written:²

$$E_{\theta \text{ Loop Dipole } 1} = K e^{-j(kr - \pi/2)} (\sin \phi + j \cos \phi \cos \theta)$$

$$E_{\phi \text{ Loop Dipole } 1} = K e^{-j(kr - \pi/2)} (\cos \theta \cos \phi - j \sin \phi)$$

$$E_{\theta \text{ Loop Dipole } 2} = K e^{-jkr} (-\cos \phi + j \sin \phi \cos \theta)$$

$$E_{\phi \text{ Loop Dipole } 2} = K e^{-jkr} (\sin \phi \cos \theta + j \cos \phi)$$

where: The loops and dipoles are assumed to be electrically small.

$e^{j\pi/2}$ expresses the phase quadrature between the loop-dipole antennas.

K is a function of range, current and length. This constant is the same for the θ and ϕ components of a single loop dipole because of the requirement for circular polarization, and equal for the two loop-dipoles because of physical similarity and equal feed currents.

The normalized total field is:

$$E_{\theta T} = E_{\theta 1} + E_{\theta 2} = (\cos \theta + 1) \angle -\phi$$

and

$$E_{\phi T} = E_{\phi 1} + E_{\phi 2} = (\cos \theta + 1) \angle 90^\circ - \phi$$

The relative phase is 90° and $E_{\theta} = E_{\phi}$ for all θ and ϕ , indicating circular polarization over the sphere. The pattern is cardioid shaped with the maximum along the helical axis. Figure 3 compares the radiation pattern of a $\lambda/2$ turn $\lambda/2$ volute (with $L_{ax} = .27\lambda$) with a cardioid.

APPLICATION

Physical Form

The radius and axial length of the volute are related by:

$$L_{ax} = N \sqrt{\frac{1}{N^2} (L_{volute} - A r_0)^2 - 4\pi^2 r_0^2}$$

where:

L_{ax} = axial length of the volute (in.)

L_{volute} = length along a helical element (in.)

r_0 = radius of the volute (in.)

N = number of turns for one element

$A = \begin{cases} 2 & \text{for the } \lambda/2 \text{ and } 1\lambda \text{ volutes} \\ 1 & \text{for the } \lambda/4 \text{ and } 3\lambda/4 \text{ volute} \end{cases}$

A slightly convex shape improves the symmetry of the radiation pattern.

Experimental Data

Measured beamwidth, axial ratio and back-front ratio data for the $\lambda/4$, $\lambda/2$, $3\lambda/4$ and 1λ volutes with the number of turns as a parameter is presented as Fig. 4. The dashed lines on Figs. 4g and 4j indicate the region

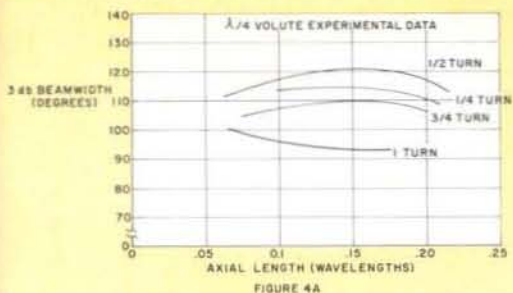


Fig. 4a — $\lambda/4$ volute experimental data.

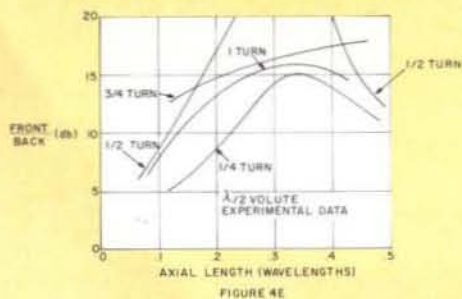


Fig. 4e — $\lambda/2$ volute experimental data.

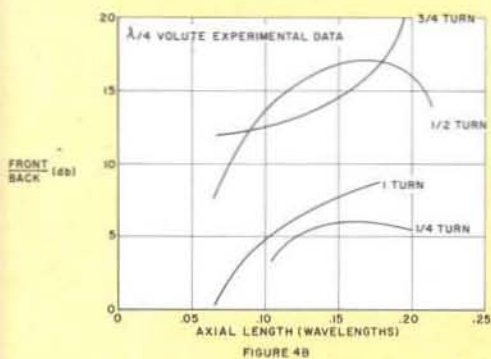


Fig. 4b — $\lambda/4$ volute experimental data.

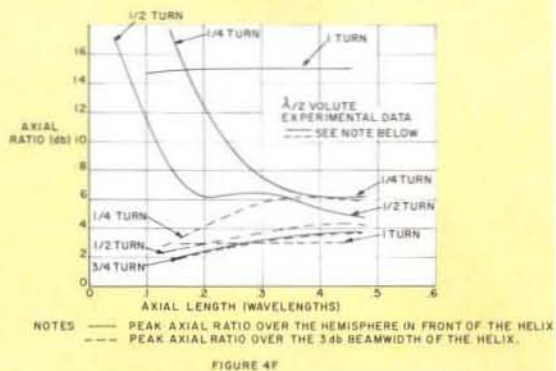


Fig. 4f — $\lambda/2$ volute experimental data.

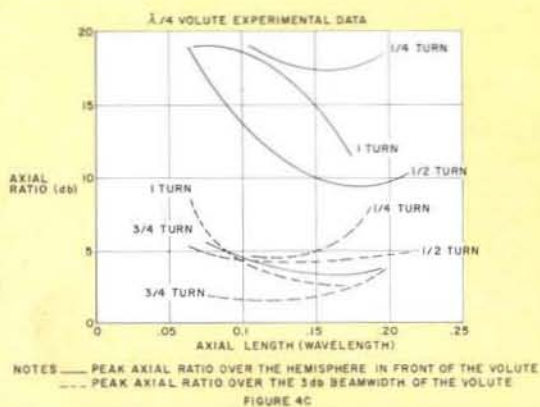


Fig. 4c — $\lambda/4$ volute experimental data.

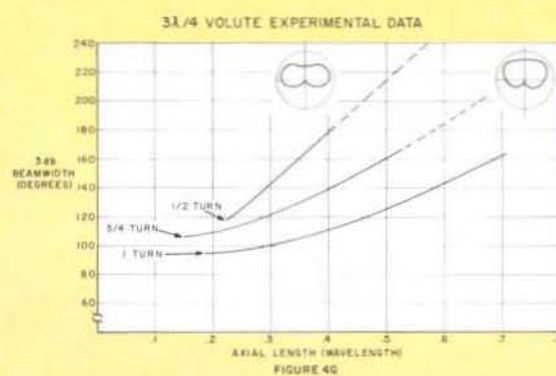


Fig. 4g — $3 \lambda/4$ volute experimental data.

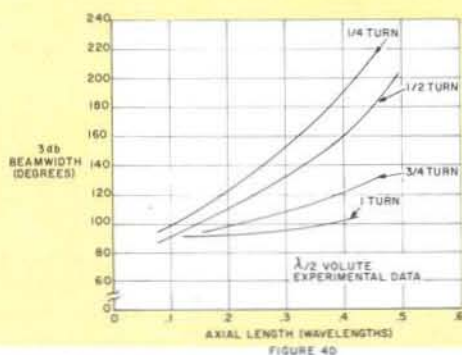


Fig. 4d — $\lambda/2$ volute experimental data.

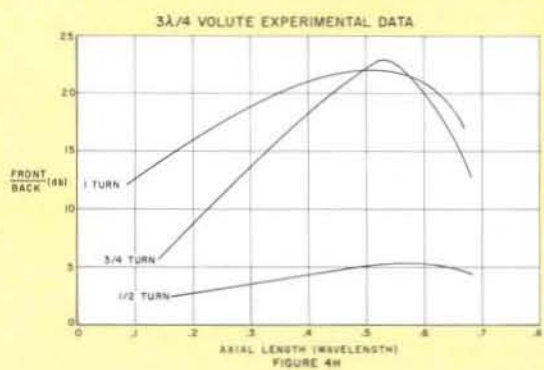


Fig. 4h — $3 \lambda/4$ volute experimental data.

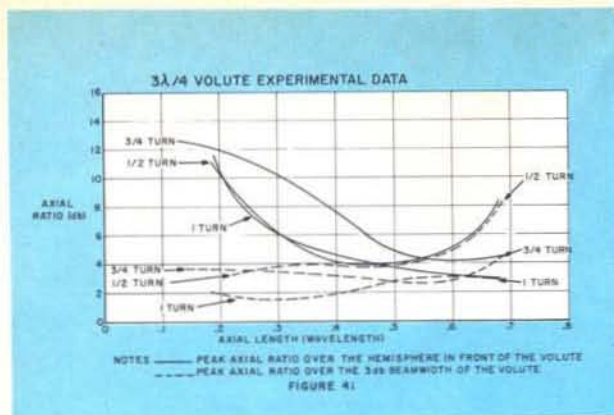


Fig. 4i — 3 λ/4 volute experimental data.

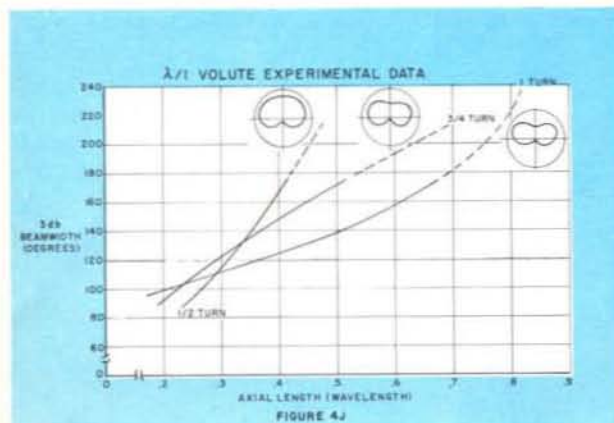


Fig. 4j — 1 λ volute experimental data.

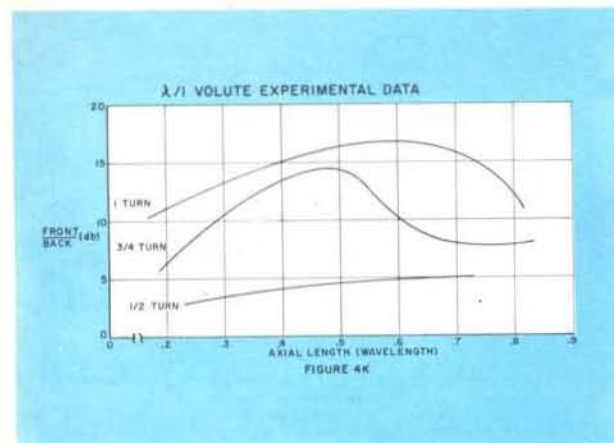


Fig. 4k — 1 λ volute experimental data.

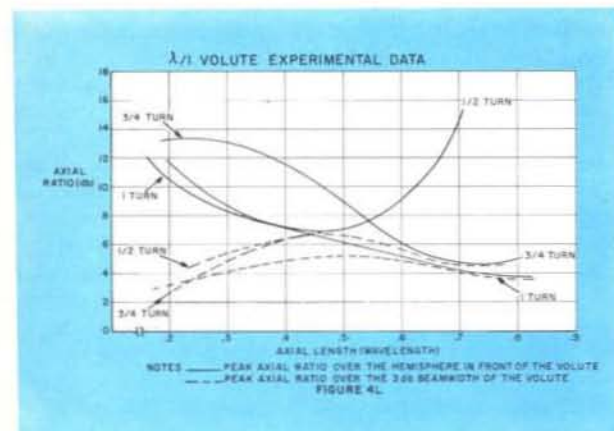


Fig. 4l — 1 λ volute experimental data.

where the maximum of the radiation pattern is not at $\theta = 0^\circ$.

Radiation patterns typical of the various types of volutes are arranged in the sequence:

Figure Number	Type of Volute	Turns	L_{vol}
5a	$\lambda/4$	3/4	.19λ
5b	$\lambda/2$	3/4	.175λ
5c	$3\lambda/4$	3/4	.535λ
5d	1λ	3/4	.64λ

The measurements were made at 400 mcs with an element diameter of .1 inches. The antennas were fed with orthogonal folded baluns as described in the following section.

Folded Balun Feed

Orthogonal folded baluns (Fig. 1) excited in phase quadrature with a 3 dB directional coupler provide a noncritical feed for the volute. The folded balun-directional coupler combination produces a cardioid pattern shape and a 50Ω input impedance over about a 2:1 frequency range. The impedance matching networks shown reduce the power in the coupler termination by matching the antenna and directional coupler impedances.

For a given application the characteristics of the impedance matching network are determined by the feed point impedance of the bifilar helix. Limited data indicates that the antenna impedance has these properties:

The resonant input resistance and the impedance bandwidth increase in proportion to the cylindrical volume enclosed by the volute.

The impedance bandwidth increases in proportion to the element diameter.

As a very rough rule of thumb, a volute with a cylindrical volume of 5×10^{-3} (wavelengths cubed) has a resonant input impedance between 25Ω and 100Ω, and an impedance bandwidth between 3% (thin elements) and 15% (.02λ diameter elements).

The $\lambda/4$ volute has a resonant impedance less than 5Ω and a bandwidth of 1% or less.

Split Sheath Balun Feed

A $\lambda/2$ or 1λ volute with self-phased elements and a split sheath balun³ allows a robust mechanical construction (Fig. 6). Both ends of the helical elements are shorted to the sheath of the balun. At the feed point the $\lambda/4$ long balun slots isolate opposite elements from one another. This feed region configuration applies the same voltage across bifilar helices 1 and 2. As the analysis indicates, the phase of the current in bifilar helix 1 relative to bifilar helix 2 must be 90° to produce the cardioid pattern shape. To obtain this phase shift in the currents, the elements of bifilar helix 1 are adjusted longer than resonance to produce an input impedance with a phase angle of $+45^\circ$, bifilar helix 2 is adjusted shorter to produce -45° . This scheme produces a cardioid pattern shape over only a small bandwidth. The parallel combination of these two impedances is matched to 50Ω by enlarging the center conductor of the coax line inside the balun to form a $\lambda/4$ transformer of the proper impedance.

In an application of the split sheath balun feed a UHF, right-hand-circularly polarized volute was stacked above a VHF, LHC volute to produce a dual frequency satellite tracking antenna (Fig. 7). The elements of both antennas were self-phased. The UHF volute was fed with a split sheath balun of the usual type. The sheath of this balun formed the center conductor of the VHF balun. The VHF balun was a slotted type with two $\lambda/2$ long slots short circuited at both ends.³ The VHF energy is fed to the balun by a parallel feed near the base of the antenna mast. The slots were loaded with fiberglass strips to waterproof the antenna.

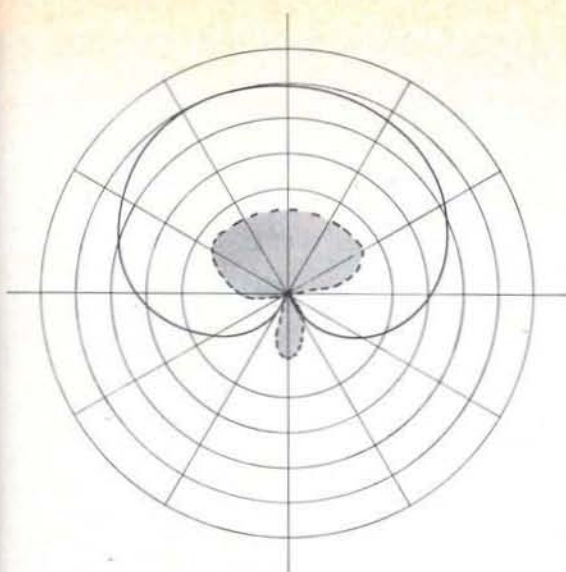


Fig. 5a — $\frac{3}{4}$ turn $\lambda/4$ volute radiation pattern.

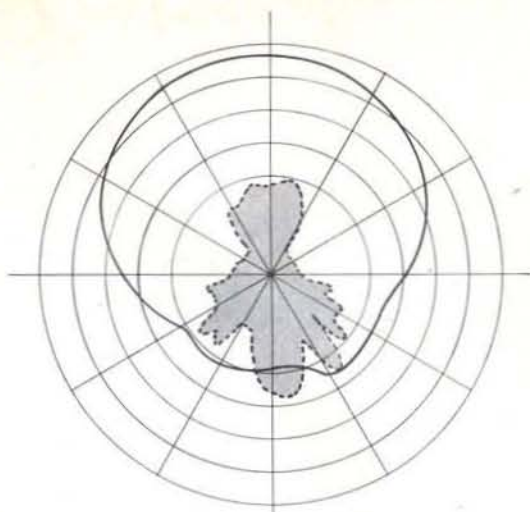


Fig. 5b — $\frac{3}{4}$ turn $\lambda/2$ volute radiation pattern.

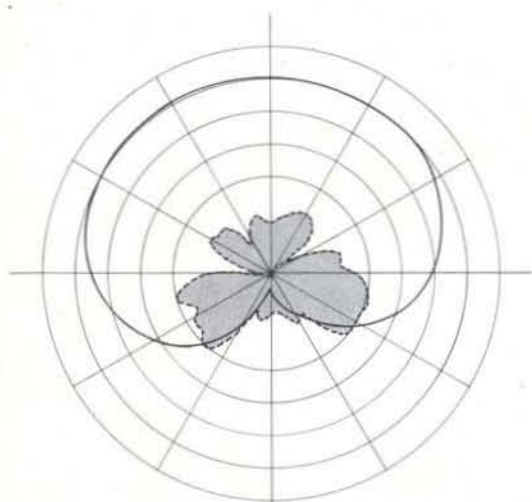


Fig. 5c — $\frac{3}{4}$ turn $3 \lambda/4$ volute radiation pattern.

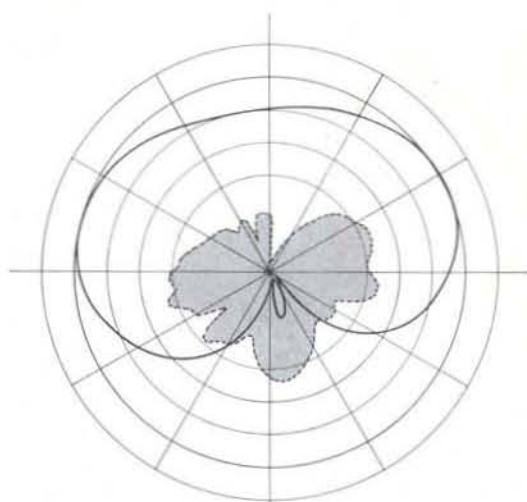


Fig. 5d — $\frac{3}{4}$ turn 1λ volute radiation pattern.

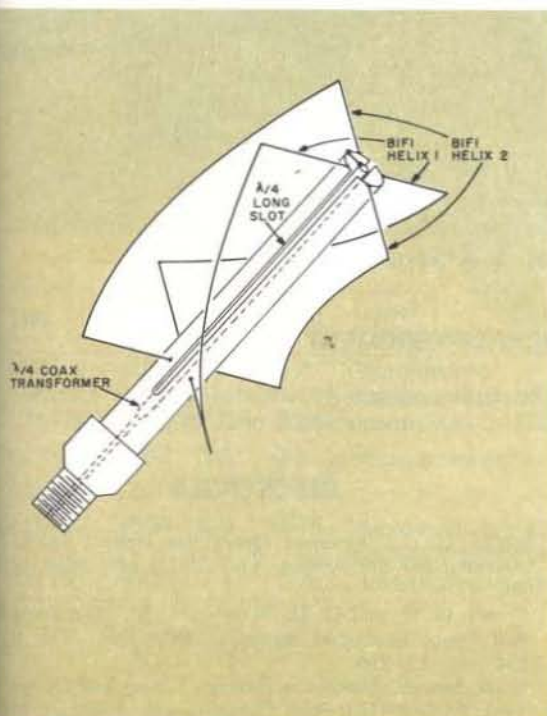


Fig. 6 — $\frac{1}{4}$ turn volute with split sheath balun.

Dual-Frequency Operation

Several dual-frequency antennas have been studied.

If the frequencies are harmonically related, a single volute can be used in the $\lambda/4$ (or $\lambda/2$) mode at the lower frequency and in the $3\lambda/4$ (or 1λ) mode at the higher frequency. In general the beamwidth, bandwidth, etc., will be quite different at the two frequencies and the phasing network becomes more complex.

Vertical stacking (Fig. 7), as already discussed, allows independent control of the antenna parameters.

Coaxial mounting (Fig. 8) reduces the overall size of the antenna and provides the same phase center at the two frequencies. The electrical performance of each volute is only slightly affected by the presence of the other under the conditions:

Outer Antenna: $\lambda/2$, 1 turn, $L_{ax} = .39\lambda$, LHC

Inner Antenna: $\lambda/2$, $\frac{1}{2}$ turn, $L_{ax} = .44\lambda$, LHC

The frequencies are related by $8/3$. The elements are self-phased, each volute is fed with a single folded balun. No work on the coaxial technique was done for other dimensions or frequency separations.

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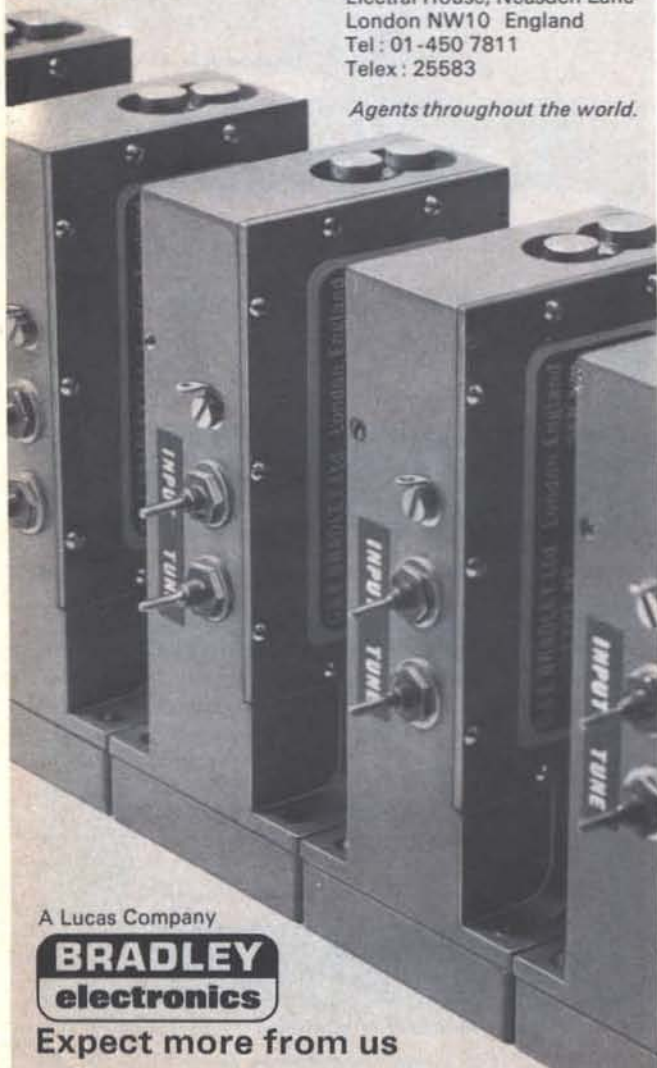
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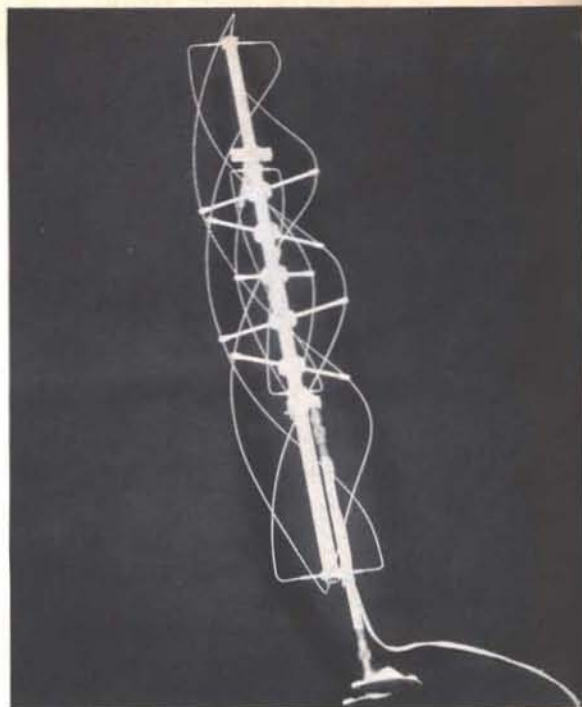


Fig. 7 — Dual frequency satellite tracking antenna.

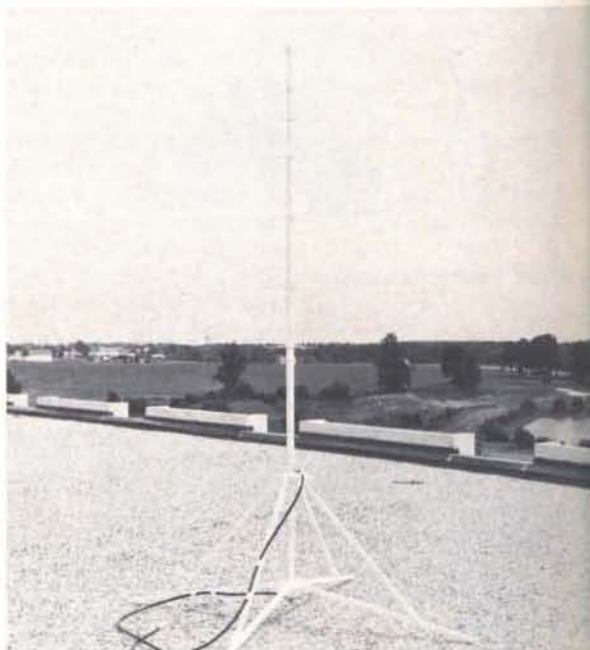


Fig. 8 — Coaxial volutes.

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