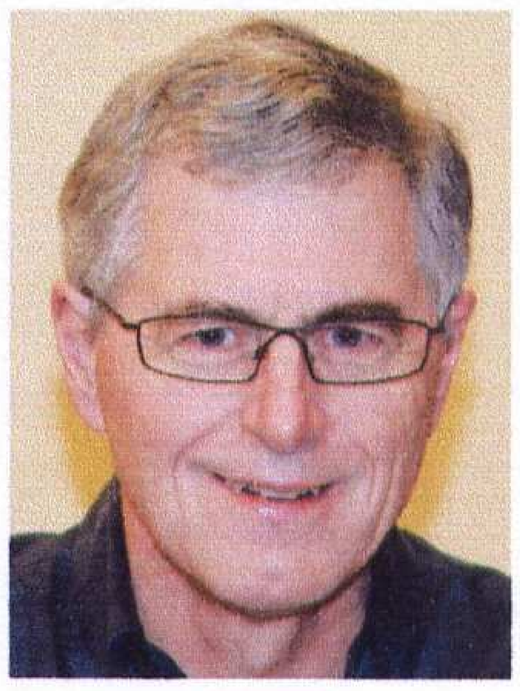

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Loss Mechanisms in the Electrically Small Loop Antenna

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Abstract

The characteristics of an electrically small loop antenna are readily calculable. Being an inherently high-Q device, it requires careful tuning. Its performance as a transmitting antenna is sometimes limited by low radiation efficiency because of inherent losses, combined with a radiation resistance that varies as the fourth power of frequency. An apparent anomaly, frequently encountered in practice, is that the measured Q factor differs significantly from that calculated or obtained by computer simulation. This finding has led some to believe that the loop has a higher radiation resistance than conventional analytical techniques would imply. However, this conclusion is unfounded. Experimental evidence presented here indicates that Q factors close to those predicted can be achieved when appropriate consideration is given to reducing the loss associated with the tuning-capacitor mechanism, in particular. The ground loss (another significant factor) is also calculable, but since it decreases rapidly with increasing loop height above ground, its effect can readily be reduced. Vital to the experimental program that accompanied this work was an effective method – using a toroidal transformer – of measuring the total resistance of the loop.

Keywords: Loop antenna theory and measurement; small loop Q factor; ground loss; low-loss variable capacitors

1. Introduction

The electrically small loop antenna (sometimes referred to as a "magnetic loop"), with a diameter typically much less than $\lambda/10$ [1], has been in service for many years, particularly at HF (3 MH to 30 MHz). Such an antenna has become increasingly used in military applications as an ideal NVIS (near-vertical-incidence skywave) antenna on vehicles, aircraft, and small ships. In those roles, the so-called "half-loop," in a rectangular configuration, is more usual, with the vehicle bodywork providing part of the return path for the antenna current. In general, a typical loop has a diameter of 1 m to 2 m. In order to reduce its losses and to make it mechanically self-supporting, it is usually constructed of thick-walled copper (or aluminum) tubing of at least 20 mm thickness. The loop is naturally inductive, and therefore requires a tuning capacitor (usually variable) to bring it to resonance at its operating frequency.

Various methods have been used to match the loop's resonant impedance to $50\ \Omega$, the usual requirement. Amongst the matching techniques adopted is the so-called miniloop [2], which is essentially a small coupling loop lying in the same plane as the antenna and fed with coaxial cable. A variation on this method is similar to the gamma match [3], in which the feed line is tapped onto the loop at some appropriate point, with its other conductor usually connected to the midpoint at the base of the loop, and diametrically opposite the tuning capacitor. An alternative (and very useful) method of feeding the loop is by means of a ferrite-cored toroidal transformer, an air-cored version of which was apparently first used by Ikrath et al. in a somewhat novel application as a means of energizing a tree as an antenna [4]! In the application described here, the loop effectively forms the single-turn tuned secondary of the transformer, while the number of turns on the primary determines the required input resistance (see Figure 1).

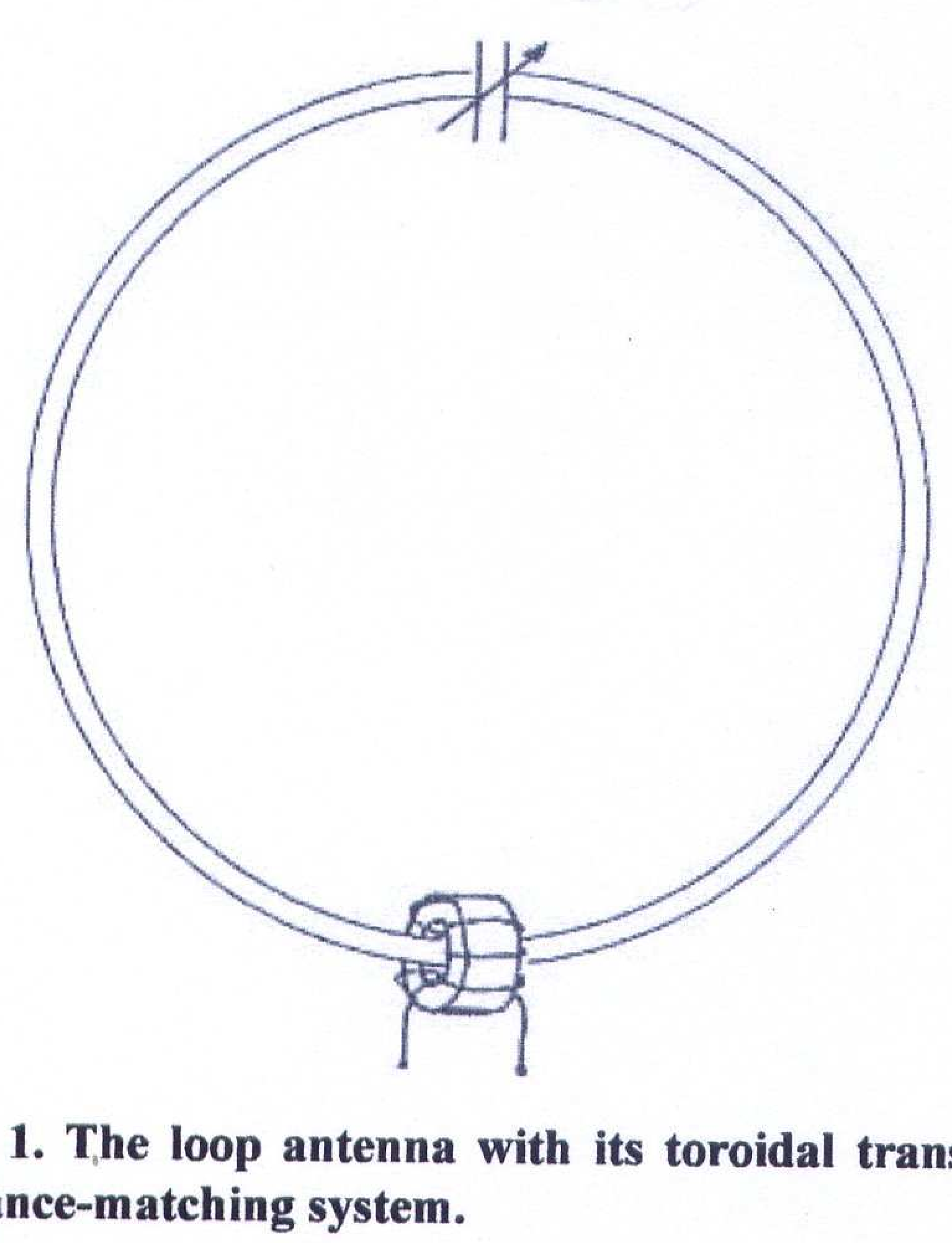

Figure 1. The loop antenna with its toroidal transformer impedance-matching system.

This toroidal matching scheme, as well as being simple to implement, offers one major advantage compared to both the others. It provides a direct means of measuring the total resistance of the loop, and hence of determining its radiation efficiency, assuming that the radiation resistance of the loop is known. The efficiency, η, relies on the simple relationship between radiation and loss resistances given by

$$\eta = \frac{R_{rad}}{R_{rad} + R_{loss}} = \frac{R_{rad}}{R_{tot}}. \qquad (1)$$

The total loop resistance, R_{tot}, is also simply related to its Q by

$$R_{tot} = \frac{\omega_0 L}{Q}, \qquad (2)$$

where $\omega_0 = 2\pi f_0$ is the resonant frequency, and L is the loop's inductance. Q can be obtained by measuring the VSWR of the antenna, and by using the fact that when $\text{VSWR} = 2.618:1$, then $Q = f_0/B$, where B is the bandwidth within which the return loss equals or exceeds 6.99 dB when the reflection coefficient is zero at the loop's resonant frequency [5].

However, in the work reported here, the toroidal-transformer method of feeding the loop was used to measure R_{tot}, and from it, along with the calculated loop inductance, the antenna's Q then follows from Equation (2). The total loop resistance, R_{tot}, follows simply from the known turns ratio of the toroidal transformer and its measured input resistance, R_{in}, when loaded by the tuned loop. For primary and secondary inductances L_p and L_s, which are simply related by the square of the turns ratio of the transformer, N, we thus have that $R_{tot} = \frac{R_{in}}{N^2}$. This simple and direct process yields the total loop resistance, which is made up of its radiation resistance plus the various loss contributors discussed below. Transformer core losses are minimized by the use of appropriate core material and by ensuring that it has an adequate cross-sectional area. Type 4C65 ferrite, either 22 mm or 34 mm in diameter, yielded a very efficient transformer. Total core and winding losses were found by experiment to be less than 1% at an applied power level of 100 W.

2. Small Loop Resistance

It is crucially important when assessing the performance of the small loop antenna to be able to accurately determine all the components of the loop's total resistance. These are the radiation resistance and the various elements that make up the loss resistance, viz., the conductor loss due to the skin effect, the ground loss due to the proximity of the loop to the ground and any other lossy objects, and finally, any other loss associated with the resonant operation of the loop. In this latter category is the loss due to the capacitor that tunes the antenna across its required operating frequency range. In many applications, this latter loss term has been ignored, because it was always assumed that typical air-spaced variable capacitors had exceptionally high Q factors, and hence extremely small losses. However, as many studies of small loops have shown, e.g., [3], the measured and computed Q values often significantly differ from one another, thus suggesting an additional loss mechanism that hitherto had not been considered.

Belrose [6] showed that the contact resistance caused by the method of making an electrical connection with the rotor of the variable capacitor was the dominant reason for this extra loss. It is therefore important to consider the loss in any capacitor used for tuning the antenna, but determining it by measuring a capacitor's Q is not a trivial task. On the other hand, if the total loop resistance can be measured – and this is straightforward when the toroidal matching method is used – then not only can that additional loss term be quantified, but so can the radiation efficiency of the antenna.

The make-up of the total loop-system resistance is as follows:

$$R_{tot} = R_{rad} + R_{loop} + R_{gnd} + R_{cap}, \tag{3}$$

where R_{rad} is the radiation resistance, R_{loop} is the skin-effect loss in the loop's conductor, R_{gnd} is the induced ground-loss term, and R_{cap} is the contact resistance of the variable capacitor.

Measuring radiation resistance is not easy, but it can be indirectly found. By measuring the field strength produced by a vertically-mounted small loop at accurately determined distances from the loop, and over a range of frequencies, Boswell et al. [3] showed by using the well-established groundwave propagation theory that within the limits of experimental error, the radiation resistance agreed with that given by the standard expressions [7], viz.,

$$R_{rad} = \frac{\zeta_0}{6\pi} k_0^4 S^2 \approx \frac{31171 S^2}{\lambda^4}, \tag{4}$$

as is commonly used. Here, $\zeta_0 = \mu_0 c \approx 120\pi$ ohms is the intrinsic impedance of free space, $k_0 = 2\pi/\lambda$ is the wave number, λ is the wavelength, and S is the loop's area.

The skin-effect loss per unit length is readily calculable and is a function of frequency, the conductivity of the loop's material, and its thickness. It is given by

$$R_{loop} = \frac{l}{2r}\sqrt{\frac{\mu_0 f}{\pi\sigma}}, \tag{5}$$

where l is the loop's circumference, r is the conductor's radius, while μ_0 and σ are the permeability of free space and the loop's conductivity, respectively (assuming the loop's material to be nonmagnetic).

Ground and other environmental losses are caused by a number of factors, with the most important being the electrical characteristics of the ground beneath the antenna, and its electrical height above the ground-air interface [8]. Both are frequency dependent. In addition, the orientation of the antenna and its generic type also influence ground loss. In all previous experimental studies of the "small loop problem," assessing this loss term presented the most difficulty. and its effect was apparently not readily quantifiable. However, work published by Vogler and Noble [9] of the US National Bureau of Standards (now NIST) in 1964 provided a very straightforward method of calculating the ground loss, and that is the procedure followed here. In this work, the antenna was a vertically positioned loop, also known as a horizontal magnetic dipole (HMD), due to the fact that its dipole moment lies along the loop axis, and was thus parallel to the ground.

3. Ground Loss

Following [8] and [9], the input impedance of the antenna in the presence of lossy ground can be written as

$$Z = Z_f + \Delta Z. \tag{6}$$

Here, Z_f is the impedance of a lossless antenna in free space, while ΔZ is the change in impedance caused by the presence of the ground. In the context in which we are considering the loop antenna here, we are interested in the real part of the impedance, where $\Re(Z) = R_f + \Delta R$. $R_f = R_{rad}$ is the radiation resistance of the antenna in free space, while $\Delta R = R_{gnd}$ is the induced ground-loss resistance.

The electrical characteristics of the ground are defined by $|N|$, the modulus of the refractive index written in terms of the ground conductivity, σ_1, and its relative permittivity, ε_r. We thus have that

$$|N| = \left[\varepsilon_r^2 + s^2\right]^{1/4}, \tag{7}$$

where $s = \sigma_1/\omega\varepsilon_0 = 60\lambda\sigma_1$, and ε_0 is the permittivity of free space. Another important variable is related to the dielectric loss angle, written here as $\varphi/2 = \frac{1}{2}\tan^{-1}(s/\varepsilon_r)$. For representative ground types, it turns out that $|N| = 5$ and $\varphi/2 = 0.4$ are most appropriate. They essentially represent ground with conductivity of 7 mS/m and relative permittivity of 17 at 7 MHz. These values are typical of pastoral land, medium hills, and forestation [10]. The physical height of the antenna, h, above the ground is given by the parameter $\alpha = 4\pi h/\lambda$.

Figure 2 shows the effect of changes in loop height at 7 MHz on the induced ground loss, R_{gnd}, of a hypothetical lossless 1 m diameter loop. By way of comparison, the graph also shows the radiation resistance, R_{rad}, and the intrinsic loss resistance, R_{loop}, of such a loop made of 22 mm copper tubing. It was clear that at low antenna height ($h < 1.5$ m or about 0.04λ), the ground-induced loss was dominant, while when the loop was higher than 3.5 m or about 0.1λ, it was minimal. Between those heights, both ground loss and the intrinsic conductor loss had to be considered when assessing the behavior of the antenna.

Also shown on the graph is the ground-loss resistance of the loop, computed using the Moment-Method-code *EZNEC*, employing the Sommerfeld-Norton method of including the effects of the ground [11] There was generally reasonable agreement between them for loop heights greater than about a twentieth of a wavelength. This confirmed the usefulness of such *NEC*-based codes (when used appropriately) for assessing or designing electrically small loop antennas above lossy ground.

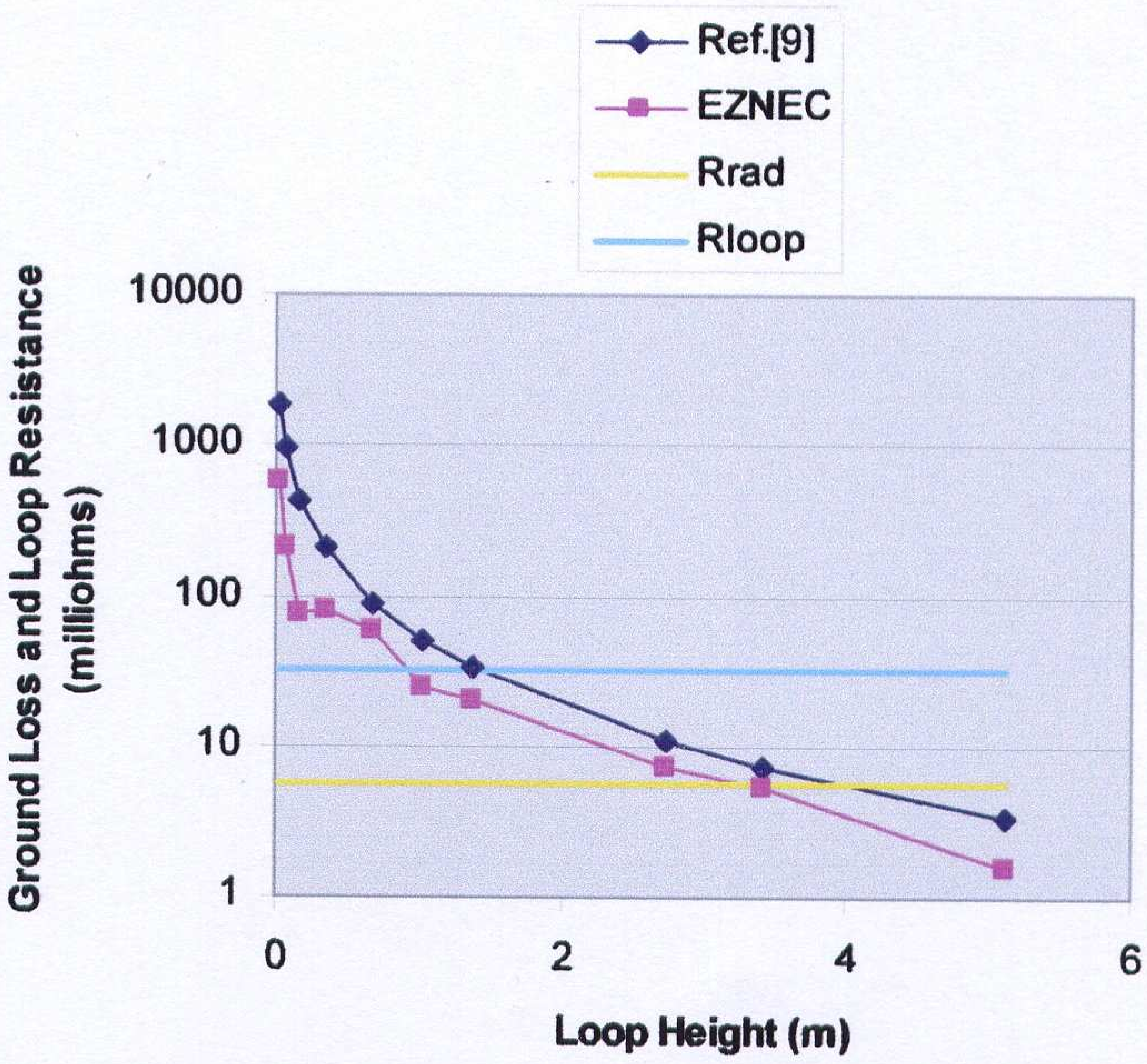

Figure 2. The ground loss as a function of loop height at 7 MHz, calculated following [9], and as computed by *EZNEC*. Also shown by way of comparison are the radiation resistance and loop resistance of the 1 m diameter copper loop of 22 mm thickness.

4. Tuning Capacitor Contact Resistance

As mentioned above, when tuned to resonance by conventional variable capacitors, small loops generally exhibit considerably lower Q factors than are predicted either by standard analytical techniques or when simulated by codes such as *EZNEC*. For example, Boswell et al. [3] determined Q over a range of frequencies for their 1 m diameter loop of 22 mm copper tubing at a height of 1.5 m above the ground. For example, at 7 MHz they measured a Q of 417, which equated to a total antenna resistance of 257 milliohms. By contrast, a similar copper loop with no capacitor contact loss, when elevated 1.5 m above a ground of $|N| = 5$, exhibited a Q of approximately 1600, when evaluated using the method in [9]. This is equivalent to a total antenna resistance of just 69 milliohms. The difference was clearly due to the capacitor's contact loss. It so happens that at this height and those ground conditions, the loop's intrinsic copper loss and that induced by the ground are just about equal, at 31 milliohms each. The increase in radiation efficiency that accrues simply by eliminating the capacitor loss amounts to 5.7 dB.

One of us (M.A.P.) set out to experimentally confirm that the capacitor's contact loss was the dominant factor reducing loop Q. He used fixed porcelain capacitors (type ATC 100E) with effective series resistance (ESR) in the region of 2 milliohms to 20 milliohms, as quoted by their manufacturer, to resonate an elevated 1 m diameter loop of relatively thin 6.3 mm copper tubing, at spot frequencies between 3 MHz and 13 MHz. The tests were conducted with the antenna sufficiently high above the ground to minimize – if not eliminate almost entirely – the ground-loss component from the loop's total resistance. Figure 3 shows the effect on the Q of the antenna by significantly reducing this capacitor contact resistance. The loop was first suspended at 3 m and then at 6 m above the ground. It will be noted in Figure 3 that the Q factors of this loop exceeded 600 at all frequencies at 3 m elevation, while at twice that height, the Q even exceeded 1000 at some of them.

Also shown in Figure 3 are the predicted results for a loop made of 22 mm copper tubing, as is often used in practical applications. In the absence of the experimental facilities to measure them (following our collective retirement), the results were extrapolated from the measured data of the 6.3 mm thickness loop described above. The loop's diameter remained unchanged at 1 m. Extrapolation was justified because the only loop parameters affected by increasing the conductor's thickness were its loss resistance and its inductance. The appropriate change in capacitor values restored resonance at the previous test frequencies. These calculated results of loop Q are also shown in Figure 3 for the same two cases, with the base of the loop elevated 3 m and then 6 m above the ground. What is most noticeable is that the thicker conductor produced significant increases in Q, with values in excess of 1000 at all frequencies, and considerably greater than that at the higher loop elevation.

This finding was also experimentally confirmed by Belrose for similar loops [6]. Using the method in [5], he measured the Q of two versions of a commercially-made loop (AMA models manufactured in Germany) in which special measures were taken to minimize any capacitor contact loss. The AMA loops were made with 32 mm thick aluminum tubing, and had diameters of 0.8 m and 1.3 m. They were elevated 2 m above

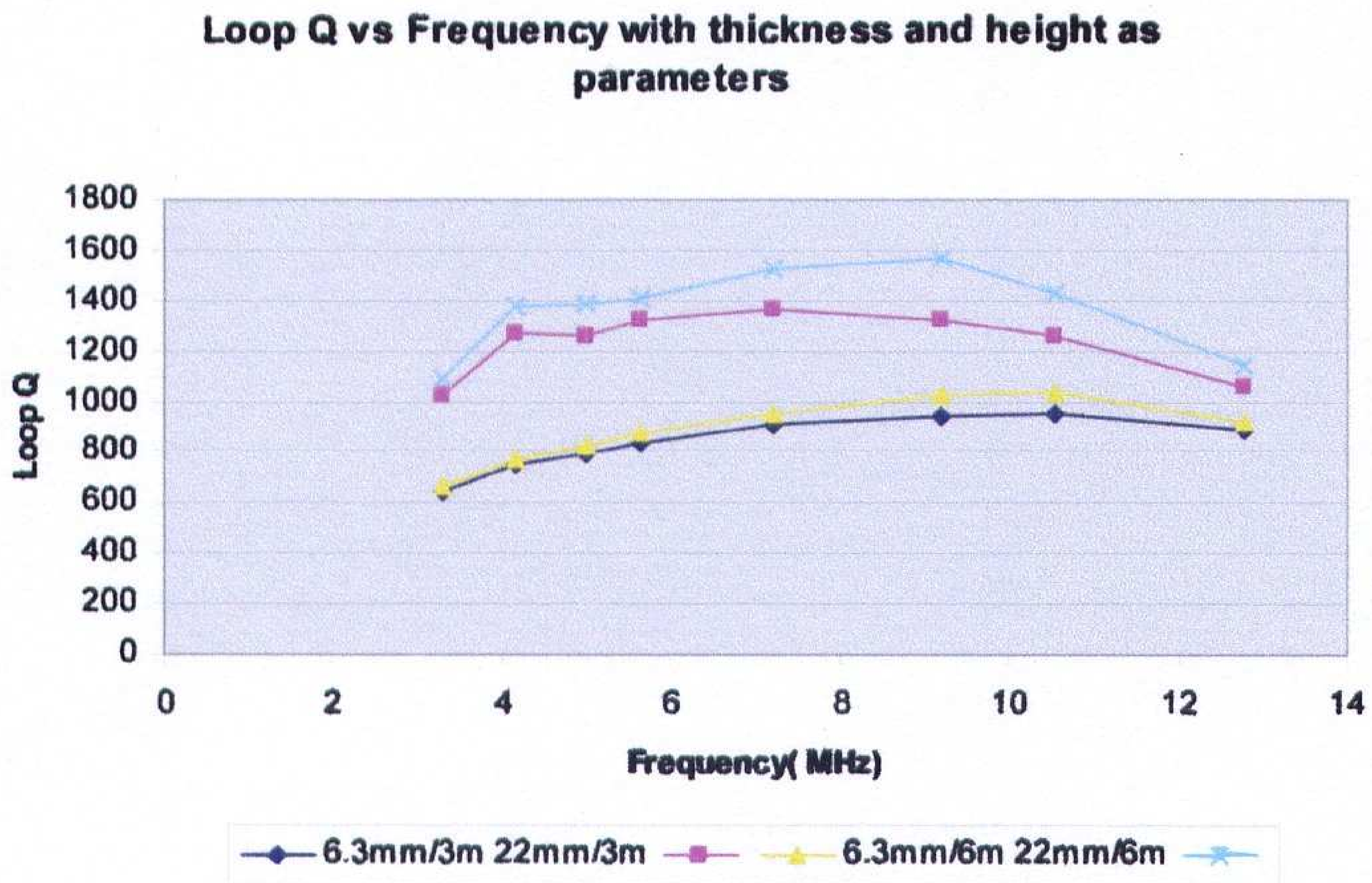

Figure 3. The measured results of the effect of frequency on the Q of a 1 m diameter loop made of 6.3 mm copper conductor with its height at 3 m and 6 m above ground. Also shown are the extrapolated results for the 1 m loop of 22 mm copper tubing at both heights.

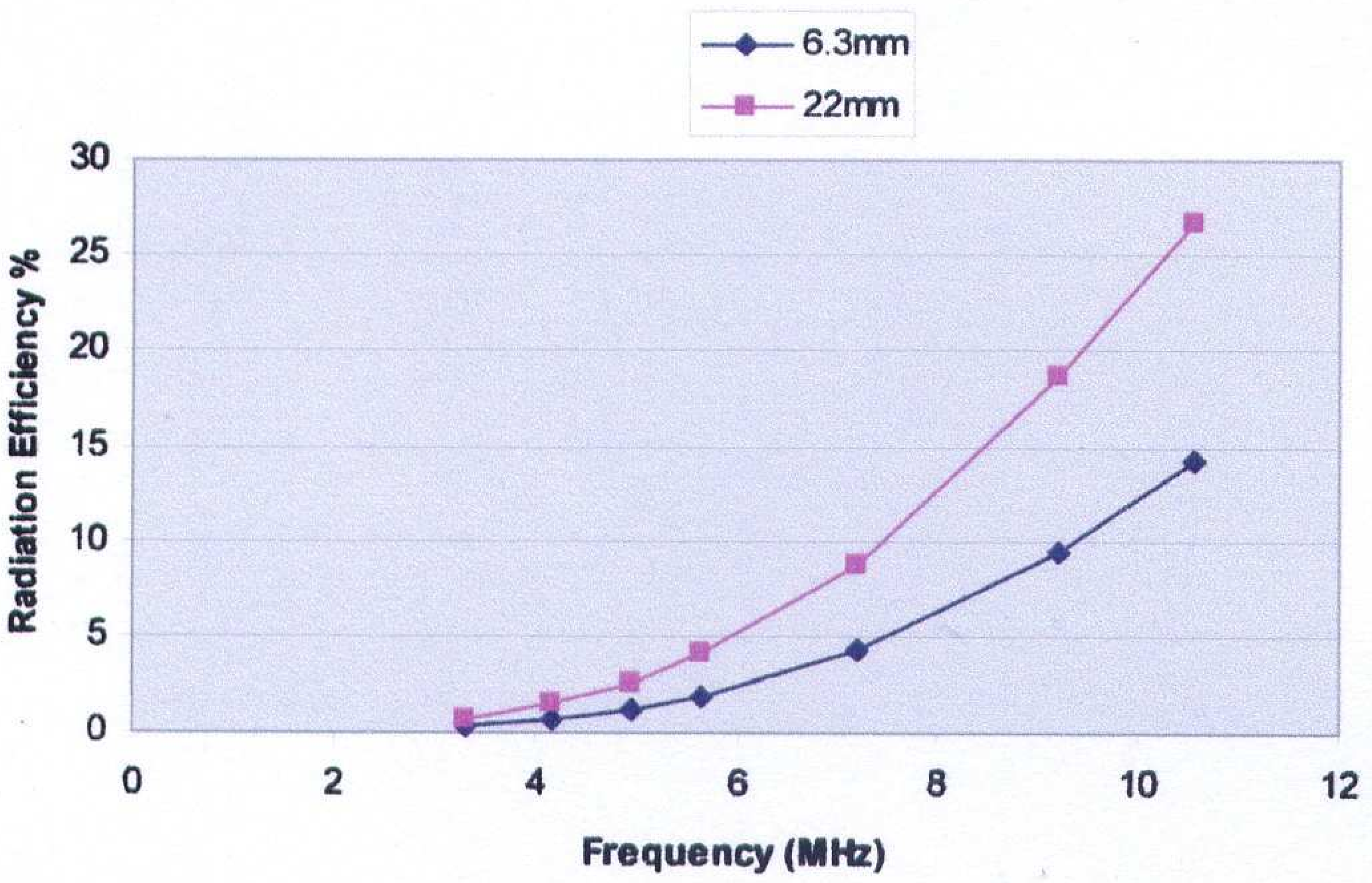

Figure 4. The variation of radiation efficiency with frequency of both the 6.3 mm and 22 mm thickness loops, when each was suspended 6 m above the ground.

average ground. Both loops exhibited Q factors well in excess of 1000 across the lower HF band.

These results all proved that the mechanism that predominantly accounts for the decreased Q factor of electrically small loop antennas when in service is the tuning capacitor's contact resistance. Loops that are tuned by vacuum capacitors, with their inherently high Q, or those such as the AMA versions mentioned above, where special measures have been taken to reduce this loss, will not suffer from this defect.

5. Radiation Efficiency

The toroidal-transformer method of feeding the loop makes measurement of the antenna's radiation efficiency a simple matter. Using Equation (1) with the calculated values of radiation resistance, R_{rad}, of the loop in question and the total loop resistance, R_{tot}, as above directly yields the radiation efficiency, η. None of the other methods of feeding the small loop antenna offers this facility. Figure 4 shows the variation of radiation efficiency with frequency for the 6.3 mm and 22 mm thick loops under discussion here. Both were suspended 6 m above the ground. Although compromised in terms of radiation efficiency, especially at low frequencies, these electrically small antennas were remarkably effective performers, when appropriately erected, in various applications, especially near-vertical-incidence skywave.

5. Conclusions

This paper has identified the various loss mechanisms that limit the performance of an electrically small loop antenna, and as part of that investigation, it used a straight-forward method of determining the total resistance of the antenna at resonance. The technique involved the use of an efficient toroidal transformer for coupling power to and from the loop. In so doing, it allowed the loop's resistance to be easily determined. From this, the antenna radiation efficiency directly followed. In addition to the intrinsic loss resistance of the loop caused by the conductor's thickness and the skin effect, there are two additional loss terms of especial interest. These are the induced ground loss, and that associated with the contact resistance of the variable capacitor that resonates the antenna. Quantifying the effect of a lossy dielectric ground beneath a small vertically positioned loop had generally been thought problematic, but a very viable technique for doing this was in fact published many years ago. Using that approach yielded values for the ground-loss resistance that agreed very closely with the values inferred from measurements. The ground loss decreases rapidly as the antenna is raised, and it becomes insignificant when the antenna is more than about a tenth of a wavelength above the ground-air interface. This result has important practical implications. In addition, given the considerable popularity of Moment-Method codes for computing antenna characteristics, the reasonably good agreement between both analytical and experimental results and those predicted by the *EZNEC* code for this important loss parameter was gratifying.

The paper also presented experimental evidence that showed that contact-loss resistance caused by the variable capacitor mechanism often has a dominating effect in decreasing the loop's radiation efficiency. Measures to reduce this include the use of a vacuum-variable capacitor, or one involving specially-designed spring-tensioned contacts to the capacitor's rotor plates. Reducing capacitor contact loss by these or any other means can bring about an increase in radiation efficiency of nearly 6 dB, all other factors being equal.

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