Performance of a Meandered Line as an Electrically Small Transmitting Antenna

Thomas J. Warnagiris, *Senior Member, IEEE*, and Thomas J. Minardo

***Abstract*— For antennas to radiate at maximum efficiency, their dimensions must be on the same order as the radiated wavelength. At frequencies below 30 MHz, antennas with efficient radiation are often too large for mobile and portable applications. Smaller antennas can be made to radiate efficiently by use of matching networks. For installation convenience and ease of adjustment, these networks are usually placed between the transmitter and the antenna input; but it has been found that for best radiation efficiency, matching network elements should be placed at points on the antenna structure. Unfortunately, such matching networks must be tuned for each transmitting frequency and, when mounted on the antenna, they cannot easily be tuned. A meander element antenna was found to present some electrical and mechanical properties allowing convenient placement of tuning elements when configured as an electrically small transmitting antenna. Some simplified design guidelines were derived from experimental data.**

***Index Terms*—Antennas, electrically small antennas.**

I. INTRODUCTION

AT ITS operating frequency, an electrically small antenna is much shorter than a quarter wavelength. It has occasionally been pointed out that such an electrically small antenna, free of dissipation, could take from a radio wave and deliver to a load an amount of power independent of the size of the antenna [1]. But the characteristics expected of an electrically small antenna are low-radiation resistance and large reactance and, therefore, very small instantaneous bandwidth with respect to the impedance of normal radio equipment [2]. It's the matching of the antenna impedance to the radio equipment that can significantly affect the overall system performance [3]. This is especially important for transmitting antennas since a good impedance match is essential for maximum power transfer and, hence, efficient radiation.

A. Improvements for Electrically Small Transmitting Antennas

It has been shown that an electrically small vertical antenna, properly designed and installed, approaches the gain of a full-size resonant quarter-wave antenna. For example, the power gain for a very small antenna, a monopole less than 1 ft (0.31 m) above a ground plane at a 40-m wavelength, is 1.5. This increases slowly to 1.513 for an 11 ft (3.35 m) antenna. These gains are to be compared to about 1.62 for a resonant quarter-wave vertical. It can be seen that this difference amounts to less than 0.4 dB [4].

Because of this theoretical near-gain equivalence of an electrically small antenna to a full quarter-wave antenna, much has been tried to improve their bandwidth and radiation resistance. Most improvements have concentrated on the addition of various types of loading to electrically small antennas. The loads have included capacitive, inductive, and resistive loads installed at various points on an antenna.

One additional technique for increasing the terminal resistance (maximum current point) and, therefore, its radiation efficiency, is antenna folding. This is a technique that seems beneficial to radiation resistance without decreasing antenna bandwidth. Seeley had found that "capacitive top loading and folding may be combined to produce a small broad-band antenna with high-radiation resistance" [5].

B. Antenna Radiation Resistance and Input Impedance

Kraus and others have also shown that the radiation resistance and, consequently, the input impedance (maximum current point) of a folded antenna can be quite high and made even higher by the addition of more folded elements. Most of the folded (monopole) antennas described in the literature are resonant structures of at least 1/4 wavelength, although Harrison [6] derived a set of general equations for folded antennas of up to three elements with series reactive loads.

In any case, the important factor provided by the folded structure is that the cancellation of opposite polarity currents from the various elements generally results in a higher average impedance along the folded element as the number of folds increases. Folding offers the possibility of reducing the size of an antenna while still maintaining a high-radiation resistance at resonance. If this folding is applied to small antennas (i.e., less than 1/4 wavelength), the increasing input impedance due to current cancellation may offset the reduction of radiation resistance resulting from the antenna size reduction. Work by Seeley *et al.* [5]–[9] seems to confirm this, but no specific data is presented as proof. Kraus did describe a four-element 3/8 wavelength folded dipole of having an input impedance of approximately 225 Ω at the antenna current maxima [10]. This is much higher than would be expected for a single-element 3/8 wavelength antenna. What apparently has not been heavily investigated is the effect on radiation resistance of electrically small antennas of many folds.

C. Meander Antennas

A meander antenna is an extension of the basic folded antenna to include a large number of folded elements in

---

Manuscript received October 27, 1995; revised August 18, 1998. This work was supported by the U.S. Army Communications and Electronics Command, Ft. Monmouth, NJ.

The authors are with the Communication Engineering Department, Division 10, Southwest Research Institute, San Antonio, TX 78228 USA.

Publisher Item Identifier S 0018-926X(98)09689-6.

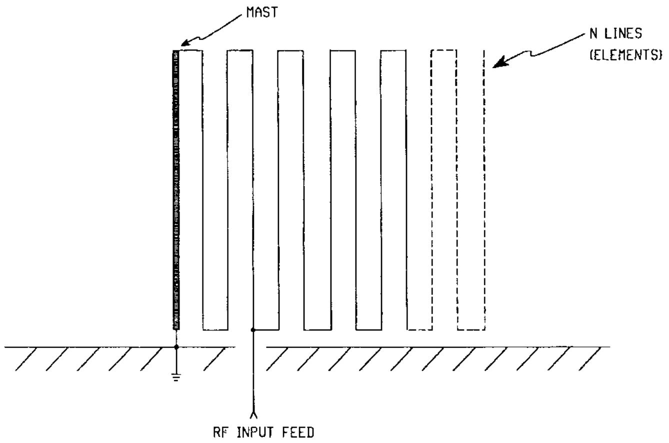


Fig. 1. Prototype antenna electrical configuration.

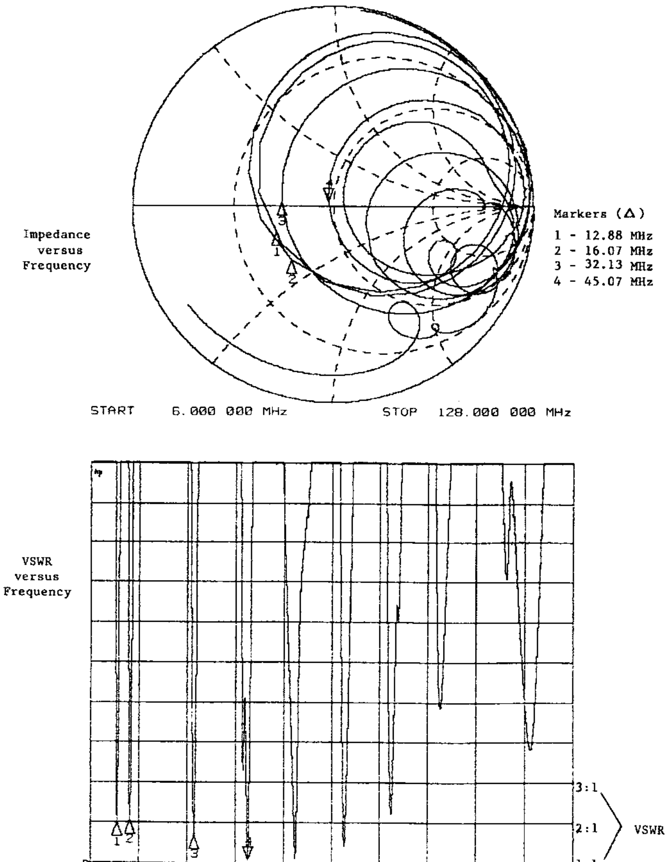


Fig. 2. Impedance and VSWR as a function of frequency for a 23-line meander antenna (connection #1).

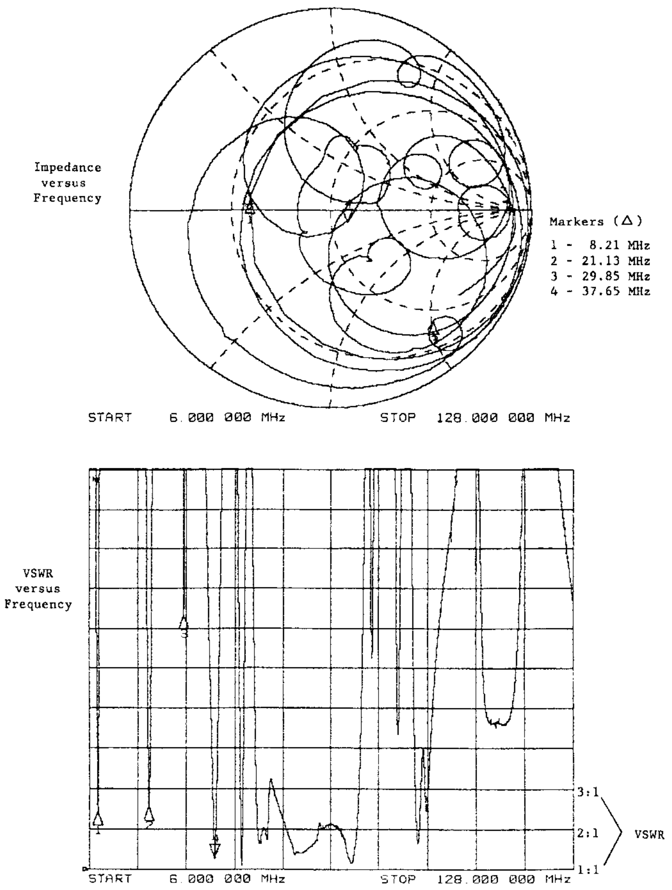


Fig. 3. Impedance and VSWR as a function of frequency for a 23-line meander antenna (connection #2).

various linear patterns (see Fig. 1). Folding the elements in a meander produces resonances at frequencies much lower than resonances of a single-element antenna of equal length. Rashed *et al.* had found that the meander antenna size reduction factor β depends primarily on the number of meander elements per wavelength and the spacing of the element widths of the rectangular loops where $\beta = l/L$ with a conventional monopole of length L having the same resonant frequency as a meander antenna of length l. They had developed an approximate analysis of this antenna using numerical methods but had not shown that radiation efficiency is maintained as antenna size is greatly reduced [7]. Rashed's work addressed analysis of a fairly simple meander antenna consisting of no more than six or seven elements. Meander antennas of great size reduction ($B = <0.5$) were not addressed.

Another interesting property of meander antennas is the number of resonant modes beyond the lowest resonant frequency. Apparently, as a consequence of the various current cancellation and reinforcements, a larger number of higher frequency resonances can occur on a meander monopole antenna than on a simple monopole of the same length. Since these resonances often result in low voltage standing wave ratio (VSWR) at these frequencies, it should be possible to make use of these resonances using the same tuning elements used to tune the lowest resonant frequency. This would allow fewer tuning elements to tune an electrically small antenna over a given frequency range. Investigation of these resonances on a multielement (23 wire lines) monopole meander antenna 45 in above a ground plane revealed that almost any frequency, VSWR, and bandwidth could be obtained by appropriately interconnecting the meander elements. Figs. 2 and 3 show selected VSWR and impedance test results for various meander element connections on the same meander antenna test model. As an example, note the test results shown in Fig. 3. For this test, approximately 20 MHz of low VSWR instantaneous bandwidth was obtained at a center frequency of 58 MHz.

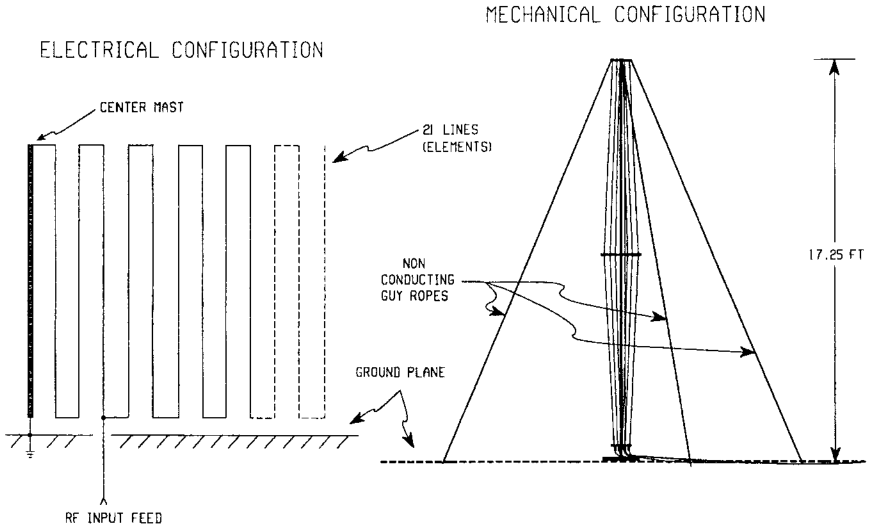


Fig. 4. Prototype antenna electrical and mechanical configuration.

II. Experimental Investigation

Investigation at Southwest Research Institute (SwRI) of small-scale meandered antennas hinted at high-input impedance for antennas much shorter than a quarter wavelength. The input impedance of a meandered 17.25 in antenna with 21 elements (#26 AWG wire lines) was tested over a 3 ft × 4 ft ground plane. Measured impedance at first resonance (20.1 MHz) was 21.9 Ω. This is much higher than would be expected from a monopole antenna 0.03 wavelengths long. The basic electric structure is shown in Fig. 4.

Of course, this may not have been the maximum antenna current point. Webb and others have measured input impedances of only a few Ω for conventional monopoles of this size. Other meandered designs tried at SwRI were fed at the bottom of the meander folds. This produced an impedance transformation that could not be predicted with any certainty. For monopoles 0.03 wavelengths long, the bottom fold feed points were usually at points 10–20% of the total antenna length and produced a 2 : 1 VSWR bandwidth of 2–4% of center frequency. This 2 : 1 VSWR bandwidth was about twice as wide as bandwidths reported for reactively loaded monopoles 0.06 wavelengths long [4].

A dipole 3 ft in overall length was fabricated having a first resonance center frequency of 14.2 MHz. VSWR bandwidth of 2 : 1 was measured over 6.5% of the center frequency (see Fig. 5). When tested for radiation efficiency using the Wheeler method, this antenna exhibited a radiation efficiency of 80% [11]. This is much higher than would be expected for a loaded dipole of 0.05 wavelengths in overall length.

A. Meander Antenna Configurations

Although meandered antenna structures have been investigated by others, there have been no known attempts to construct practical meandered antennas for tunable applications. SwRI has developed several basic meander structures that lend themselves to switch tuning; switch tuning being the low-loss connection or disconnection of elements at various points on the antenna to optimize performance. Practical RF switches can be solid-state devices such as p-i-n diodes, field effect transistors (FET's), or even mechanical switches. Fig. 6 shows the basic electrical configuration of the meandered antenna structures, and Fig. 7 shows the physical configuration. The switches can be placed near the base of the structures for easy access and efficient bypassing of conductive control lines. The grounded mast allows the first meander element to be a high-strength conductive mast that can be directly connected to the ground plane. This also offers increased safety to equipment connected to the antenna from lightning strikes. Series RF switches or shorting switches between elements are possible or a combination of series, shunt, and shorting switches can easily be accommodated at the base of the antenna structure for optimization of antenna bandwidth, tuned frequency, or VSWR. Wide spacing between the elements and high RF voltage points allows transmission of high-power without arcing. The meander antenna appears to be equivalent electrically and physically to a vertical monopole and so can be optimized for any electrical feature of a monopole. As previously described, dipole configurations can also be

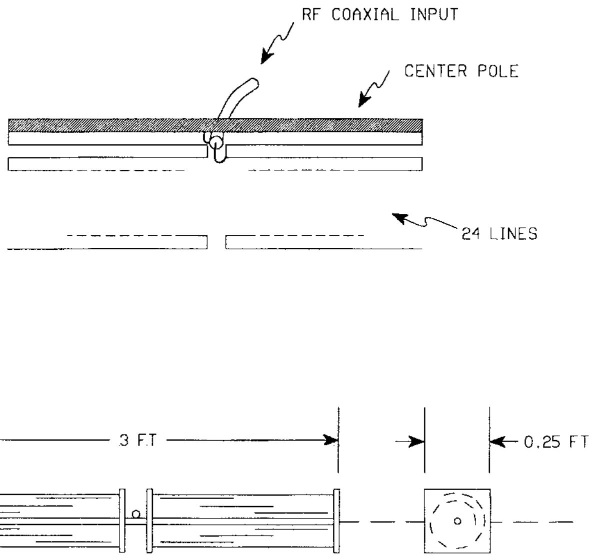


Fig. 5. A 14.2-MHz meander dipole.

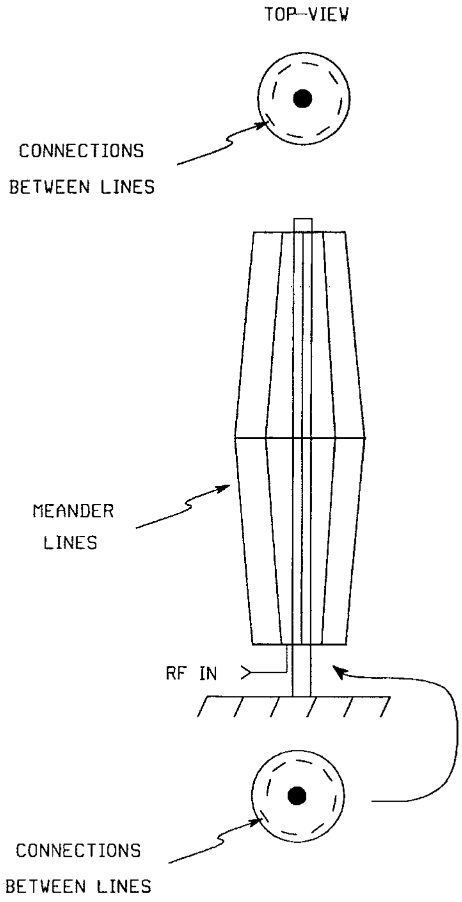


Fig. 6. Typical meander structure.

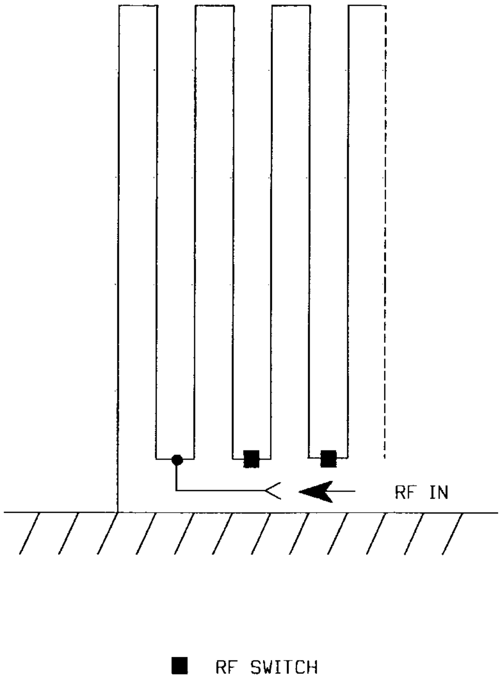


Fig. 7. Basic switched meandered antenna schematic.

constructed consisting of two monopole meandered structures end-to-end fed through a balun or unbalanced at their common point (see Fig. 5).

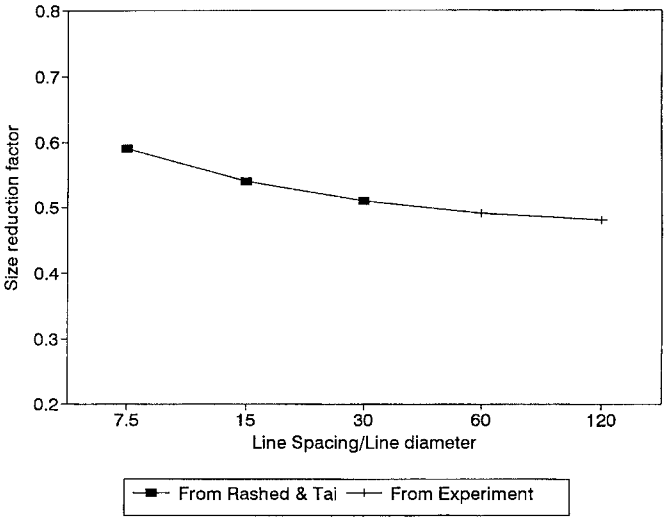


Fig. 8. Typical meander antenna size reduction factor as a function of line spacing.

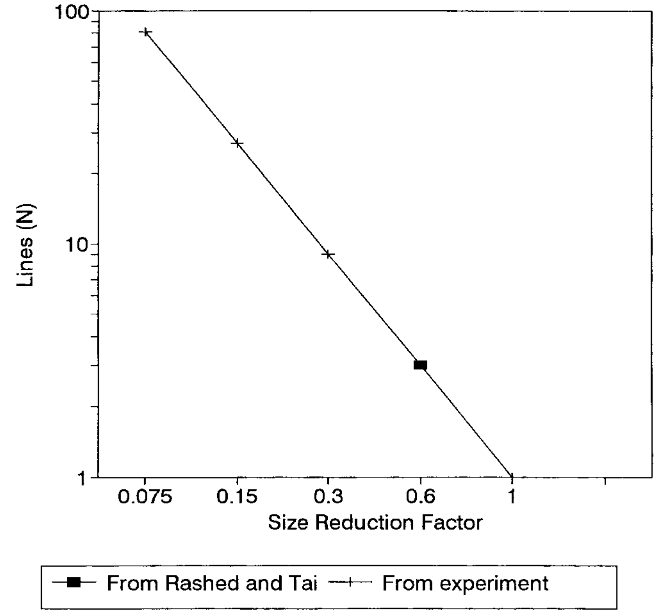


Fig. 9. Number of lines for a typical meander antenna as a function of antenna size reduction factor.

B. Meander Antenna Design

The meander design information supplied by Rashed and Tai was minimal, but proved a starting point [7]. As a result, several meander antenna test models were built and their resonant frequency and VSWR measured. From this test data and that supplied by Rashed and Tai, it was possible to generate a set of rudimentary nomographs for design of any meander antenna of the $n = 2$ type per Rashed and Tai (two folds per three lines as shown in Fig. 1). Fig. 8 shows the expected antenna size reduction for a typical $n = 2$ type meander antenna as a function of the line-spacing to line-diameter ratio. Note that the reduction factor does not change greatly for line-spacing to line-diameter ratios exceeding about 20. Fig. 9 shows antenna size reduction factor β as a function of the number of antenna lines. The nomograph of Fig. 9

applies to antennas with high line-spacing to line-diameter ratios (>20).

These nomographs are only useful for determining the lowest resonance for a meander antenna of a particular size and element spacing. The higher frequency resonances are difficult to predict because of the variation in current distribution with frequency on an antenna with more than three or four folds (six or eight elements). Although these resonances are difficult to predict, they are movable in frequency and VSWR by changing the ground plane size, feed point, and/or electrical length of the antenna. So, by placing a number of switches at key points, a band of interest could statistically be covered with acceptable low VSWR at most if not all frequencies.

III. CONCLUSIONS AND OBSERVATIONS

Meander antennas of many elements appear to offer good radiation efficiency with considerable size reduction compared to conventional half- and quarter-wavelength antennas. Although the VSWR bandwidth of meander antennas is better than many electrically short antennas, it can also be improved by switching the phase relationship of the various elements. Switching can be accomplished mechanically or by electrically controlled switching elements (p-i-n diode switches, FET switches, etc.) on the antenna structure.

To date, no attempt has been made to measure the radiation pattern of the meander antenna models described. Since the meander antenna is essentially linear and electrically short, with closely coupled elements, it would seem that its pattern would be essentially identical to an electrically short dipole or monopole above a ground plane (depending on the antenna model). Due to the element interconnections, there may be some end effects that produce axial far-field radiation, but these should be very small compared to the primary radiation pattern. More work is needed to characterize the many possible meander antenna variants. Available finite-element computer programs should be able to characterize meander antennas for input impedance radiation pattern and efficiency at least at the first resonance.

REFERENCES

[1] H. A. Wheeler, “Fundamental limitations of small antennas,” *Proc. IRE*, vol. 35, pp. 1479–1482, Dec. 1947.

[2] R. A. Burberry, “Electrically small antennas: A review,” *IEEE Colloquium on Electrically Small Antennas*. London, U.K.: IEEE, 1990, pp. 1–5.

[3] K. Fujimoto, A. Henderson, K. Hirasawa, and J. R. Janes, *Small Antennas*. New York: Wiley, 1988, pp. 4–9, 37, 236–239.

[4] J. Sevick, “The W2FMI ground-mounted short vertical,” in *The ARRL Antenna Anthology: American Radio Relay League*. Newington, CT: Amer. Radio Relay League, 1978, ch. 1, pp. 25–29.

[5] E. W. Seeley, “An experimental study of the disk-loaded folded monopole,” *IRE Trans. Antennas Propagat.*, vol. AP-4, pp. 27–28, Jan. 1956.

[6] C. W. Harrison, “Monopole with inductive loading,” *IEEE Trans. Antennas Propagat.*, vol. AP-11, pp. 394–400, July 1963.

[7] J. Rashed and C.-T. Tai, “A new class of resonant antennas,” *IEEE Trans. Antennas Propagat.*, vol. 39, pp. 1428–1430, Sept. 1991.

[8] J. A. Seeger, R. L. Hamson, and A. W. Walters, “Antenna miniaturization,” *Electron. Design*, vol. 3, pp. 64–69, Mar. 1959.

[9] E. W. Seeley, D. Burns, and K. L. Welton, “Cap-loaded folded antenna,” IRE Nat. Convention Rec., Naval Ordinance Lab., Corona, CA, pt. 1, pp. 133–138, 1958.

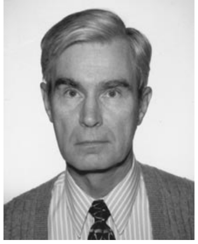
[10] J. D. Kraus, *Antennas.* New York: McGraw-Hill, 1950, p. 418.

[11] H. A. Wheeler, “Small antennas,” *IEEE Trans. Antennas Propagat.*, vol. AP-23, pp. 462–469, July 1975.

Thomas J. Warnagiris (SM’67) was born in Kingston, PA, on April 6, 1945. He received the B.S.E.E. degree from Pennsylvania State University, University Park, PA, in 1967.

From 1973 to 1975, he performed graduate work at the University of South Florida, Tampa, FL. He has worked as an Engineer at ARINC Research Corp., the ECI division of NCR, C-COR Electronics, and HRB Singer Inc. He has been employed by Southwest Research Institute, San Antonio, TX, since 1984 and is currently a Staff Engineer in the Communications Engineering Department. He holds several communications-related patents.

Mr. Warnagiris is a registered Professional Engineer in Pennsylvania and Florida.



Thomas J. Minardo was born in Rochester, NY, on January 13, 1942. After completing high school, he joined the U.S. Air Force in 1962 and remained on active duty until 1982, attending many service schools during his Air Force career.

In 1982, he joined the staff at Southwest Research Institute (SwRI), San Antonio, TX, as a Senior Technician working in the TEMPEST area. In 1986, he was NSA-certified as a TEMPEST Professional Level II and joined the professional staff at SwRI as an Engineering Technologist. He is now working in the wireless and high-power systems section of the Communications Engineering Department of the Automation and Data Systems Division. He has recently been involved with upgrades to various radar systems and antenna research. His current interests include studies of long-term effects of high-voltage application to insulating materials.