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Improvement of Ferrite Antennas through Size and Geometric Engineering

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1. INTRODUCTION

The background radio noise in the VLF (Very Low Frequency) region are of very low levels. For this reason relatively large ferrite cores (1” diameter and 7.5” long) have been used to collect the flux. There is interest in making the ferrite antenna smaller and more portable. This short study explores the possibilities to this end.

2. SIGNAL LEVELS

The background VLF signal levels are on the order of around 30 femto-Teslas/ rt(Hz) at 10 kHz. One femto-Tesla is 10^{-15} Tesla. A ferrite core (1” diameter, 7.5” long) antenna with around 250 turns will typically present an output of around 0.0003 V/nT. A background noise of 30 fT/rt(hz) will generate a voltage signal of 9nV/rt(Hz). If a signal analyzer has a bandwidth of 125 Hz, then the output shown on the analyzer is 99nV or ~ 0.1uV. Suppose we add a low noise amplifier with gain of 600, then the analyzer will show the background VLf noise to be 60 uV. It’s not surprising that the self-noise of the low noise amplifier is around 50 uV, just barely able to discern background VLF noise. Narrow band communications signals from VLF stations are usually much larger than 60 uV and are discernable from the background noise.

The above discussion shows that even with the relativity large ferrite core we are using, the background VLF noise is barely discernable. We will work with known concepts to design new antenna(s) that can output similar values but with a smaller footprint.

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3. IMPROVINGTHE EFFECTIVE PERMEABILITY THROUGH GEOMETRY

The chart in Figure 1 shows that effective permeability of a ferrite rod (denoted as μ_{rod}) is a function of the length to diameter ratio. Whether we use the term permeability or intrinsic permeability, it is meant to be relative permeability which is denoted by μ_r. Consider a 1” diameter, 7.5” long rod with an intrinsic permeability of 2000. The L/D ratio is 7.5. Reading from 7.5 on the horizontal axis of Figure 1, it is seen that the effective permeability is around 40.

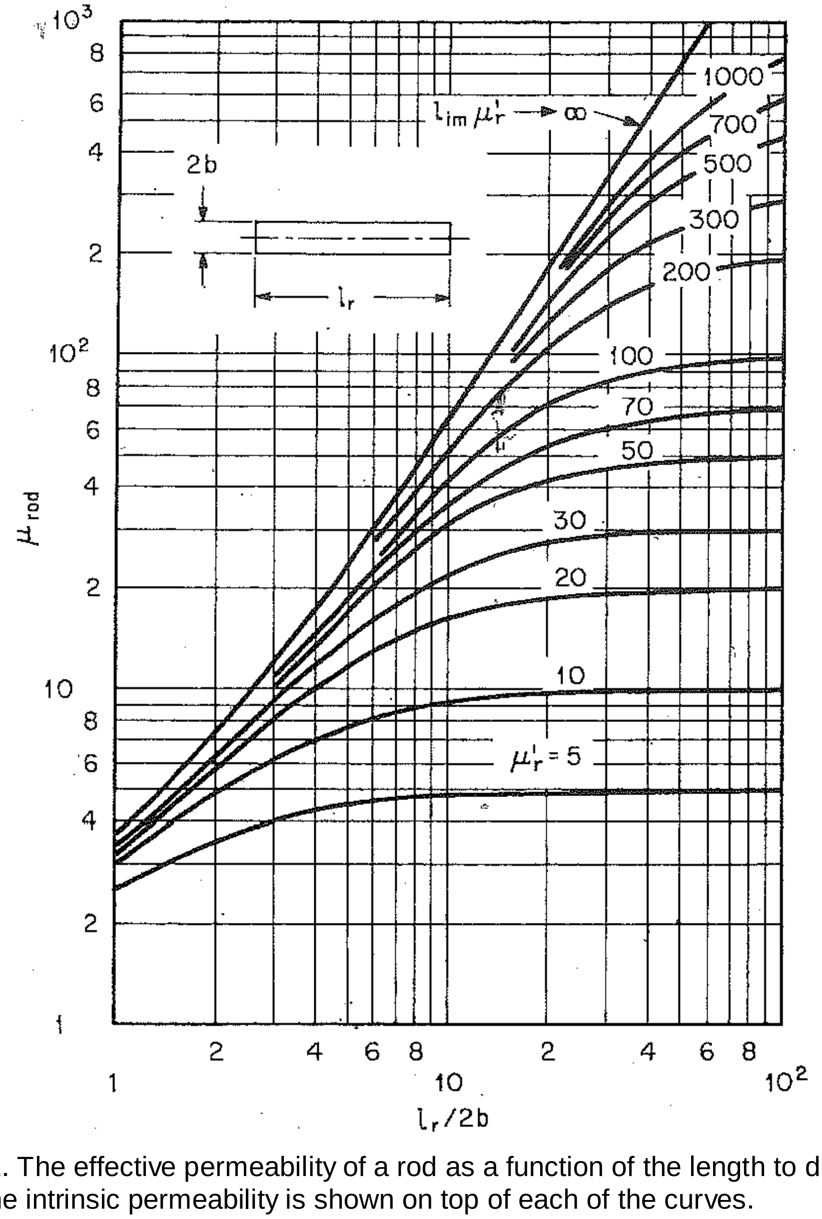


Figure 1. The effective permeability of a rod as a function of the length to diameter ratio. The intrinsic permeability is shown on top of each of the curves.

The net flux collection area is the product of the effective permeability and the cross-sectional area of the rod, as shown in Equation 1 (diameter must be in cm).

$$Flux\ Collection\ Area = \mu_{rod} * \pi * \left(\frac{D}{2}\right)^2 \qquad \text{Equation 2}$$

Therefore, our 7.5” long, 1” (2.54cm) diameter rod with an effective permeability of 40 has an effective flux area of 202 cm^2. Figure 2. shows an example of two 7.5” long rods with different diameters. Since the effective permeability is dependent on the length to diameter ratio, decreasing the diameter will increase the effective permeability.

(a) (b)

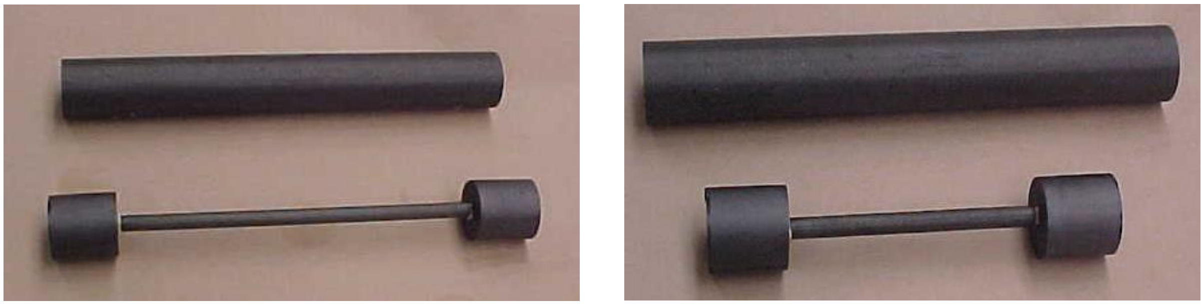
Figure 2. (a) A 7.5” long rod with diameter of 1” (b). A 7.5” long rod with diameter of ¼”.

Consider the two rods in Figure 2. . Both have the same length of 7.5”, but the thin rod’s diameter is 0.75” smaller (for the purposes of this report, a thick rod has a diameter of 1” and a thin rod has a diameter of ¼”). The L/D ratio of the thin rod is 30, which, from Figure 1, gives an effective permeability of 360. This is quite a bit larger than the effective permeability of 40 for the 1” diameter rod. Unfortunately, from Equation 3, the flux collection area also depends on the rod’s diameter. This gives us a flux collection area of 114 cm^2 for the thin rod. Thus, we see that decreasing the rod’s diameter improved its effective permeability but not enough to off-set the drop in net flux collection area.

What would happen if we marry thin rod with large diameter ends, such as that shown in Figure 3?

Figure 3. A thin rod with larger diameter end pieces.

An antenna with a thin ferrite rod and thick diameter end-pieces such as that shown in Figure 3 can be achieved by simply attaching the end-pieces with epoxy glue. The results are shown in Figure 4.



(a) (b)

Figure 4. Standard 7.5” long, 1” diameter rods on top. (a) A 5.5” long, 0.25” diameter rod with 1” long, 1” diameter end pieces. (b) A 3.5” long, 0.25” diameter rod with 1” long, 1” diameter end pieces.

Consider the end pieces shown in Figure 4. A 1” diameter rod that is 1” long, with an effective permeability of 3.8 and a flux collection area of 19 cm^2. Now, consider the ¼” diameter rod with a length of 5.5” from Figure 4(a). The L/D ratio is 22. The effective permeability is seen to be around 210. Thus, the flux collection area is 66.5 cm^2. Similarly, from Figure 4(b), the ¼” diameter rod with a length of 3.5” has an L/D ratio of 14, an effective permeability of 90, and a flux concentration area of 28.

In a first attempt to work out the effective area of the three pieces (Figure 3.), the concept of reluctance is used. Reluctance is equal to L/(µ*area), where L is the length of the rod, and µ is the absolute permeability ($=\mu_0 * \mu_r$). Figure 5 shows an example the total reluctance, which is the sum of the individual reluctances.

Figure 5. The total reluctance is the sum of the individual reluctances. R = R1 +R2 + R3.

$R1 = R3 = L1 / (\mu_0 * \mu_{r1} * area1)$ where $\mu_{r1} = 3.8$, L1= 1” = 0.0254m, area1 = 0.0005067m^2

$R2 = L2 / (\mu_0 * \mu_{r2} * area2)$ where $\mu_{r2} = 210$, L2 = 5.5 x L1, area2 = 1/16 * area1

$R = R1 + R2 + R3 \rightarrow 2R1 + R2 \rightarrow 7.5*(.0254) / (\mu_0\ 8.0 * area1)$

We identify 8.0 is the effective permeability of the system with 1” diameter. The net flux collection area is 8 x 5.067 cm2 = 40.5 cm2 . This is much too small because the answer should lie between 114 cm^2 (5.5” diameter rod) and 202 cm^2 (1” diameter rod).

This answer is not correct because we have tried to solve a non-linear problem using a linear approach which does not work. However, we can solve this problem using a physics approach. Consider the 1” long cylinder ferrite. The field lines from the environment are concentrated by the ferrite piece as shown in Figure 6 below.

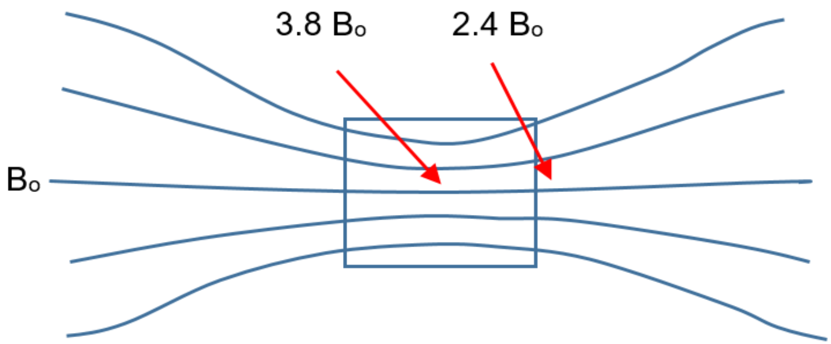


Figure 6. The environment B_o field is concentrated by the ferrite block to the values shown.

At the center of the ferrite cylinder the B field is 3.8 B_o , where 3.8 is the effective permeability. On the surface the field is 0.63 * 3.8 B_o (=2.4 B_o) where 0.63 is the demagnetizing factor. The demagnetizing factor is found from calculating the field of a magnet from any magnetic calculator such as https://www.dextermag.com/field-on-axis-of-cylindrical-magnet/ . The procedure is to perform a calculation of the field of a magnet 1" in diameter and 1" long. Then the ratio of the field at the surface and at the center is taken. That ratio will be 0.63.

Next, the thin 5.5" rod will be analyzed. At both ends of the thin rod, the field will be 2.4 B_o. The effective permeability is 210. The effective permeability * end field = field at center of rod. Thus, the field at the center of the thin rod is 2.4 * 210 B_o = 504 B_o Teslas. The net flux is 504 B_o * area = 159.8 B_o Webers. Thus, we find the flux collecting area is 159.8 cm^2,which is intermediate between that of the thin rod (114 cm^2) and that of the tick rod (202 cm^2). Thus, we find that adding two larger pieces to the ends of a thin rod will significantly increase its effective permeability. We will also perform measurements to measure the effectively permeability.

Similar analysis applied to a thin 3.5" long rod with two thick 1" long ends shows that the effective permeability is 90. At the center of the 3.5" rod the field is 2.4 x 90 * B_o = 215 B_o Teslas. The net flux is 215 B_o * area = 68 B_o Webers. Thus, the flux collecting area is 68 cm^2. Table 1 summarizes these results.

Table 1. Estimated Perm Area Products.

Core Type	Effective Permeability	Area (cm2)	Effective Flux Collection Area
Thick Rod, L=7.5"	40	5.067	202
Thin rod, L=7.5"	360	0.317	114
5.5" thin rod with 1" thick ends	210	0.317	160
3.5" thin rod with 1" thick ends	90	0.317	68

It is seen that the 5.5" thin rod has a good flux collection area but is much lighter than the thick 7.5" long rod.

4. TAPERING THE ENDS

The two ends of the system in Figure 4 can be tapered to save space, weight and material. The space saved can be used for more coil windings. Figure 7Figure 8 shows a drawing of a system with tapered ends.

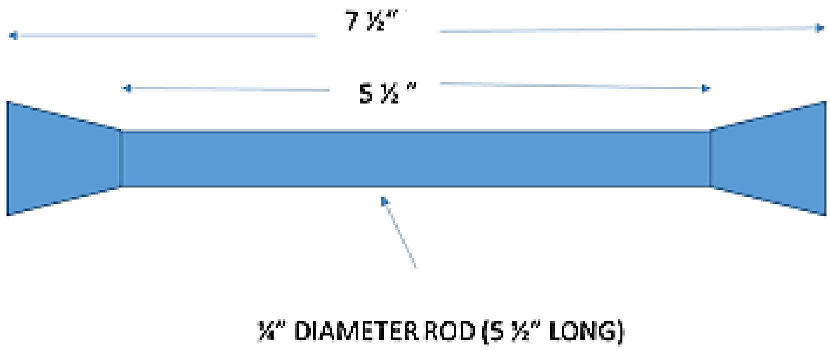


Figure 7. A thin rod with two tapered thick ends.

The tapering is not expected to reduce significantly the effective flux collection area from that of the 5.5" thin rod with 1" thick ends in Table 1. Thus, it is expected that the effective flux collection area is around 160 cm^2. Figure 8 shows this tapered core design made from gluing two tapered ends to a ¼" diameter rod with a length of 3.5".

Figure 8. A 7.5" long, 1" diameter rod and a 3.5" long, ¼" diameter rod with tapered end pieces.

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5. TAPERED ANTENNAS

To use the ferrite cores as B-field antennas, insulated wire is wound around the core material. Figure 9 shows a long and short tapered core antenna. Both were wound with 300 turns of 28 AWG insulated wire. The long-tapered antenna has a 5.5” long, ¼” diameter core; and the short-tapered antenna has a 3.5: long, ¼” diameter core. Both antennas have 1” long tapered end pieces with a larger diameter of 1”.

Figure 9. Long tapered antenna, 7.5” long, 300 turns. Short tapered antenna, 5.5” long, 300 turns.

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6. FLUX COMPETITION AMONG ANTENNAS

When antennas are placed close to each other, they can compete for the ambient flux. The change in reception of an antenna was measured when another antenna is brought nearby. Figure 10 shows both parallel competition and orthogonal competition.

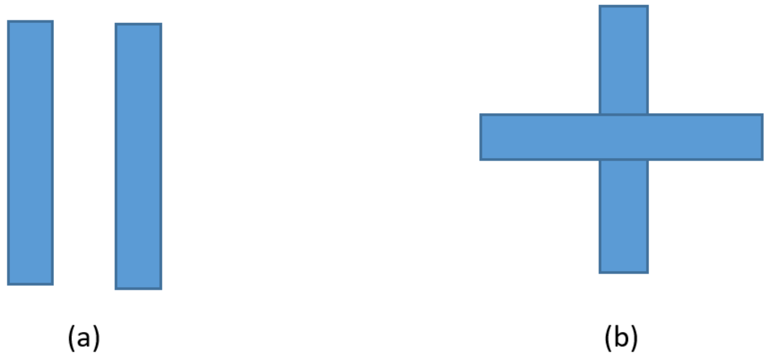

Figure 10. (a) Parallel competition. (b) Orthogonal competition.

The measurements show that in all cases (for both standard and tapered antennas), there was little effect until the antennas were closer than 4” in the parallel configuration. At 4” and closer the drop in signal was about 5%. In the orthogonal configuration, the signal drop was insignificant up to 1” from each other.

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7. SIMULTANEOUS PERFORMANCE COMPARISON

Four antennas were compared simultaneously using four identical receivers and four channels of recording. The four antennas are (1) the standard 7.5” long, 1” diameter 2000 perm antenna, (2) a 125 perm antenna, (3) long tapered antenna, (4) short tapered antenna. The recordings were done at Finger A of Pier 160 in order to get farther away from the electrical noise on land. All antennas performed well, and all standard VLF stations normally within range were received at a large S/N ratio. In order to quantitatively rate each antenna by the S/N ratio of the reception of, Lualualei VLF station (Hawaii) will be used. Figure 11 shows the FFT of the recordings from the four types of antenna.

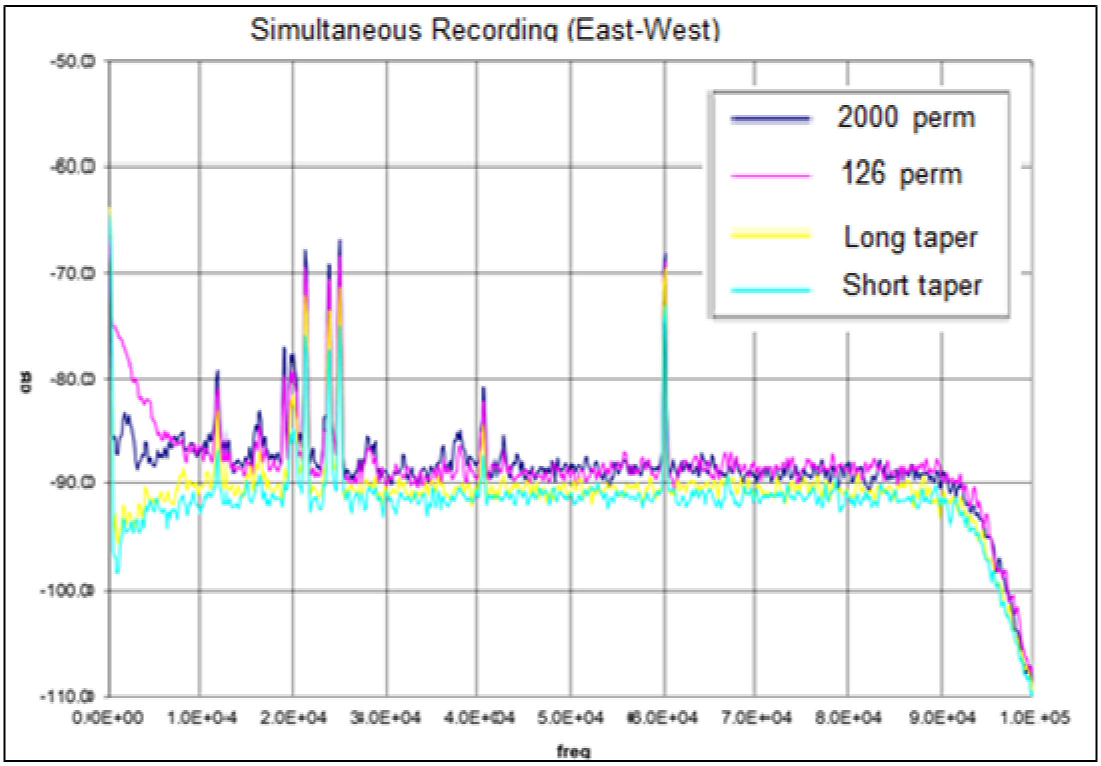

Figure 11. The FFT plot of recordings using the four types of antenna.

The Lualualei VLF signal is at 21.4 kHz. The background noise at 21.9 kHz is used as the noise standard. Figure 12 shows the S/N ratio using the formula, S(21.4kHz)/N(21.9kHz).

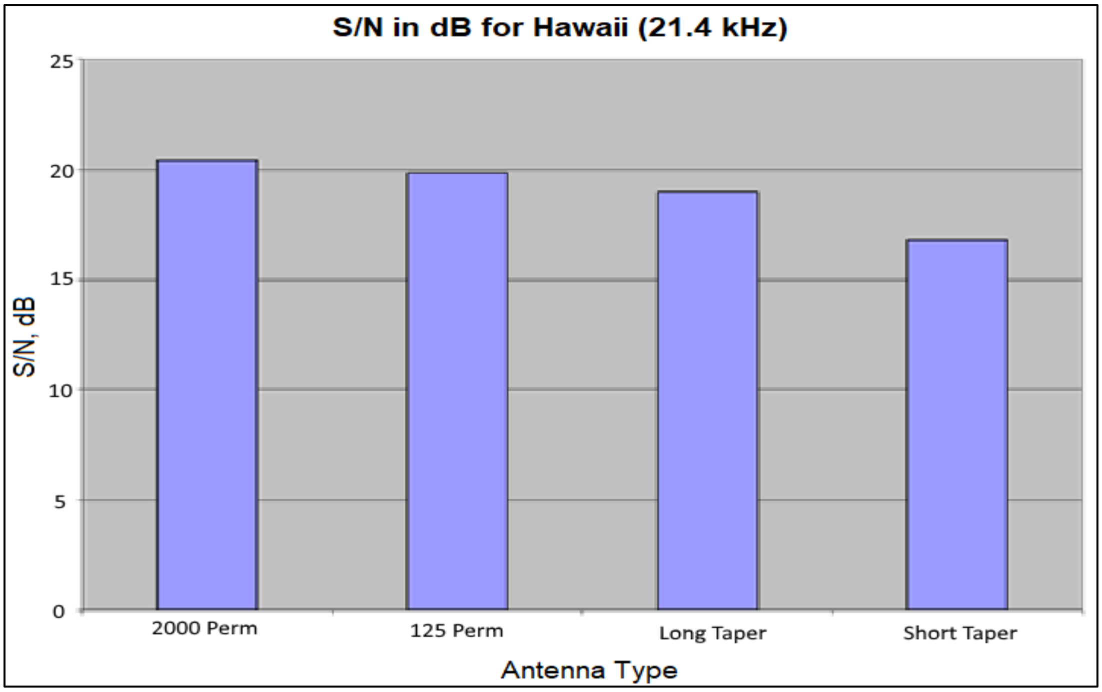

Figure 12. The S/N as measured for each of the four types of antennas.

The results show that the best S/N is from the standard antenna with 20.4 dB. This is followed by the 125 perm antenna with 19.8 dB, then followed by the long tapered antenna with 19.0, and finally the short tapered antenna with 16.8 dB. The long tapered antenna losses 1.4 dB signal as compared with the standard antenna. This is not a significant loss if weight and space considerations are of higher priority.

8. CONCLUSION

This report has shown that physical space and weight of ferrite rod antennas can be reduced by using tapered ends. There is a small loss in dB when the long tapered antenna is used. However, when there is a priority with weight and space, this small loss can be acceptable.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

This short study explores the effectiveness of altering the lengths and geometries of ferrite-core based antennas for the purposes of creating smaller and/or lighter antennas with similar signal-to-noise ratios (SNR). These antennas were primarily being used to record background atmospheric signals in the Very Low Frequency (VLF) range. Several width-to-length ratios are tested, as well as different styles of end pieces to help concentrate the flux in the ferrite cores. In the end, it is shown that long tapered ferrite cores can be used to save weight and space, if a small signal loss can be tolerated.

15. SUBJECT TERMS

Tapering antennas; long tapered antenna; ferrite rod antenna; permeability; short tapered antenna

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