Performance of a Small Loop Antenna in the 3-10 MHz Band

Alan Boswell, Andrew J. Tyler, and Adam White

BAE SYSTEMS Advanced Technology Centre
Great Baddow, Chelmsford CM2 8HN, UK
E-mail: alan.boswell@baesystems.com

Abstract

The performance of a typical small loop antenna of 1 m diameter is presented at frequencies in the range 3.6-10.1 MHz. It is argued that the antenna may reasonably described as electrically small in this frequency range. Measurements of the antenna's bandwidth and, hence, Q factor are presented, along with direct measurements of the radiated field at various distances with a carefully measured RF input power. The radiation efficiency of the loop is derived from the measurements, and is compared with theoretical predictions of the efficiency based on classical electromagnetics. Close agreement is demonstrated between measurements and predictions. Consistency with the Chu bandwidth limit is also demonstrated for this antenna.

Keywords: Antenna measurements; loop antennas; HF antennas; Q factor

1. Introduction

Loop antennas have been used since the early days of radio, and are in common use at many frequencies below about 1 GHz. They have become widespread for applications in the HF band (3-30 MHz), particularly for mobile communications on vehicles using the near-vertical-incidence skywave (NVIS) propagation mode. A typical loop for this application is 1 m to 2 m in diameter; is a single turn, which may be circular or square; is fabricated from copper or aluminum tubing; and is tuned to the appropriate frequency with a capacitor placed in series or in parallel with the loop. Multiple turns can also be used. Power may be introduced via a small coupling loop that may take one of several forms, although other feeding methods are also used. It has proven difficult to find measurements of the radiation efficiency of this type of antenna in the literature, and the present measurements were designed to remedy the deficiency.

In the modal analysis of the current distribution on a loop antenna – given, for example, by Lo and Lee [1] – there are various modes. These include the two lowest modes: the magnetic-dipole mode and the folded-dipole mode. These were also described by King [2] and by Whiteside and King [3]. The relative amplitudes of the radiated fields from the two lowest modes were described by Boswell [4] for a typical HF loop. The importance of including any tuning and/or matching circuit in the calculation of the radiation efficiency of small antennas was pointed out by Smith [5].

This paper describes measurements of input impedance and radiation efficiency for a loop of 1 m diameter at frequencies of 3.6 MHz, 5.1 MHz, 7.04 MHz, and 10.1 MHz. At each frequency, the loop was carefully matched to a continuous-wave source the output power of which was monitored. The radiated field was measured at distances up to 80 m, and the radiation efficiency was derived from the measured field strength and the input power. The measured radiation efficiency is compared with predictions based on classical electromagnetics, and good agreement is demonstrated.

2. Antenna Configuration and Analysis

The schematic antenna configuration is shown in Figure 1, which shows the loop with its self-inductance and resistance, and a tuning capacitor in series. A balanced feeder is connected via a coupling loop, the magnetic flux of which links the main loop. The input impedance into the coupling loop can be expressed as follows, by circuit analysis:

$$Z_{in} = j\omega L_2 + \omega^2 M^2 / \left(R + j\omega L_1 + 1/j\omega C\right). \qquad (1)$$

The mutual inductance is related to the transformer coupling factor, k, by the expression

$$M = k\sqrt{L_1 L_2}\,, \quad k < 1. \qquad (2)$$

Further details of this equivalent circuit are given by Barrick [6]. An example of the use of these formulas is given below, in the section on input-impedance measurements. It is shown that after the practical loop antennas was matched to 50 Ω, the formula correctly predicted the input impedance in a range of frequencies about the resonant frequency.

It can be seen from Equation (1) that in the narrow band of frequencies around the resonant frequency, f_0, at which $\omega = \omega_0$,

ISSN 1045-9243/2005/$20 ©2005 IEEE

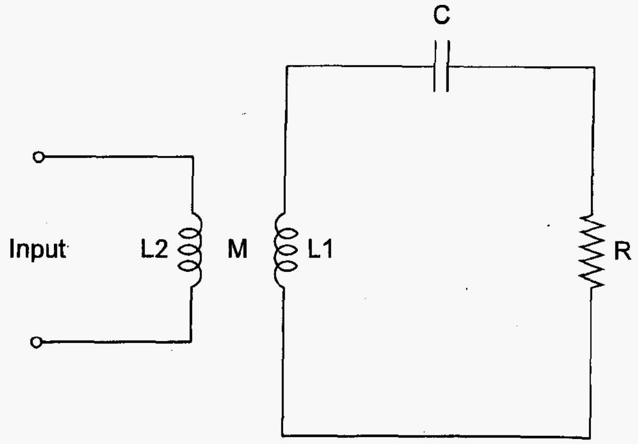

Figure 1. The equivalent circuit of the loop. L_1: main loop; L_2: coupling loop; M: mutual inductance; C: resonating capacitance; R: total resistance.

the input impedance to the coupling loop is similar to that of a tuned circuit the Q factor of which is determined by the ratio of the main-loop reactance, $\omega_0 L_1$, to the total series resistance, R. It is practicable to measure the bandwidth and, hence, the Q, for a small loop. Furthermore, the reactance may be measured or estimated with good accuracy. The ratio $\omega_0 L_1 / Q$ then provides a value for the total resistance, which is otherwise difficult to obtain.

The general relationship between bandwidth and Q factor is addressed by Yaghjian and Best [7], who derive the following formula:

$$Q = \frac{2\sqrt{\beta}}{FBW_V}, \qquad \sqrt{\beta} = \frac{s-1}{2\sqrt{s}}, \tag{3}$$

where FBW_V is the fractional matched VSWR bandwidth, and s is an arbitrary choice of VSWR about the matched and resonant frequency. It follows from this that if a particular reflection-coefficient magnitude equal to $1/\sqrt{5}$ is chosen – corresponding to a VSWR of 2.618:1, or a return loss of 6.99 dB – then the following is true:

$$Q = \frac{1}{FBW_V} = \frac{f_0}{B}, \tag{4}$$

where B is the bandwidth within which the return loss indicated by a network analyzer equals or exceeds 6.99 dB when the reflection coefficient is zero at the resonant frequency. Equation (4) therefore relates the measured bandwidth to the Q factor.

Classical theory in, for example, Weeks [8], predicts the radiation resistance for an electrically small single-turn loop:

$$R_r = \frac{\mu_0 c}{6\pi} k_0^4 A^2 \approx 20 k_0^4 A^2 \text{ Ohms}, \tag{5}$$

where A is the loop area and $k_0 = 2\pi/\lambda$, with λ being the free-space wavelength. The self-inductance is also given by Weeks:

$$L_1 = \frac{\mu_0 D}{2}\left(\log_e \frac{8D}{d} - 2\right), \tag{6}$$

where D is the loop diameter and d is the conductor diameter.

3. Practical Antenna

The practical antenna tested was a loop of 1 m diameter, fabricated from 22 mm-diameter copper tubing with a tuning capacitor placed at the top, as shown in Figure 2. Results from [4] suggest that at 10.1 MHz, the radiated field from the magnetic-dipole mode exceeds that from the folded-dipole mode by 12 dB, and that the ratio is greater at lower frequencies, increasing at the rate of 6 dB per octave. Thus, at 10.1 MHz and below, the loop can be considered electrically small.

The coupling loop was a length of insulated stranded power wire of 1.5 mm^2 cross section, close to the loop, and connected to it by a clip at a point approximately one-eighth to one-quarter of the way around the loop. The position of the connection, together with the spacing between the loop and the coupling wire, gave the adjustments necessary to match the antenna at any frequency in its operating range, after the capacitor had been adjusted to the required frequency. The coupling loop was connected as an auto-transformer, but since coupling was via the magnetic flux, as for a more conventional coupling loop, Equation (1) was considered sufficiently accurate. This was confirmed by comparison with input-impedance measurements, reported below.

Equation (6) indicates an inductance of 2.45 μH for the main loop, requiring a capacitance of 800 pF for resonance at 3.6 MHz, the reactance then being 55 Ω.

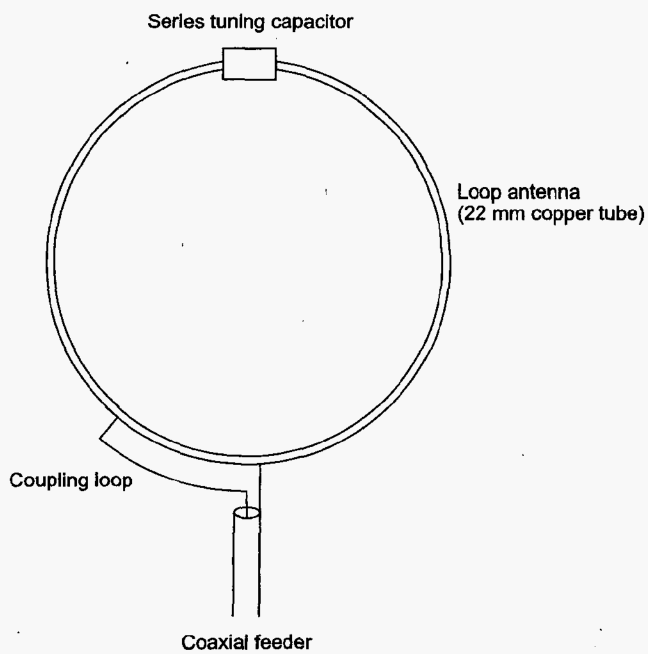

Figure 2. The arrangement of the loop antenna.

4. Input Impedance Measurements and Predictions

The input impedance to the coupling loop was measured with a Hewlett-Packard network analyzer type 8753C. A coaxial, rather than a balanced, feeder was used, producing no significant radiation from the feeder. The tuning capacitor was adjusted to the required resonant frequency, and some adjustment was made to the coupling-loop connection and the tuning capacitor. It was found that a good match was obtained at 3.6 MHz with the coupling loop connected at a distance of 680 mm from the base of the loop, with the coupling wire running parallel to and 25 mm distant from the main loop. The measured input impedance is shown in Figure 3, a Smith chart, about a center frequency of 3.604 MHz. The Q factor was measured by noting the antenna's -3 dB bandwidth, the band edges being those two frequencies above and below the center frequency at which the return loss was 6.99 dB.

It was found that the band edges occurred at 3.59895 MHz and 3.61000 MHz, indicating a bandwidth of 11.05 kHz and a Q of 326. At this center frequency, the loop's calculated reactance was 55.5 Ω, and this value divided by the measured Q gave the total circuit resistance, R, of 0.170 Ω. These and other measurements are summarized in Table 1.

A prediction of the input impedance around 3.604 MHz was also carried out by using Equation (1) with values as follows: $L_1 = 2.45\,\mu\text{H}$, $C = 796\,\text{pF}$, $L_2 = 0.14 L_1$, $k = 0.14$, $R = 0.170\,\Omega$. The value for L_1 was calculated from Equation (6) and the loop dimensions, and the capacitance value was derived from the inductance and the resonant frequency from the relation $C = 1/\omega_0^2 L_1$. The value for resistance was taken from the measurement of the Q factor. Values for the inductance of the coupling loop and the coupling factor were estimated. In the absence of more detailed information, the ratio of L_1 to L_2 was set equal to the coupling factor, and a value was selected that gave good agreement with the measured impedances. A precise value for these quantities would depend on analysis of the magnetic-field distribution, which is outside the scope of this article. However, the value of 0.14 chosen is not inconsistent with a coupling loop connected one-eighth to one-quarter of the way around the main loop. The Smith chart resulting from the prediction is shown in Figure 4, indicating good agreement with the measurement shown in Figure 3, and providing confirmation of the estimated component values and the validity of Equation (1).

In both the predictions and the measurements, the input reactance crossed from positive to negative as the frequency was increased through resonance, as in a parallel-tuned circuit. At frequencies well below and well above resonance, the input impedance was small, approximating a short circuit, as the Smith charts show.

Detailed analysis and predictions can also be carried out at the other three frequencies used in the measurements, using the principles described here for 3.6 MHz. The positions of the coupling loop were as follows: at 5.1 MHz, 680 mm; at 7.0 MHz,

Table 1. The measured bandwidth, derived Q factor, predicted reactance, and derived total resistance for the 1 m loop antenna.

Center Frequency (MHz)	Bandwidth (kHz)	Q Factor	Reactance (Ω)	Total Resistance (Ω)
3.6	11.05	326	55.5	0.170
5.1	18.35	278	78.7	0.282
7.04	16.90	417	108	0.260
10.1	14.70	688	155	0.225

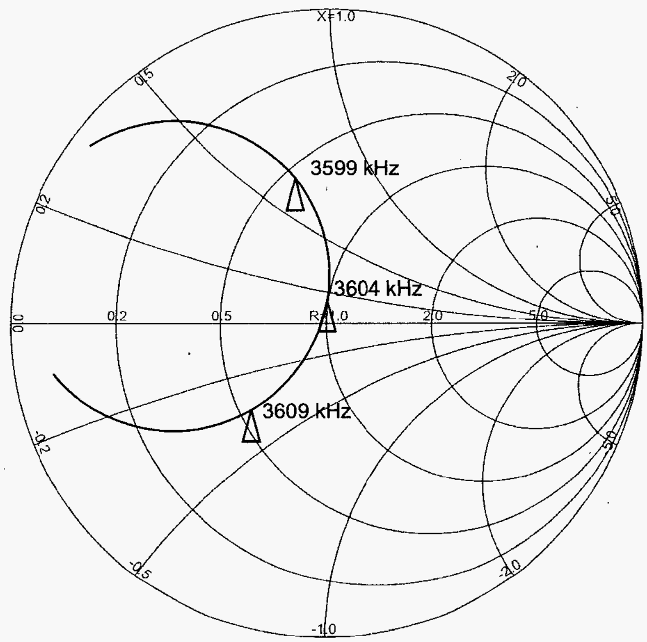

Figure 4. The predicted impedance to the coupling loop, 3.6 MHz (the markers are at 3604 kHz and 5 kHz above and below).

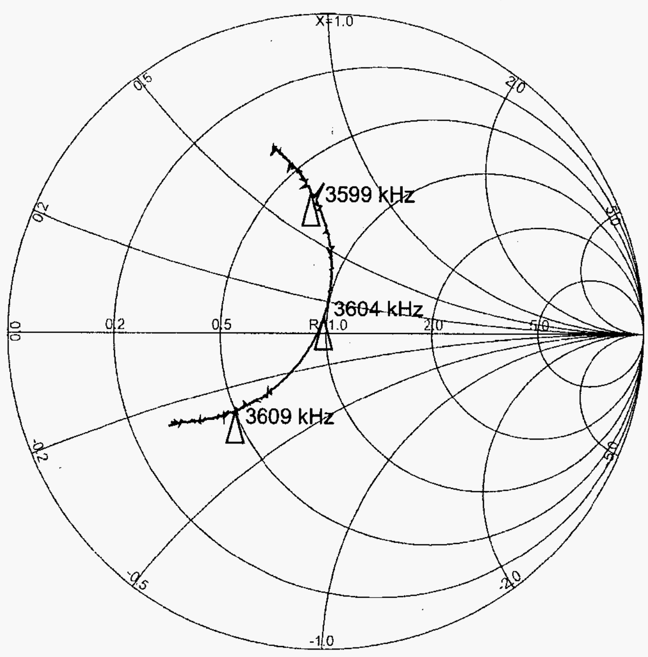

Figure 3. The measured input impedance to the coupling loop, 3.6 MHz (the markers are at 3604 kHz and 5 kHz above and below).

510 mm; at 10.1 MHz, 390 mm. In each case, the coupling wire ran parallel to the main loop, 25 mm distant from it.

5. Radiated Field Predictions

A small loop in free space produces omnidirectional radiation in the plane of the loop. When placed vertically (i.e., with its axis horizontal) at height h over perfect ground, the loop can be shown to produce a pattern that in the plane of the loop is proportional to $\cos(k_0 h \sin\theta)$, where θ is the angle of elevation. For $k_0 h \ll 1$, the vertical pattern over perfect ground is omnidirectional, as shown in Figure 5. Figure 5 also shows the predicted far-field pattern of the present loop at 7 MHz, at a height of 1.5 m over lossy ground with a conductivity of 5 mS/m. It can be seen that the far-zone pattern amplitude approaches zero at grazing incidence in the far-field pattern when the ground is lossy. However, at finite distances over lossy ground, there is a predictable surface-wave field at zero height: it was this field that was measured to determine the antenna's radiation efficiency, on the basis that the ground wave would be similar to that over a perfect ground with a small additional reduction in amplitude.

Outside the plane of the loop, the azimuth pattern has a null along the axis of the loop. Over a perfect ground plane, the radiated field is expected to show the usual inverse-distance reduction in field amplitude. Since in free space a small loop has the same maximum directivity as a short dipole, namely 1.5 (i.e. 1.76 dB), it follows that at a small distance above perfect ground both antennas show the same maximum directivity of 3 (i.e., 4.77 dB). The additional factor is attributable to the fact that the power is radiated only into the upper half-space.

Over lossy ground, the ground wave suffers additional attenuation over and above the inverse-distance law, the additional attenuation being predictable by the Norton theory [9] for distances of one wavelength and upwards from the transmitting antenna. For distances of under one wavelength, a complete solution of the fields above a homogeneous ground is given by King and Sandler [10]. The resulting small near-field error in the Norton theory was assessed at 3.6 MHz by a direct comparison. This showed King giving the same results at 80 m, 0.2 dB additional field intensity at 40 m, and 1.9 dB extra at 20 m. These discrepancies are negligible at distances of 40 m and above, at 3.6 MHz and higher frequencies.

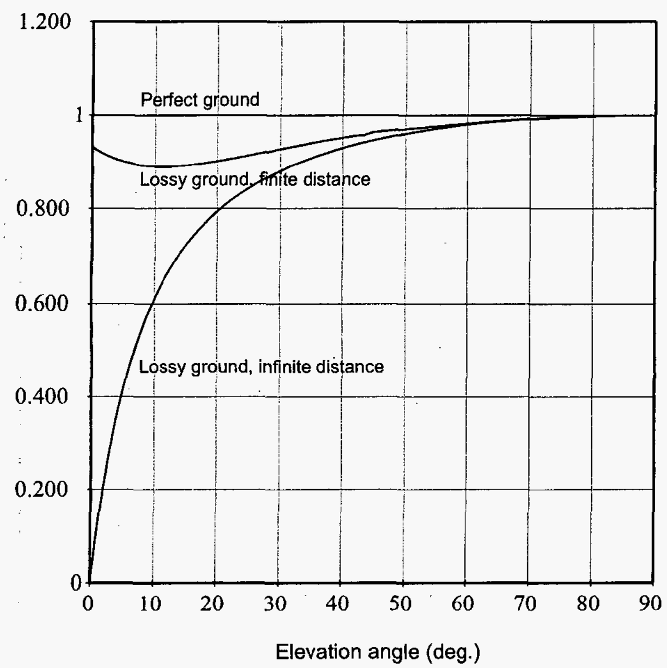

Figure 5. The vertical radiation pattern for a small vertical loop above ground.

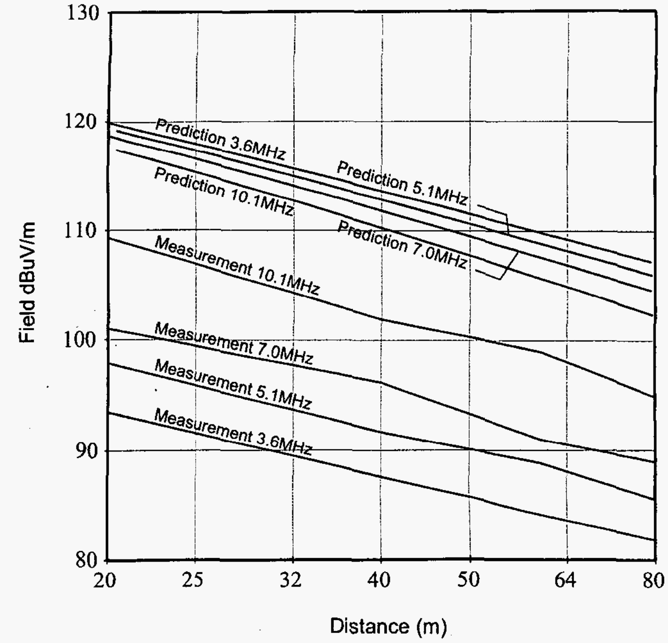

Figure 6. The predicted and measured field strengths (5 W RF power).

In Figure 6, the top four curves show the field strengths predicted by the Norton theory at 3.6 MHz, 5.1 MHz, 7.0 MHz, and 10.1 MHz for 5 W carrier power over a ground with a conductivity of 5 mS/m and a relative permittivity of 10. These constants have been characterized as typical conditions for southern England, where the measurements took place (the results are not strongly dependent on the values of these constants). The predictions assumed an antenna of 100% efficiency. All fields were plotted in dB relative to 1 μV/m rms. The logarithmic distance scale gives a theoretical straight-line graph of field strength for far-field measurements made either in free space or over perfect ground, with a slope of −6 dB for every doubling of the distance. Over lossy ground, the graphs exhibit a slightly greater downward slope, more so at the higher frequencies. The predictions are based on in-house software using the particular Norton algorithm quoted by R. E. Collin [11].

6. Radiated Field Measurements

The field measurements were made with the transmitting and receiving antennas placed 1.5 m above the ground, and oriented to lie in the same vertical plane. CW carrier power was generated with an ICOM transceiver, and the power input to the antenna was monitored by a Bird "Thruline" wattmeter, Model 43, and adjusted to 5 W forward power. The indicated reverse power was negligible. Radiated field measurements were carried out by an Anritsu field-strength meter, type ML428B, with a loop antenna designed and calibrated by the manufacturer for use with this meter.

It is important to realize that calibrated loop antennas supplied with field-strength meters detect the local magnetic field, and that the result is then multiplied by the free-space wave impedance, $\mu_0 c$, before being displayed as the electric-field equivalent assuming plane-wave propagation. This introduces a potential inaccuracy in the near-field region. This was assessed at 3.6 MHz by evaluating the full expression for the near field of a magnetic-current element, giving 0.3 dB at 40 m distance, and 1.1 dB at 20 m. Again, the discrepancies were negligible at 40 m and above. At higher frequencies, the discrepancy was expected to be smaller, because the distances were larger in wavelengths.

Measurements were made at distances between 20 m and 80 m from the antenna at the four frequencies, and the measured field strengths are shown plotted in the lower four curves in Figure 6. At each frequency, the vertical separation between the two curves can reasonably be interpreted as a measure of the antenna's radiation efficiency. It can be seen that at 3.6 MHz, the measured field from the loop fell consistently 26 dB below the Norton prediction, so that as a percentage, the efficiency was therefore 0.25%, on this basis. The measured radiation resistance then followed as the product of the total resistance, derived from the Q measurements described above, and the efficiency.

It can be seen from Figure 6 that the predicted field strength was lower as the frequency was increased, and this is generally true for groundwave propagation. In the same figure, however, the measured field strength was greater at the higher frequencies. This was due to the increased antenna efficiency observed at the higher frequencies, which more than offset the additional propagation losses.

At the three higher frequencies, the differences between prediction and measurement were less marked. The radiation efficiencies and radiation resistances at all four frequencies are summarized in Table 2, which also shows the radiation resistances predicted by Equation (3). The differences between the measured and predicted radiation resistances were 2.04 dB at the highest frequency, and less at the three lower frequencies.

7. Conclusions

The radiation resistance of an electrically small loop of 1 m diameter has been measured at four frequencies in the HF band. This was done by first measuring the antenna's Q factor to determine the total resistance, and then by measuring the input power and radiated field to determine the radiation efficiency and, hence, the radiation resistance.

The results closely confirmed predictions of the radiation resistance made from the classical theory (Equation (5)), and it is therefore concluded that the classical theory is sufficiently accurate for practical purposes. The radiation efficiency of small loops in the HF band can therefore be estimated by calculating the inductance from Equation (6), above, and hence the reactance, and then calculating the radiation resistance from Equation (5). The "lossless" Q is then equal to the reactance divided by the radiation resistance. The actual Q can then be determined by an input-impedance measurement, as described, and the efficiency is accurately estimated as the ratio of the measured and lossless Q factors. This approach allows the efficiency to be estimated only from input-impedance measurements.

Table 2. The measured radiation efficiency, and the measured and predicted radiation resistance, for the 1 m loop antenna.

Frequency (MHz)	Radiation Efficiency (%) (Measured)	Radiation Resistance (mΩ)	
		Measured	Equation (5)
3.6	0.25	0.42	0.36
5.1	0.84	2.4	1.6
7.0	2.3	6.0	5.7
10.1	18	40	25

The results also lend support to the accuracy of modeling by computer codes such as *NEC*, which are in general agreement with classical theory. Computer analysis of small loops over lossy ground has been carried out extensively by Belrose [12].

The Chu bandwidth limit for an antenna of 1 m diameter indicates a theoretical maximum bandwidth of 0.19 kHz at 3.6 MHz, rising to 12 kHz at 10.1 MHz. Since Chu's theory assumes arbitrary antennas of 100% radiation efficiency, the Chu limit should perhaps more properly be described as a bandwidth-efficiency limit. The present loop measurements give a calculated bandwidth-efficiency product of 0.028 kHz at 3.6 MHz and 2.6 kHz at 10.1 MHz. These are both approximately one-fifth of the theoretical maxima, thus demonstrating consistency with the Chu theory.

The radiation-efficiency results described here are believed to be typical of loop antennas of similar dimensions in the HF band. As an example, a Racal Antennas HF loop – a square loop of 1.2 m on the side – has a quoted gain of −16 dBi at 4 MHz, and −9 dBi at 7 MHz [13]. Although loop antennas of 1-2 m^2 area do not appear, on present evidence, to possess good radiation efficiency at the low end of the HF band, this does not necessarily rule them out as effective components in practical applications. Successful communications links are often maintained with a radiated power of 1 W or less at frequencies of 3-6 MHz, especially for links of up to 300 km where NVIS is used. Loops have to be judged against the performance of the available alternatives, taking into account the constraints imposed by mobile use on small vehicles. That is why small HF loops and half-loops enjoy a steady level of usage in the land-mobile and other categories of radio systems, and this is likely to continue.

8. References

1. Y. T. Lo and S. W. Lee, *Antenna Handbook*, New York, Van Nostrand Reinhold, 1988.

2. R. W. P. King, "The Rectangular Loop Antenna as a Dipole," *IRE Transactions on Antennas and Propagation*, **AP-7**, 1, January 1959, pp. 53-61.

3. H. Whiteside and R. W. P. King, "The Loop Antenna as a Probe," *IEEE Transactions on Antennas and Propagation*, **AP-12**, 4, May 1964, pp. 291-297.

4. A. G. P. Boswell, "Loop Antennas in the 3-30 MHz Band," Eighth International Conference on HF Radio Systems and Techniques, IEE Conference Publication 474, April 2000.

5. Glenn S. Smith, "Efficiency of Electrically Small Antennas Combined with Matching Networks," *IEEE Transactions on Antennas and Propagation*, **AP-25**, 3, May 1977, pp. 369-373.

6. D. Barrick, "Miniloop Antenna Operation and Equivalent Circuit," *IEEE Transactions on Antennas and Propagation*, **AP-34**, 1, January 1986, pp. 111-114.

7. A. D. Yaghjian and S. R. Best, "Impedance, Bandwidth and Q of Antennas," IEEE International Symposium on Antennas and Propagation *Digest*, **1**, Columbus, Ohio, June 2003, pp. 501-504.

8. W. L. Weeks, *Antenna Engineering*, New York, McGraw Hill, 1968.

9. K. A. Norton, "The Propagation of Radio Waves over the Surface of the Earth," *Proceedings of the IRE*, **24**, 10, October 1936, pp. 1367-1387.

10. R. W. P. King and S. S. Sandler, "The Electromagnetic Field of a Vertical Electric Dipole over the Earth or Sea," *IEEE Transactions on Antennas and Propagation*, **AP-42**, 3, March 1994, pp. 382-389.

11. R. E. Collin, *Antennas and Radiowave Propagation*, New York, McGraw Hill, 1985.

12. J. S. Belrose, "Performance of Electrically Small Transmitting Loop Antennas," *Radcom*, Radio Society of Great Britain, London, UK, June/July 2004.

13. Publication 6559-1, Racal Antennas Ltd., UK, 1983.

Editor's Comments *Continued from page 50*

been asked and I've been honored to serve as a reference many times. However, in the past two years or so I have noted a couple of disturbing trends, and it's happened often enough that I feel I must comment. The first trend is being contacted directly by a candidate for Fellow to be asked to serve as a reference. The procedures for Fellow nominations are very clear: it is the responsibility of the nominator to contact the references and ask if they will be willing to serve as references. It is embarrassing to have to tell a Fellow candidate that you don't feel you can serve as a reference for his or her nomination. What makes the whole situation worse is that the reason I have most often had to refuse to serve as a reference isn't that I don't feel the candidate is qualified to be a Fellow. Rather, it is that I am not qualified to serve as a reference for that particular candidate. This relates to the second disturbing trend.

I have been asked on several occasions to serve as a reference for someone with whose work I am not sufficiently familiar. According to instructions on the Fellow Reference Form, in order to be eligible to serve as a reference, "You must be qualified to judge the candidate's work from a personal knowledge standpoint." Indeed, the first major question on the Reference Form is, "How long have you known the candidate and in what capacity?" I do not think this means that you have to have worked side-by-side with the candidate in order to serve as a reference. However, I do interpret this to mean that you certainly should know the candidate in some capacity, and you definitely have to be sufficiently familiar with the candidate's work to be able to provide an appropriately knowledgeable evaluation. For example, I am comfortable serving as a reference for someone whom I have met at AP-S annual Symposia over the years, and whose published work I have studied and used. Hopefully, I've also corresponded with or had other discussions with the candidate about the work. I am not comfortable serving as a reference for someone whose work I have not previously encountered.

It's certainly reasonable for a Fellow candidate to suggest possible references to the nominator. However, the nominator should make the request to serve as a reference. The nominator should also hopefully know those working in the field of the candidate well enough to be able to judge whether or not a potential reference meets the requirement of being able to judge the candidate's work from a personal-knowledge standpoint.

Multimedia Content in IEEE *Xplore*

Many authors have expressed interest in being able to add multimedia content (e.g., everything from static color graphics and extended data sets to MPEG movies and AVI sound files) to papers published in IEEE publications, particularly to the versions available on IEEE *Xplore*. I and many others have been under the impression that this capability wasn't available. It turns out that is incorrect.

If you go to the IEEE home page at http://www.ieee.org, choose Publications from the menu at the left, choose the About IEEE Journals and Transactions sub-menu, and choose Tools for Authors from the left of that page, you'll end up at a page that has tools for authors. The third item on that page is a set of three PDFs that describe how to submit multimedia content. The most useful information seems to be in MMdocumentation.pdf.

You can identify papers that have multimedia content on *Xplore* because when you find a listing for the paper, after the Abstract and PDF-Full Text links below the title and author information, there will be a link labeled Extended Object. Clicking on that link takes you to a page that describes the available multimedia files, and allows you to download them.

From the Screen of Stone Lite: The IBM ThinkPad T42p

Yes, I know it's not really IBM anymore: it's Lenovo. However, so far, they still appear to be making the same great notebook computers, and I remain very pleased with the ThinkPad T series. I've written several times about these in the past ("From the Screen of Stone," *IEEE Antennas and Propagation Magazine*, **45**, 3, June 2003, pp. 143-144; "Editor's Comments: From the Screen of Stone Lite A Newer IBM Notebook," *IEEE Antennas and Propagation Magazine*, **46**, 3, June 2004, pp. 73, 78). The newer version I've recently been using adds several nice features: features that are actually valuable enough to be the determining factors in buying a notebook computer. This includes an integrated fingerprint reader. This is a swipe-sensor-based fingerprint reader, and it is very well implemented. Combined with the included security hardware and software (there is one piece of software you have to download yourself for security reasons), it also provides a very interesting and useful array of options.

Continued on page 100