An Energy-Density Antenna for Independent Measurement of the Electric and Magnetic Field

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An energy-density antenna which can measure both the E field and H field of a plane wave simultaneously has been developed, consisting of two small orthogonal semiloops over a ground plane. Hybrids were used to take the sum and difference of the loop outputs, giving voltages uniquely proportional to the E and H fields. The loop dimensions and optimum configurations were experimentally determined by measurements at a frequency of 836 MHz in a man-made free-space environment. Energy-density computation from the measured E and H fields of a standing wave in free space showed that the maximum-to-minimum range of the energy density is much less than that of either the E or H fields alone.

I. INTRODUCTION

A new way of reducing the signal fading encountered on a mobile radio transmission path is being investigated.[1] One source of fading is due to the fact that plane waves propagating in opposite directions at the same frequency produce a standing wave with nulls in the electric field every half free-space wavelength. The magnetic field also has nulls like the electric field but displaced a quarter wavelength from the electric field nulls. The electromagnetic energy density of such a pure standing wave is constant. If we sample E and H in free space and amplify the signals by the appropriate relative gains, square and add them, we obtain a signal proportional to electromagnetic energy density

$$w = \tfrac{1}{2}(\epsilon E^2 + \mu H^2). \tag{1}$$

The resulting output would be constant as we move through this idealized standing wave pattern. This method of energy-density utilization may be helpful in overcoming the rapid fading due to motion through the more complicated standing wave patterns in the mobile radio electromagnetic field. To utilize the energy concept, we need an antenna that has three outputs independently proportional to the field components E_z, H_x, and H_y at any point in the field (assuming vertical polarization). Since neither the ordinary loop antenna nor the shielded loop antenna can be used in this particular case, an investigation was undertaken to develop a suitable antenna.

This paper describes a particular antenna* which satisfactorily meets these requirements. The antenna consists of two small orthogonal loops and will be described later. Measurements on such an antenna and several other comparable ones were made in a simulated free-space environment.

II. METHOD OF TESTING THE PROBES

First of all, we need a method of test which tells us how well the antenna is responding to the H field alone. As mentioned before, the nulls of the E and H field in an ideal standing wave pattern are $\lambda/4$ apart. Therefore, if we can establish such an ideal pattern, the E nulls can be located accurately by a whip antenna; then the positions of the H nulls are known. Then we can test the magnetic probe in this environment, looking for nulls at these H-null positions.

A conducting ground plane 16 feet $\times$ 3 feet was surrounded with commercially available absorbers (minimum absorption is 17 dB one-way) to provide a man-made free space. Two waves traveling in opposite directions were produced by exciting two identical transmitting antennas from a common source. These two transmitting antennas "S" and "N," approximately 12 λ apart, were $\lambda/4$ whip antennas operating at 836 MHz over the ground plane as shown in Fig. 1(a). The receiving antenna under test could slide in a slot about 2 λ long which is in between the two transmitting antennas. E fields were first tested separately from the two transmitting antennas in order to make sure that the reflections in the man-made free space were small, and that the individual fields were sensibly constant along the length of the slot. The two curves shown in Fig. 2 are the amplitudes of the signal from each of the transmitting antennas. The field from the "N" antenna had a maximum-to-minimum variation range of about 2.5 dB, and that from the "S" antenna a variation range of about 3.5 dB.

*A brief description of this antenna appears in two papers: (1) Theoretical and Experimental Study of the Properties of the Signal from an Energy Density Mobile Radio Antenna, presented at the IEEE Vehicular Communications Conference on December 2, 1966, in Montreal, Canada. (2) Statistical Analysis of the Level Crossings and Duration of Fades of the Signal from an Energy Density Mobile Radio Antenna, B.S.T.J., *46,* February, 1967, pp. 417–448.

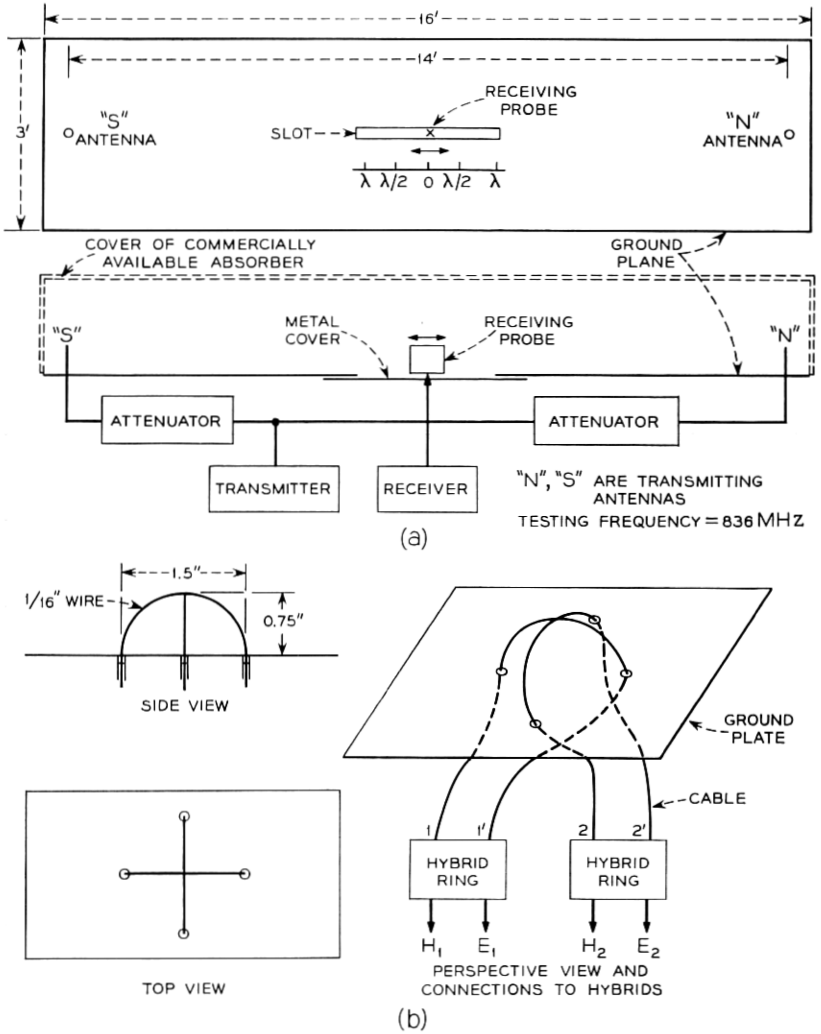

Fig. 1 — (a) Experimental set-up. (b) Energy-density antenna—double orthogonal loop antenna.

These variations, due to residual reflections, were felt to be acceptable. Since the average amplitudes of signal strength of two transmitting antennas were not quite the same, 11-dB attenuation was put on "*S*" antenna, and 10 dB on "*N*" antenna in order to get a good standing wave. The peak-to-null value of the standing wave produced when

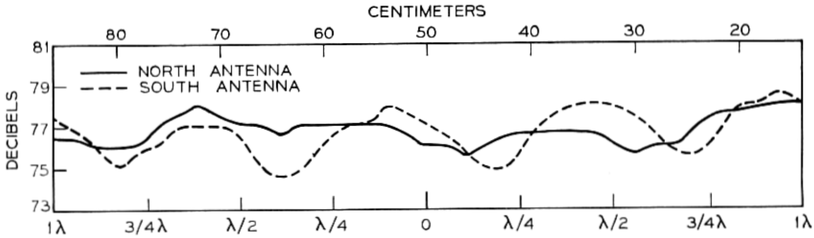

Fig. 2 — Amplitude of signal strength along the slot receiving from one transmitting antenna only.

both transmitting antennas were excited was then 23 dB, as shown in Fig. 3. We should remember that the measured standing wave was obtained from two E fields. Then we know a standing wave of the H field exists which will have the same peak-to-null value but a $\lambda/4$ shift from the standing wave of the E field.

III. TYPE OF ANTENNAS TESTED

3.1 *Single-Ended Loop*

A semiloop with one end grounded and the other end as output can be used as a magnetic field probe. However, the size of the loop is critical. Large errors are obtained in measuring the magnetic fields unless its diameter is less than 0.01 λ (about 0.14 inch diameter at 836 MHz).[2]

3.2 *Double-Ended Loop*

A semiloop with two output ends can be used as a combined electric and magnetic probe.[3] If the double-ended loop is in the field of a plane wave, the sum of the two outputs of the semiloop is proportional to the E field, and their difference to the H field. If the plane of the loop is in line with the direction of propagation the output is proportional to the total H field, otherwise only to a component of H field. This would be a limitation in using this type of probe for general purposes.

3.3 *Two Orthogonal Loops*

This antenna has been proposed for receiving a linearly polarized wave coming from a remote source which may not necessarily be in line with the plane of the loop. It consists of two double-ended loops with their planes perpendicular to each other. The "orthogonal loop antenna" has two pairs of outputs. Adding two pairs of outputs separately gives two values which should be identical and expressed theoretically as proportional to the total E field. Subtracting two pairs of outputs separately gives the two components of the H field. These two components are the components along the rectangular coordinates which have been defined by the planes of the two loops. The orthogonal loop antenna is an electric and magnetic field probe which appears to be promising for probing the energy density of the total field. Hence, it is called the energy-density antenna.

3.3.1 *Connected Loops*

The two loops are electrically connected at the top point. Since this configuration can allow the two loops to be identical, the two values of E field obtained from the two loops are expected to be equal, the currents in the two loops are correspondent to the two components of the H field which are normal to the planes of two loops. However, the connection at the top points is not exactly at the middle, which may introduce some errors.

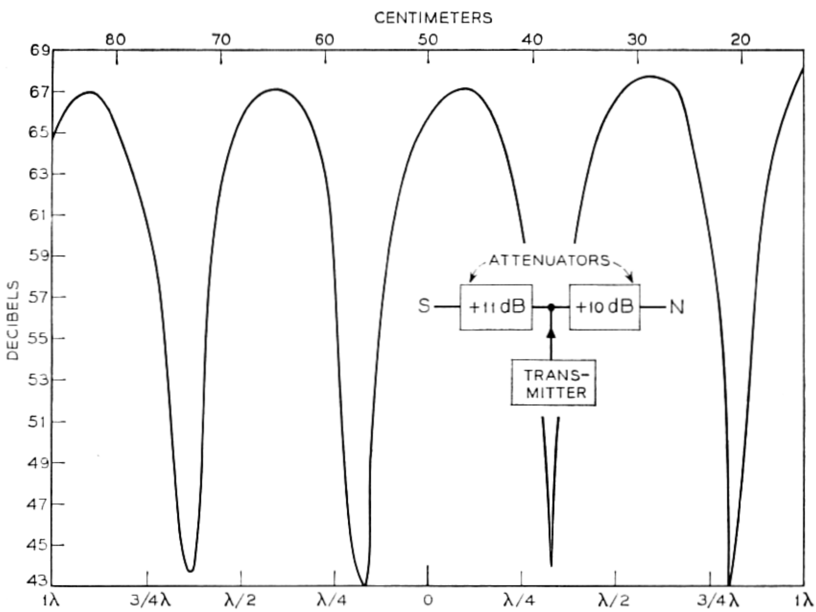

Fig. 3 — Standing wave along the slot by using a whip antenna as a receiving probe.

3.3.2 *Unconnected Loops*

The two loops are not connected electrically at the top points. In this configuration the two loops cannot be identical. One loop must be bent at the top in order to disengage the top point from that of the other loop. Therefore, the E field obtained from two loops may be different; also the two H component fields. However, the current in one loop may not be affected by the other due to the fact that the two loops are unconnected.

IV. EXPERIMENTAL RESULTS

4.1 *Single-Ended Loop*

The standing wave along the slot was measured by using different sizes of the single-ended loop. Investigation of three loops, 1, 1.5, and 2 inches in Fig. 4 shows that a 1.5-inch loop is better than the other two. The nulls of H field of the 1.5-inch loop are located more like the true H field though the amplitude of H field is 2 dB less than the 2-inch

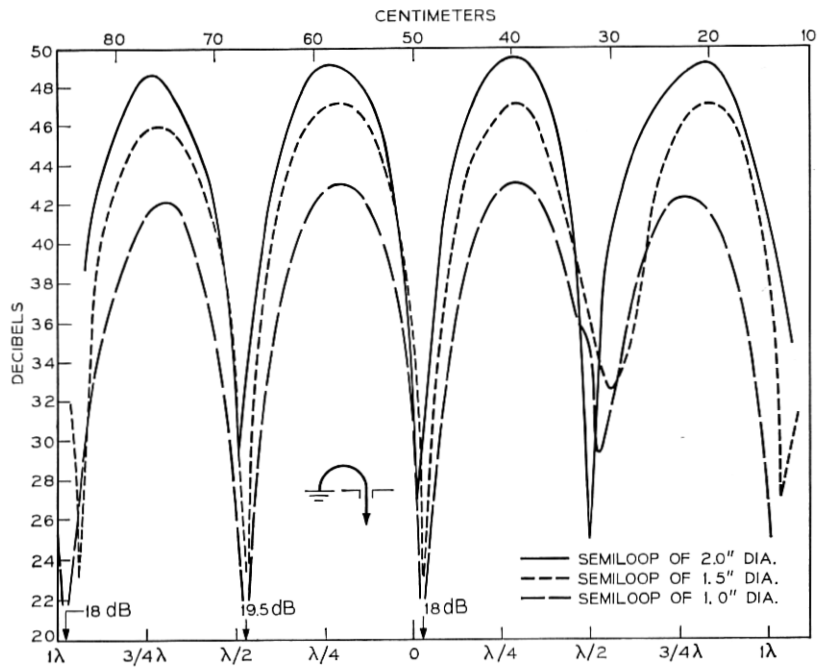

Fig. 4 — Standing wave of H fields along the slot by using a semiloop as a receiving probe (one end output).

loop. Comparing the 1.5-inch loop with the 1-inch loop, the amplitude of the 1.5-inch loop is 3 dB higher and the nulls are still located slightly better than in the 1-inch loop. Hence, the 1.5-inch loop is chosen even though it is 1/36 λ off the true H field (the standing wave of the true H field should be exactly a $\lambda/4$ shift from the E field). This was due to the effect of the electric field. The 1.5-inch loop is approximately 0.1 λ in diameter. This size of the loop was selected and used in the other types of loop configurations.

4.2 *Double-Ended Loop*

The standing wave along the slot was measured by using a semiloop as a receiving probe. The two outputs from the 1.5-inch semiloop were connected to a hybrid ring where the sum port gave the E field, and the difference port gave the H field. Since the plane of the loop was in line with the two transmitting antennas, the H field was a total H field. The E field and the H field outputs are shown in Fig. 5. The first null of the H field on the right had a slight disturbance which was probably due to the imperfect free space.

4.3 *Two Orthogonal Loops (unconnected)*

This probe consisted of two semiloops 1.5 inches in diameter. The size of the loop was chosen from Fig. 4. The circuit arrangement is shown in Fig. 1(b), except the top points of two loops were not connected.

4.3.1 *45° Orientation*

A double orthogonal semiloop was tested at an orientation of 45° to the line between the two transmitting antennas. Fig. 6 shows the two components of H field: H_1 and H_2. The two H components should be equal since the two loops were oriented 45° to the axis. However, the two loops, due to the fact they were roughly hand-made, were not precisely 45° to the axis. They were also not connected at the top points. So the fact that H_2 was higher from loop 2 than H_1 was from loop 1 was not a surprise. Fig. 6 also shows the E fields from the two loops, and we note that the nulls of the E field from loop 2 were lower than loop 1. The difference between the two loops was that loop 2 had more cross section area than loop 1.

4.3.2 *90° Orientation*

A double orthogonal semiloop was oriented at 90° to the line between the two transmitting antennas. In this case, H_2 should equal

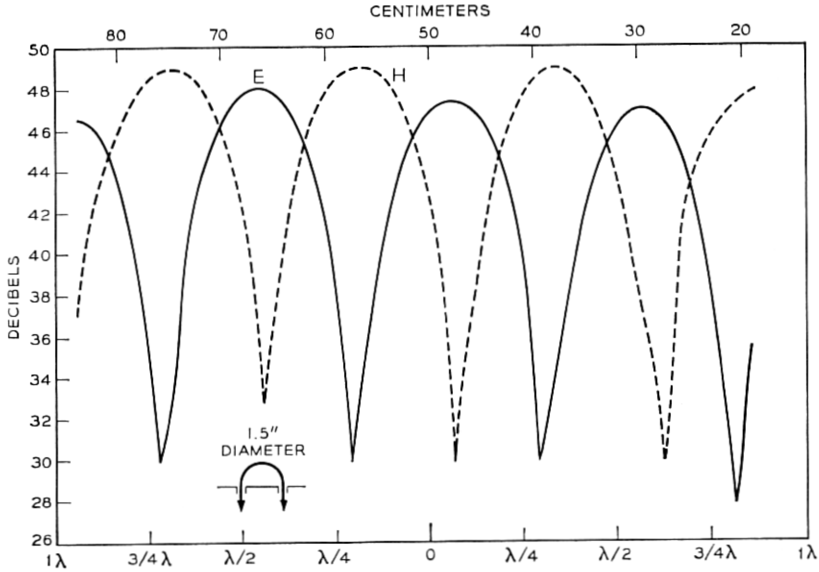

Fig. 5 — Standing waves of E and H fields along the slot by using a semiloop as a receiving probe.

the H field and H_1 should read zero output. From Fig. 7 we see that H_1 is 18 dB down compared with H_2, but has apparently picked up some E field since the peaks of H_1 are almost located at the nulls of H_2 and vice versa. H_2 in Fig. 7 is almost equal to the vector sum of the two components, H_1 and H_2, in Fig. 6 (45° case) as one would expect. E_1 and E_2 in Fig. 7 should be identical. They both represent the E field. In an ideal situation, E_1 and E_2 in Fig. 7 and in Fig. 6 should all be the same. Since the two loops were not connected at the top point, the maximum output from loop 1 was slightly lower than loop 2. Hence, the nulls of the four E's were not the same.

4.4 *Two Orthogonal Loops (connected) — Energy-Density Antenna*

The two orthogonal loops (1.5 inches in dia.) were connected at the top point of two loops, shown in Fig. 1(b).

4.4.1 *45° Orientation*

A double orthogonal semiloop was oriented at 45° to the two transmitting antennas. Fig. 8 shows the two components H_1 and H_2. Since the loops, due to the fact they were roughly hand-made, were not oriented precisely 45° to the axis and were not actually quite symmetrical to the center, the two components H_1 and H_2 were not equal. There was no remarkable difference between Fig. 8 and Fig. 6. Fig. 8 shows the two E fields: E_1 and E_2. Their peaks are almost the same, which might be due to the fact that the two loops were connected at the top points, but the nulls did not coincide with each other due to the two unsymmetrical loops. Comparing Fig. 8 and Fig. 6, we found that we had better results when there was a connection at the top points of the two loops in that the nulls of E_1 were somewhat deeper.

4.4.2 *90° Orientation*

A double orthogonal semiloop was oriented at 90° to the two transmitting antennas. Fig. 9 shows H_2 which is the amplitude of the total H. Loop 1 picked up some E field, as H_1 shows, of about the same value as in the unconnected case. H_1 was almost 20 dB down compared with H_2. There was no remarkable difference between Fig. 9 and Fig. 7 except that H_1 in Fig. 9 picked up more like a pure E field although

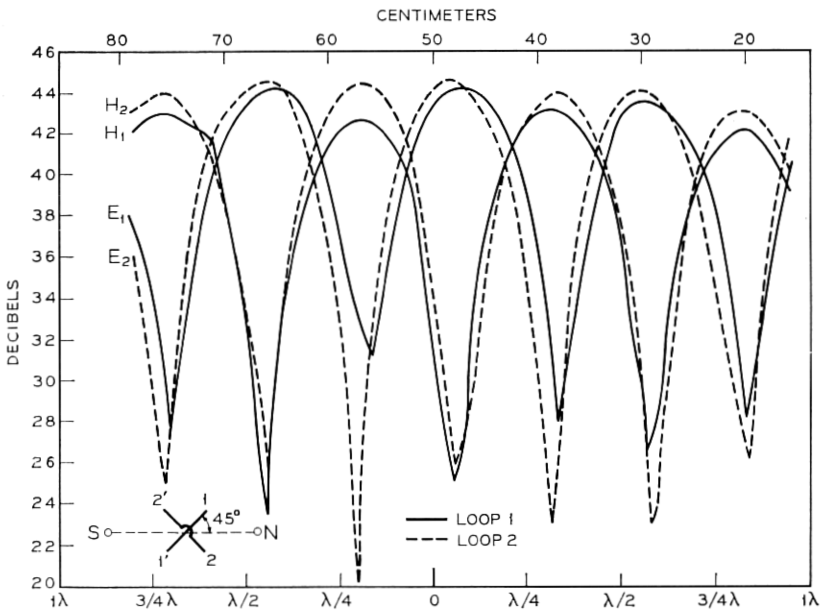

Fig. 6 — Standing waves of H fields and E fields along the slot by using a double orthogonal semiloop antenna unconnected at the top point (oriented at 45°).

it has small field strength. Fig. 9 shows that E_1 and E_2 almost coincided, but in Fig. 7 they did not. Hence, it is better when the two loops connect at the top points than when they do not.

V. ENERGY-DENSITY COMPUTATION

We used the H and E components of two connected orthogonal loops oriented at 45° (Fig. 8) and 90° (Fig. 9) to compute two sets of energy density from the measurements made in the free-space environment. Since both E and H were measured in volts, the energy density we computed from (1) is

$$w = \frac{\epsilon}{2}\left(E^2 + \left(\frac{\mu}{\epsilon}\right)H^2\right)$$

$$= \frac{\epsilon}{2}\,[E^2(\text{volts}^2/\text{m}^2) + (377\ \text{ohm})^2 \times H^2(\text{amp}^2/\text{m}^2)]$$

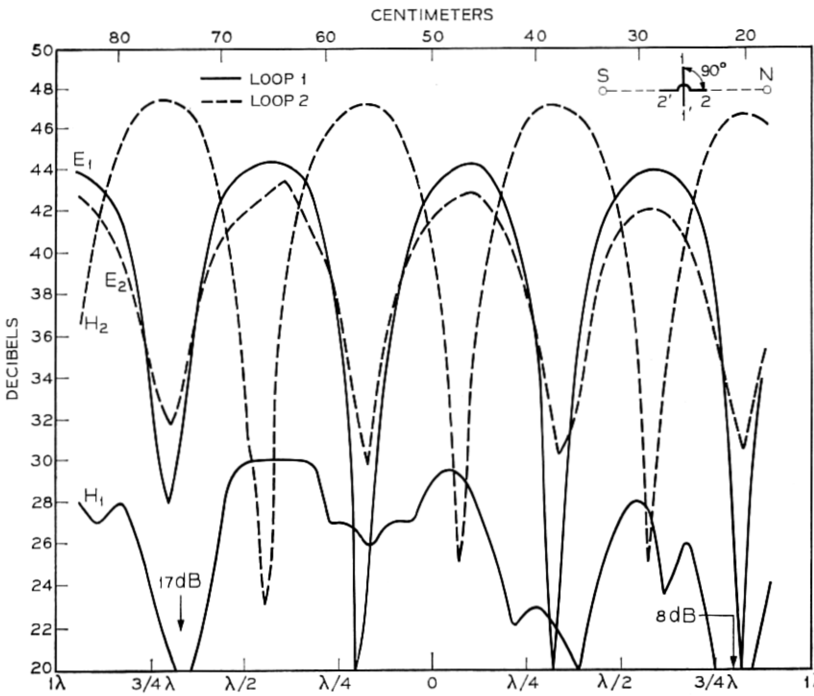

Fig. 7 — Standing waves of H fields and E fields along the slot by using a double orthogonal semiloop antenna unconnected at the top point (oriented at 90°).

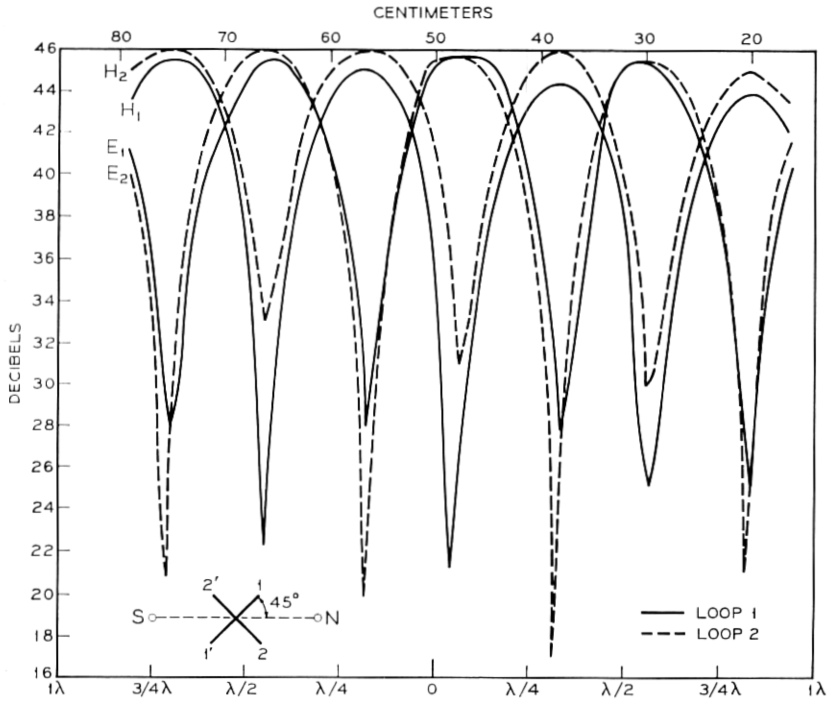

Fig. 8 — Standing waves of H fields and E fields along the slot by using a double orthogonal semiloop antenna connected at the top point—an energy-density antenna (oriented at 45°).

$$= \frac{\epsilon}{2}\,[E^2(\text{volts/m})^2 + H^2(\text{volts/m})^2]$$

$$= \frac{\epsilon}{2}\,(w'), \tag{2}$$

where

$H^2 = \alpha_1 H_1^2 + \alpha_2 H$,

$E^2 = E_1^2$ or E_2^2 ,

α = a weighting factor (a factor relating the level of average peak values of H_1 and H_2 components to the E field), and

w' = the energy density in our calculation.

From Fig. 8 we found that the maximum value of H_1 was about 1 dB less than H_2. Also from Fig. 9 we found that the maximum value

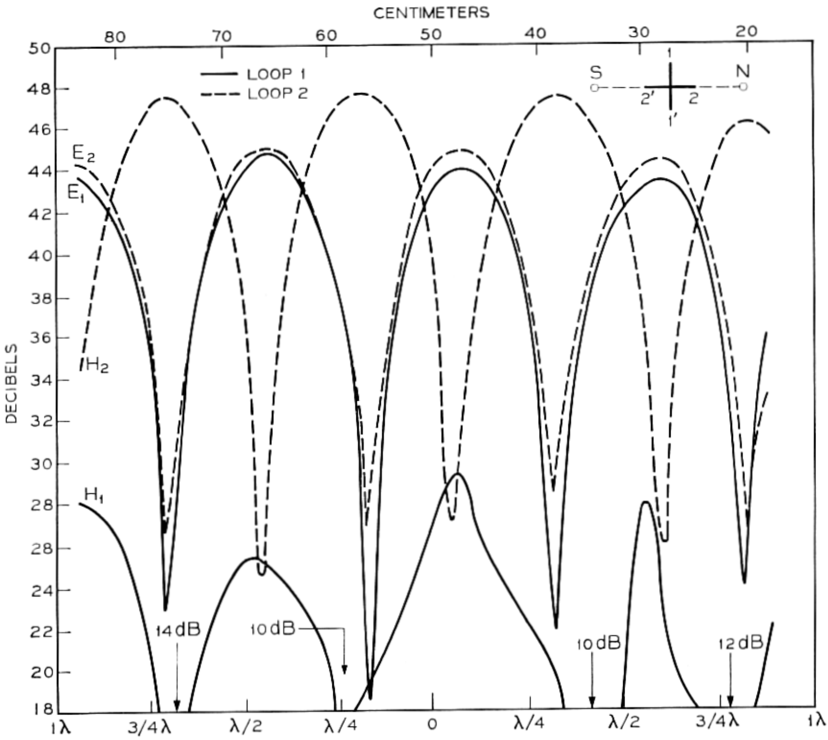

Fig. 9—Standing waves of H fields and E fields along the slot by using a double orthogonal semiloop antenna connected at the top point—an energy-density antenna (oriented at 90°).

of either of two E fields was about 2 dB less than H_2. Hence, we might suggest the following equation representing the energy density obtained from this particular antenna:

$$\begin{aligned} w' &= (1.122H_1)^2 + H_2^2 + (1.26E_2)^2 \\ &= (1.26)^2[(0.89H_1)^2 + (0.795H_2)^2 + E_2^2], \end{aligned} \tag{3}$$

where $\alpha_1 = 0.89$ and $\alpha_2 = 0.795$. From (3) we can calculate two energy-density curves, one shown in Fig. 10 for the orientation of antenna at 45° and another also shown in Fig. 10 for the orientation of antenna at 90°. From both curves, the maximum-to-minimum range was only about 2.4 dB, compared to 18–20 dB in Fig. 8 and 9 for the E and H fields alone.

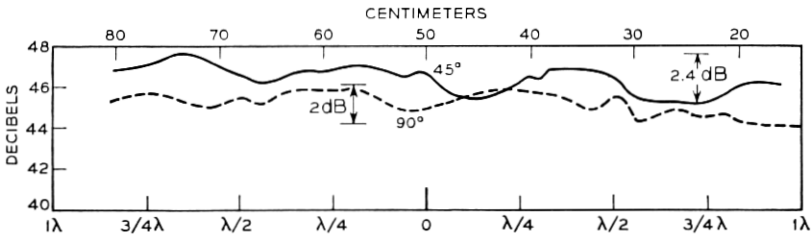

Fig. 10 — The energy-density calculation of an energy-density antenna (oriented at 45° and 90°).

VI. CONCLUSION AND COMMENTS

An energy-density antenna with loops of 1.5 inches in diameter was selected from the measurements as the one to test in the mobile radio field. The connected orthogonal loops were somewhat better than unconnected ones. For two orientations of the loop in the standing wave field in the test environment, the computed energy density varied much less than any of the field components. The configuration of the energy-density antenna could be used at other frequency ranges by scaling the diameter of the loops. After an energy-density antenna was made, a calibration to obtain the weighting factors α_1 and α_2 was needed to set up a proper energy-density equation for this particular antenna.

I wish to take this opportunity to thank W. C. Jakes, Jr., for his advice and suggestions.

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