THE RADIATION RESISTANCE OF FERRITE ROD ANTENNAS

The accepted theory for the radiation resistance of ferrite rod antenna is based on the theory of demagnetisation. This is shown to be flawed and a new theory is given which agrees well with experiment.

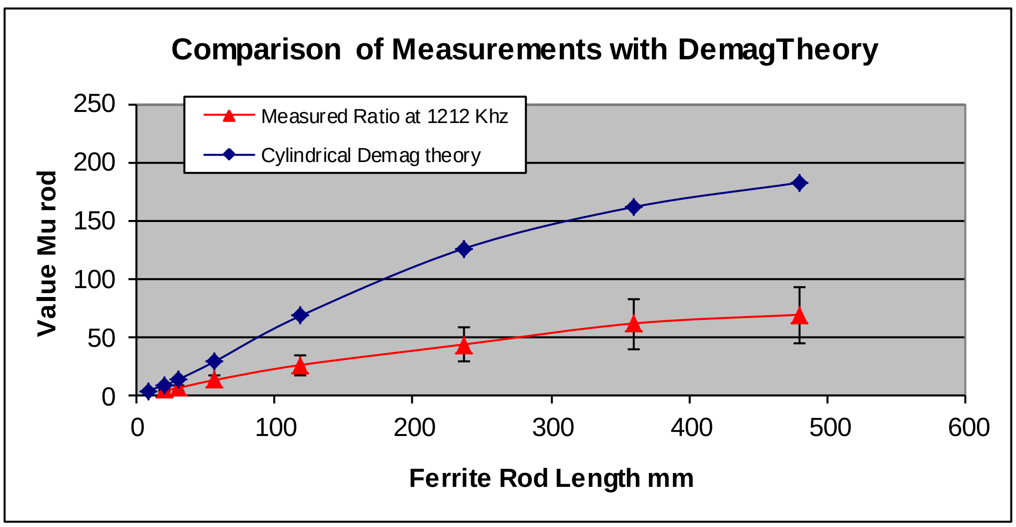
1. Introduction

The signal received by a small coil can be enhanced considerably by inserting a ferrite rod into it, because the rod captures a volume of the incident electromagnetic field which is much larger than itself, and concentrates this into the loop. This capture effect is not unique – a conventional wire dipole antenna also has an effective area vastly larger than its physical area.
In the accepted theory this enhancement when the ferrite is introduced is considered to be due to the permeability of the rod (which is related to the ferrite permeability), and so the ferrite antenna is seen as a *coil* antenna with an enhanced effective area. An alternative view is that the ferrite rod is a *magnetic dipole*, and the coil merely provides a means for detecting its flux, and this viewpoint leads to a more accurate analysis.

In this report the most significant equations are highlighted in red.

2. Far Field Tests of Conventional Theory

In the conventional theory the key to the calculation of the signal strength is the determination of the effective permeability of the rod, μ_{rod}, and this is given by the theory of demagnetisation. This theory is accepted by all the respected references on ferrite antennas, and so a good correlation with measurements should be expected, but this is not so. In an experiment described later the signal strength received from a nearby broadcast station was measured using firstly an antenna consisting of a coil only and then with ferrite rods of various lengths inserted into it. The ratio of the signals with and without ferrite should be equal to $\mu_{rod,}$ and the results are shown below :



The signal enhancement predicted by the demagnetisation theory was up to 3 times greater than that measured. Given the widespread use of this theory, one must first question the accuracy of the measurements, and certainly the measurement of signal strength is difficult, and great care must be observed to minimise errors (see Measurement Technique). However the curve according to the accepted theory falls a long way outside any reasonable estimate of the measurement error, and in addition there are other good reasons to believe that it is wrong.
So next we look at the theory of demagnetisation.

3. Demagnetisation and μ_{rod}

The effective permeability of the rod, μ_{rod} , is less than that of the ferrite, and in the accepted theory this is explained by demagnetisation. This was developed for permanent magnets, and explains why it is easier to magnetise a long thin bar down its length rather than across its width. The key idea is that when a ferromagnet forms an open magnetic circuit such as a bar magnet, the field *within* the material works against the magnetising field. So imagine a bar magnet with N pole at one end and S pole at the other. The field *inside* the bar due these magnetic poles is in the *opposite* direction to the field which set them up, and to the field outside the bar. This internal field is known as the demagnetising field, and for a long thin object it is weak because the poles are well separated. For a field across a squat flat object the demagnetising field is large because the poles are closer together, which explains why it is difficult to magnetise a bar across its width.
More details on demagnetisation are given in Appendix 1, and it is shown there that if the permeability of the ferrite rod is very high the value of the effective permeability μ_{rod} tends towards a value of :

$$\mu_{rod\,\infty} = 2(l / 2a)^{1.5} + 2 \qquad 3.1$$

where l is the length of the ferrite rod, and
a its diameter

It is significant that this equation shows μ_{rod} proportional to $l^{1.5}$, and the implications of this are discussed in the next section.

4. Demagnetisation Theory of Radiation Resistance

The radiation resistance of a ferrite rod antenna is given by Johnson & Jasik, (ref 4 equation 5-16, p 5-8) as:

$$R_{r\,rod} = 120\pi/(6\pi)\ \beta^4 (\mu_{rod} F_v NA)^2$$
$$= 31200\ (\mu_{rod} F_v NA)^2 \qquad 4.1$$

Where N is the number of turns in the loop
A is the area of the loop
$\beta = 2\pi/\lambda$ where λ is the wavelength

This equation is the well established radiation resistance of a simple loop, increased by the factor $(\mu_{rod} F_v)^2$, where F_v is a fudge-factor introduced to make the equation agree with experiment. In this regard, reference 4 says that the radiation resistance is somewhat dependent on the length of the coil compared to that of the rod, and the factor F_v allows for this. It is highest when the coil is short compared to the length of the rod and then F_v is equal to unity. For longer coils the above reference gives an empirical curve of F_v, dropping to 0.79 when the coil is equal in length to the ferrite. Significantly the reference implies that Equation 4.1 has been verified by experiment, when it says 'F_v was determined from an average of experimental results…', but no details of these experiments are given. However in the author's experiments no strong evidence for this reduction was found (see Section 8).

Notice that in Equation 4.1 the radiation resistance is proportional to the square of μ_{rod}, and this has an important implication. It is shown in Appendix 1 that as the ferrite permeability tends towards infinity, μ_{rod},

is proportional to $(l/2a)^{1.5}$, so for a given rod radius the radiation resistance will be proportional to l^3. It is interesting to compare this with an electric dipole (with infinite *conductivity*, to compare with the infinite permeability) whose radiation resistance is proportional to l^2. This is the first puzzle with the accepted theory, since it seems surprising that the magnetic radiator will be different in this respect to the electric radiator.
In case the assumption of infinite permeability is seen as a weakness in the above argument, it should be noted that for $\mu_f = 1000$, an achievable value, a good approximation is $\mu_{rod} = 3.1\ (l / 2a)^{1.3}$ which gives R_r proportional to $l^{2.6}$, again exceeding the more likely value of l^2.

5. Published Experimental Results

At this point the author decided to scan the literature to find experimental proof of the accepted theory. One difficulty with ferrite antennas is that the radiation resistance is very small ($\approx 10^{-6}\ \Omega$, see Section 10) and thus difficult to measure, and so experimenters instead measured a received signal, both with and without the ferrite and compared the two. This is perfectly valid and Belrose (ref 5) gives the received signal in an air loop, for an incident electric field intensity E_s as :

$$e_s = 2\pi\ A\ N\ E_s / \lambda \qquad 5.1$$

When the ferrite rod is inserted the conventional theory says the signal increases by μ_{rod}, and this is what experimenters were attempting to measure (NB note that e_s and E_s can be either maximum or RMS values)
A surprising result of the literature search was that there were very few published measurements, and those that do exist are without exception all *near-field* measurements. This is in contrast to the author's far field measurements given in Section 2.

Poole (ref 6) gives the most detailed account of measurements that was found, and his results agreed with the demagnetisation theory. He generated an RF magnetic field at 2 Mhz with a loop of radius 0.125m exciting a ferrite cored receiving coil. This coil had 8 turns with a diameter of 10mm, and length 8mm, and positioned *at distance of 0.6M, the two aligned coaxially*. Notice coaxially. So he was measuring the field off the end of the ferrite, where there is a *null* in the radiated field. Also note the very short range: he could well have been measuring the *inductive* field at this range, and indeed that is exactly what it seems to have been (see Stewart below).

Stewart (ref 7) gives theoretical support to near-field measurements, by giving the relationship between the near field and the far field. He then carries out near-field measurements similar to Poole above, except that he does these at *audio* frequencies at a range of 1.25 metres. To emphasise his near field approach he says **(**top of his p45) 'In fact, it is not necessary to measure a quantity related to radiation intensity such as tangential magnetic field at all: rather a uniquely defined radial component of magnetic field is adequate. The most convenient measurement is that of the radial component of the magnetic field in the direction of the dipole under test, *which is the null direction of the figure-8 radiation pattern'* (my italics). He also states that the field he is measuring *is* the inductive field, when he says (top page 44) 'All the electromagnetic field components about the dipole are proportional to the dipole moment. These fields vary with the distance R as k^2/R for the radiation field components, k/R^2 for the transition field components, and as $1/R^3$ for the induction field components, where $k=2\pi/\lambda$'. He then explains that at sufficiently low frequency the first two components are negligible compared with the induction field, so this alone can be measured to find the dipole moment. He also says 'Results of static tests ….have been verified in a few specific cases ..'(p43), but he does not give any details.

Johnson & Jasik (ref 4) provide further support for the accepted theory (see Section 4 above). However they do not give details of the measurements and so it is not clear whether these were of the near field or the far field.

H van Suchtelen (ref 8) and J S Belrose (ref 5), provide the two most widely quoted papers on ferrite antenna design, and both accept the demagnetisation concept for the calculation of μ_{rod}.

Snelling (ref 1) also accepts the demagnetisation concept without proof, but he does give some measurements of the flux distribution along a cylinder immersed in a uniform magnetic field and this provides evidence that the *near field* is consistent with demagnetisation.

6. The Field Equations

So all the known measurements rely upon the assumption that a measurement of the near-field can be translated into the strength of the far-field, using well proven equations for the simple loop antenna. This seemed a reasonable assumption given that in the accepted theory it was assumed that the coil was the antenna, and the ferrite merely enhanced its area.
However it is shown in Appendix 2 that the equations are only applicable to the ferrite rod if *its* diameter is very small compared to its length, and this is never the case in practice since it would then be a poor antenna. But experimenters have used these equations to justify their near-field measurements, and to verify the demagnetisation theory and μ_{rod}.
To avoid any of these problems the author has measured the far field, and derived a new theory which agrees very well with these measurements. This new theory is described in the next section.

7. New Theory

It is now apparent that the ferrite rod should be viewed as a magnetic dipole, and the same approach can be taken to determine its performance as has been established for a normal electric dipole. In that case if an antenna wire which is l meters long is immersed in an Electro-Magnetic (EM) field having an electric intensity of E_s volts/meter, then the induced emf will be of $E_s\, l$ volts.
Similarly if a ferrite antenna of length l meters is immersed in an EM field of H_s amps/meter, then the induced magneto-motive force, mmf, will be :

$$\text{mmf} = H_s\, l \quad \text{amp turns} \qquad 7.1$$

where l is the length of the ferrite rod, assumed to be aligned with the exciting field.

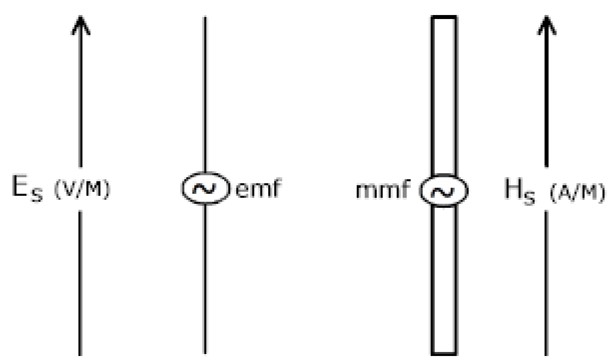


Figure 2 Comparison of Electric and Magnetic Dipole.

To appreciate what Equation 7.1 means, the EM field sets up a magnetizing force, mmf, in the ferrite equivalent to that of an imaginary one turn coil wound around the ferrite, covering its whole length and carrying an exciting current of $H_s\, l$ amps. So with this equivalent exciting coil and its magnetizing force simple magnetic theory can be used to calculate the flux (see Payne ref 11), and therefore the voltage induced in the receiving coil.
The total flux in the ferrite will therefore be :

$$\Phi = \text{mmf}/\ \mathcal{R} = \quad H_s\, l\ /\ \mathcal{R} \quad \text{webers} \qquad 7.2$$

Where $\mathcal{R}$ is the reluctance of the path which the flux takes from one end of the ferrite to the other, returning through the outside air. The total reluctance is equal to the sum of these two paths :

$$\mathcal{R} = [1/\ \mu_o\ ] \sum l/\ (\mu_r\, A) \qquad 7.3$$

Where μ_r is the relative permeability of the medium ie $\mu_r = \mu_f$ for the ferrite, and $\mu_r = 1$ for air.
The sum $\sum l/\ (\mu_r\, A)$, has been shown by Payne (ref 12) to be

$$\sum l/\ (\mu_r\, A) = [l_c\ /\ (\mu_f\ \pi\ a_c{}^2)]\ + [1/(3.49\ a_c)] \qquad 7.4$$

l_c and a_c are the dimensions of the coil, but since the imaginary *exciting* coil has the same dimensions as the ferrite we can substitute l_f for l_c and a_f for a_c. The above equation is accurate if $l_f\ /\ a_f > 0.8$, ie if the ferrite is not too short.

The signal voltage e_s induced in a *receiving* coil surrounding the ferrite, and having N turns, will be $e_s = N\ d\Phi/dt$, so for a sinusoidal excitation the induced voltage will be :

$$\begin{aligned} e_s &= \omega\ N\ H_s\ l\ /\mathcal{R} \\ &= \omega\ N\ H_s\ l\ \mu_o\ \ /\ \sum l/(\mu_r\, A) \qquad 7.5 \end{aligned}$$

This equation is in terms of the *magnetic* field intensity H_s, but it is conventional to describe the strength of an electromagnetic wave by its *electric* field intensity, E_s, and there is a simple relationship between them: $H_s = E_s\ /\ (120\ \pi)$. Also putting $\omega = 2\pi\ c/\lambda = 2\pi\ 3\ 10^8\ /\lambda$, and $\mu_o = 4\pi\ 10^{-7}$ henrys per meter gives :

$$e_s = 2\pi\ N\ l\ E_s\ /\ [\lambda\ \ \sum l/\ (\mu_r\, A)] \qquad 7.6$$

where $\sum l/(\mu_r\, A)$ is given by equation 7.4

If the relative permeability of the ferrite, μ_f is very large, then the first term in Equation 7.4 is small and $\sum l/(\mu_r\, A)] \approx [1/(3.49\ a_f)]$, and Equation 7.6 becomes :

$$e_s \approx 2\pi\ N\ l_f\ \ 3.49\ a_f\ E_s\ \ /\ \lambda \qquad 7.7$$

for very large μ_f

Notice that the received signal is proportional to the length of the rod and also to its radius.

For the measurements, it is convenient to measure the *increase* in signal strength when a ferrite is introduced into a coil, since the signal received by a coil is well understood and documented. Belrose (ref 5 p42) gives the signal received by a loop as :

$$e_{sl} = 2\pi\ A\ N\ E_s\ /\ \lambda \qquad 7.8$$

When the ferrite is introduced this signal increases, and we will call the ratio of the signal received by the ferrite plus coil, to the coil only, the gain of the rod G_{rod}. This ratio is (taking the ratio of Equations 7.6 and 7.8):

$$G_{rod} = e_{sf}\ /e_{sl} = \ l\ /\ [A\ \ \sum l/(\mu_r\, A)\ ] \qquad 7.9$$

where $\sum l/(\mu_r\, A)$ is given by equation 7.4

In the accepted theory, G_{rod} is called μ_{rod} but this term is avoided because it can be confused with the permeability of the ferrite material forming the rod, and it also incorporates the misleading idea that it is the *permeability* which is the key factor. The permeability of a ferrite dipole, while important, is no more significant to the operation than is the electrical conductivity in a normal wire dipole.

Equation 7.9 can be simplified to :

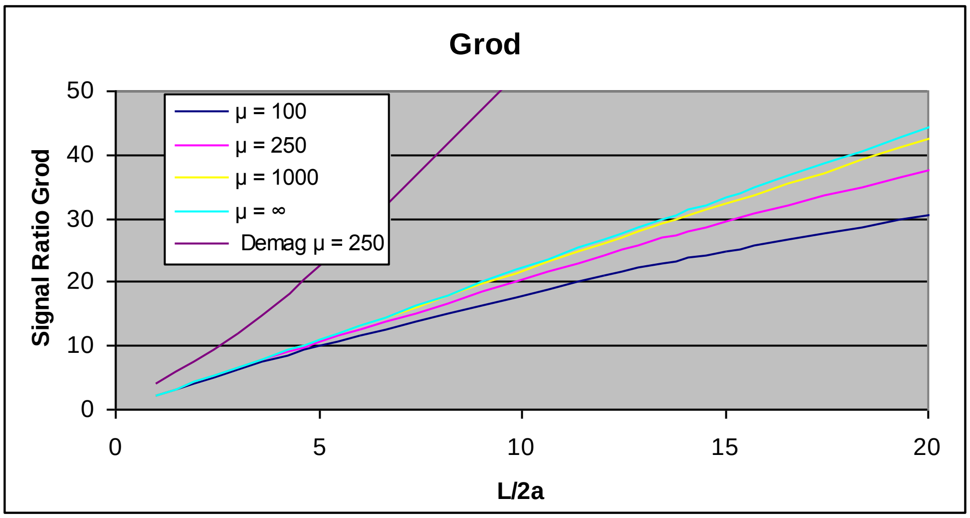
$$G_{rod} = \mu_f \;/\; (\, 1{+}D\,(\mu_f - 1) \qquad 7.10$$

$$\text{where } D = 0.45/(l/2a)$$

NB strictly Equation 7.9 reduces to $G_{rod} = \mu_f \;/\; (\, 1{+}D\,\mu_f\,)$, and for normal values of permeability the difference is negligible. The difference becomes apparent only when the permeability is small and then Equation 7.10 goes to unity as it should.

Interestingly this equation is similar in form to demagnetisation equations, such as Equation 14.1.1, even though the derivation seems to be far removed.

A plot of Equation 7.10 is shown below for various ferrite permeabilities. For comparison the curve according to the cylindrical demagnetisation theory is also shown for $\mu_f = 250$:



Notice that there is a much lower sensitivity to the ferrite permeability than that predicted by the demagnetisation equations (Appendix 1). So taking a usual ratio for l /2a of 12, reducing the ferrite permeability from 1000 to 100 results in a drop in G_{rod} of only about 20%.

If the ferrite permeability is very high, the gain due to the ferrite becomes :

$$\mathbf{G_{rod} \approx 6.98/\pi\ (\mathit{l}/2a) = 2.22\ (\mathit{l}/2a)} \qquad \mathbf{7.11}$$

This should be compared with the approximation for the cylindrical demagnetisation theory for high μ_f, of $\mu_{rod} \approx 2\ (l\ /\ 2a)^{1.5}$ (Equation 3.1).

The above equations assume that the ferrite inside the receiving coil totally fills the space, but usually the ferrite radius is slightly smaller than the coil radius, leaving a small radial gap. The effective susceptance μ_f-1 of the core is therefore reduced by the ratio of the areas $(a_f\,/a_c)^2$ (see Snelling ref 4). So we have :

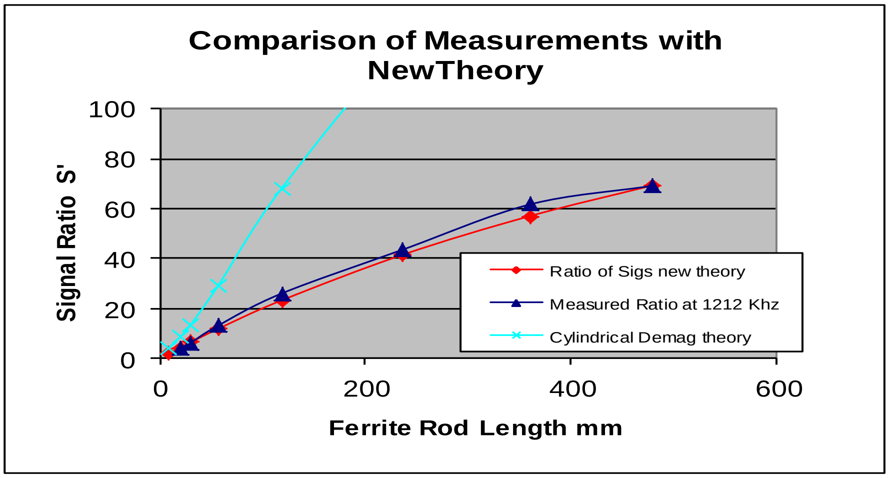
$$\mathbf{\mu_{fe} = (\mu_f - 1)(a_f\,/a_c)^2 + 1} \qquad \mathbf{7.12}$$

So Equation 7.10 becomes :

$$\mathbf{G_{rod} = [\mu_{fe}\,/\,(\,1{+}D\,(\mu_{fe}{-}1)]} \qquad \mathbf{7.13}$$

$$\mathbf{where\quad D = 0.45/(\mathit{l}/2a)}$$
$$\mathbf{\mu_{fe} = (\mu_f - 1)(a_f\,/a_c)^2 + 1}$$

A comparison of the measurements given in Section 2 with this new theory, Equation 7.13, gives :



The coil had a mean diameter of 11.2 mm, and the ferrite diameter was 10 mm, with a published permeability of 325 at this frequency. However separate measurements showed the permeability to be somewhat lower at 250 and this was the value used in Equation 7.13.
The measured curve shows a reduction from the rising trend at the longest length. However to achieve this length 4 rods were butted together end to end, with only a small end pressure, and there was therefore a small air gap between each of them and this could explain the reduced gain
It is seen that agreement is very good, and gives support to the theory given above. However there is other supporting evidence and this is given in the next section.

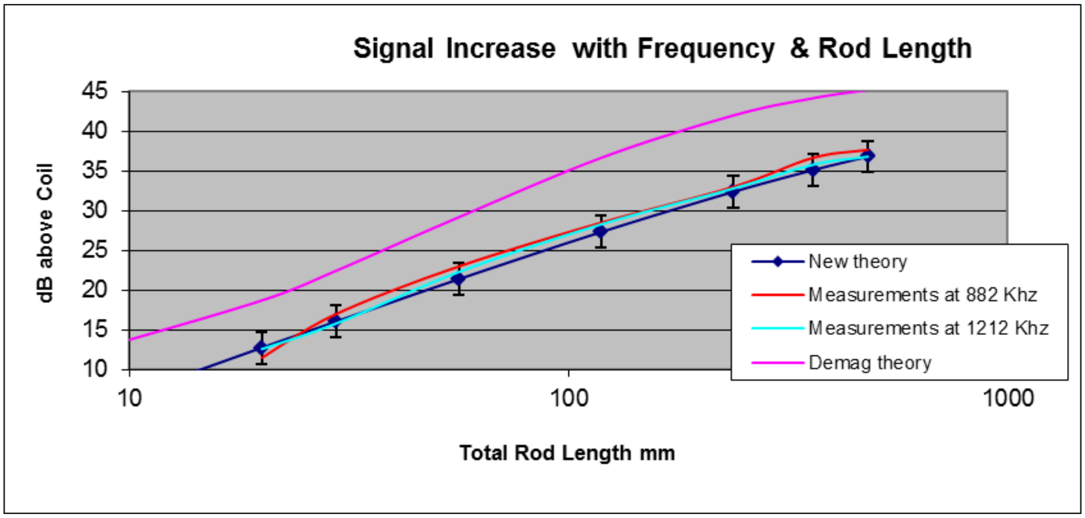
8. Experimental Support for new Theory

8.1. Introduction

To thoroughly test the new theory it was necessary to change all the parameters and to compare measurements with the theory. So according to Equation 7.13 the signal gain with the ferrite, G_{rod}, is independent of frequency and the number of turns, but dependent upon the rod length and its radius. Each of these was tested and the results given below. The only parameter not changed was the rod permeability, because only one material was available. However a change in the *effective* permeability was achieved by air gaps in the core (Section 8.3).
Details of the measurement technique are given in Section 9.

8.2. Received Signal v Rod Length and Frequency

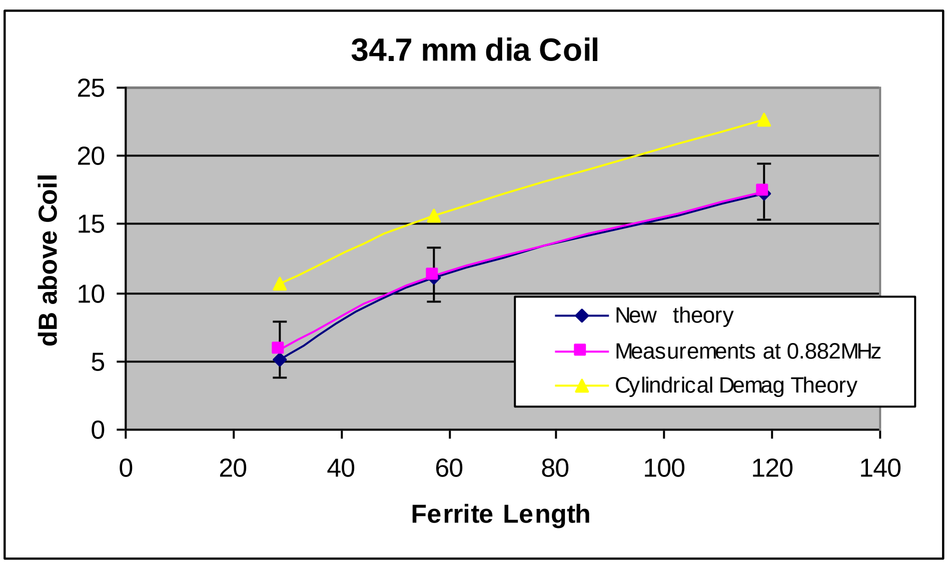
The effect of frequency was tested on a single layer coil having 75 turns wound onto a thin plastic former which was just larger than the 10mm dia ferrite. The ferrite could therefore be inserted into the coil and a comparison made of signal strength with and without the ferrite. The coil was 20mm long with a mean winding diameter of 11.2mm and the wire was stranded with an overall diameter of 0.27mm
Measurements were made of the far field signal from broadcast stations at two frequencies 882kHz and 1215kHz with the following results. Note that the y axis is in decibels.



The measurements show the signal gain, G_{rod}, to be independent of frequency and dependent on rod length as predicted by Equation 7.13.

8.3. Received Signal versus the Coil Diameter and the number of turns N

To test the effect of increasing the coil diameter and changing the number of turns, measurements were carried out on a coil of 19 turns of 0.5mm diam copper wire, wound onto a plastic former of diameter 34.3mm giving a mean winding diameter of 34.8mm. The length of the winding was 28.6mm. The inside diameter of the former was 29.9mm and this would accept 7 rods each of 10mm dia and 120mm long. So there were gaps between the rods and the filling factor in the winding was 58% (ie total area of winding/total area of ferrite). To test at a shorter ferrite length a *toroid* of length 28.5mm was introduced having an outside diameter of 28.3mm and inside diameter of 13.7 mm, so this had a filling factor of 51%. Two of these, butted together, gave a rod length of 57mm.
Measurements on a broadcast station at 882 kHz gave the following results:



Again there is good correlation with the Equation 7.13, for this changed diameter and number of turns.

One interesting aspect of this experiment was that none of the ferrite cores filled the winding. We can therefore expect the apparent permeability of the cores to be reduced according to their areas (Equation 7.12), to 145 for the longest length and 128 for the two shorter lengths, and these are the values used for the theoretical curve above. However G_{rod} is only weakly dependent on rod permeability**,** because the reluctance (Equation 7.4) is much higher in the air path than through the ferrite. For instance, if the rod permeability is reduced considerably to only 45, the theory gives a reduction of only 1db.

9. Measurement Technique

9.1. Broadcast Signals

To measure the gain of the antenna, an accurate known field could be generated and the signal received by the antenna measured. Alternatively, the received signal can be compared with that from an antenna of known gain. The latter was used here because it has the advantage that the signal source does not need to be calibrated, and also signals from powerful distant broadcast transmitters can be used so that the antenna under test is definitely in the far field of the radiator.
For most measurements the signal from the BBC Radio Wales transmitter at Washford, England was used. This station is about 36 km from the author's location and transmits 100kw, vertical polarisation at 882 kHz. Also used was the signal from Absolute Radio on 1215kHz, also transmitted from Washford. Both transmissions are amplitude modulated and therefore some changes in the average signal strength were observed with the modulation. By averaging readings over several seconds these small changes could be reduced considerably.

9.2. Received Signal

The signal received for a coil without ferrite is given by Belrose (ref 5 p42) as :

$$e_s = 2\pi \text{ A N } E_s / \lambda \qquad 9.2.1$$

So an assumption in using this equation is that the signal in each turn of the coil had essentially the same phase. This is likely to be true since the coil with the longest wire, the 75 turn coil had a wire length of 2.6 meters and the signals had quarter wavelengths of 85 meters and 62 meters respectively. However the coils were very long (L/D ≈2) compared with normal loop antennas and it is assumed that the above equation still holds.

9.3. Receiver

Signals were received on a Yaesu FRG 7700 receiver with its AGC voltage monitored via a digital voltmeter. The receiver was connected to the coils via a 0-59dB step attenuator, this being adjusted at each ferrite rod length to give a constant AGC voltage in the receiver. The attenuator setting therefore gave a measure, in dB, of the increase in signal when the ferrite was introduced. The minimum attenuator step was 3dB, but by interpolation a resolution of ±1dB was probably achieved.
The attenuator had a characteristic impedance of 600Ω, which is also the nominal input impedance of the receiver. However to ensure that the attenuator always saw a good match, and therefore gave accurate attenuation steps, a constant 3dB attenuator was included between it and the receiver terminals.

9.4. Correction for Coil Reactance and Resistance

The coil under test was connected across the input terminal of the attenuator, so the signal received was reduced because of the inductive reactance of the coil. This reactance X_L was measured and used in the following equation to adjust the received signal:

$$\Delta = 20 \text{ Log } 10[600/(X_L^2 + 600^2)^{0.5}] \quad \text{dB} \qquad 9.4.1$$

However, for the 75 turn coil the inductive reactance was large when the ferrite was introduced and the above adjustment was therefore large and subject to errors. So with the ferrite introduced a series capacitor was included to tune-out the inductive reactance, and the signal recorded without the adjustment above. The resistance of the coils was very small compared to 600Ω and was therefore not significant.

An alternative configuration of the coil would have been to couple it into the attenuator via a coupling loop, the coil being resonated by a capacitor. This was tried and had the advantage that the received signals were higher in amplitude and therefore less prone to measurement error. However, the received signal was now dependent on the Q of the coil and ferrite, and so any measurements would have to be adjusted for this. While this would have been possible the errors involved would probably not have compensated for the higher signal strength.

9.5. Dipole Reception

It is important that any stray 'dipole' reception is minimised eg pickup on the leads, and so the coils and tuning capacitor were enclosed in a U section aluminium screening box. Nevertheless, the received signal levels with the coil only are very small and some measurements may have been affected by dipole reception. This would have had the effect of reducing the measured gain, G_{rod}.

10. Radiation Resistance according to New Theory

The conventional theory gives the radiation resistance with the ferrite as that of a loop but increased by μ_{rod} (Equation 4.1), which we have now seen is inaccurate. However there is no reason to believe that the equation is wrong *in principle*, so we can assume it will be accurate if we use an accurate value of the signal enhancement G_{rod}. So the radiation resistance is assumed to be :

$$\mathbf{R_{r\,rod} = 120\pi/(6\pi)\ \beta^4\ (G_{rod}\ NA)^2}$$
$$\mathbf{\approx 31200\ (G_{rod}\ NA/\lambda^2)^2} \qquad \mathbf{10.1}$$

where G_{rod} is given by Equation 7.13

The radiation resistance is extremely low : taking a typical ferrite antenna with a loop dia of 12 mm, frequency of 2 Mhz (λ= 150 m), and N= 36, then the radiation resistance of the loop alone (ie G_{rod} =1) is $R_{rL} = 10^{-9}\ \Omega$. If a long ferrite rod introduced so that G_{rod} =50, then the radiation resistance increases 50^2 to $2.5\ 10^{-6}\ \Omega$.
It would be nice to have experimental confirmation of the above equation but the value of the radiation resistance is so low that is impossible to measure in the reception mode because of the presence of the loss resistance which is much larger, probably by a factor of at least 10^6. It would be possible to measure the radiation resistance in the transmit mode by exciting it with a known current and measuring the far field, but this has not been done to date. However we know from the principle of reciprocity (Jordan ref 10, p327-) that the enhancement in the transmit mode will be same as that in the receive mode, so we can expect the radiated signal to increase by G_{rod} with the insertion of the ferrite, and therefore for Equation 10.1 to be correct.

If the permeability of the rod is high (say >250) and it is not too long compared with its radius (say $l/2a$, < 15), then $G_{rod} \approx 2.22\ (l/2a)$ (Equation 7.11). Equation 10.1 then becomes :

$$R_{r\,rod} \approx 1.2\ 10^5\ N^2\ (l/\lambda)^2\ (A/\lambda^2) \qquad 10.2$$

It is interesting to compare this with the radiation resistance of a short electric dipole (Jordan p312):

$$R_{\,dipole} \approx 200\ (\boldsymbol{l}/\lambda)^2 \qquad 10.3$$

Notice that in both cases the radiation resistance is proportional to the square of the length, measured in wavelengths. So we can safely talk of the ferrite rod as a magnetic dipole. Interestingly its radiation resistance is *also* proportional to the cross-sectional area, again normalised to wavelength.
Notice that $R_{r\ rod}$ is proportional to the volume lA multiplied by the length l. So for a given volume of ferrite it is best to have as large a length as possible (for this case where the permeability of the rod is high).

11. Resonant Length

Having established that the ferrite rod is a magnetic dipole it raises the question as to what is its resonant length?
Initially considering the velocity of an EM wave in the ferrite, this will be very much less than the velocity of light c, because of the high permeability and high permittivity. If a permeability of 250 is assumed and a permittivity of 10 (for Ni Zn, see Snelling ref 1, p127), then the velocity will reduced to c/ $\sqrt{(2500)}$ = c/50, so at frequency of say 3 Mhz (λ_o=100m), a half wavelength in the ferrite will be 1 metre. For MgZn ferrite this will be much smaller, but this type of ferrite is unlikely to be used at RF frequencies because of its higher loss.
The velocity calculated above is that of the EM wave launched by the coil, and we now need to consider the direction of this wave. An EM wave propagates in a direction which is normal to its E vector *and* normal to its H vector. The E vector is down the wire (ie the direction of the emf in the wire), and the direction of the H vector is down the length of the ferrite, and so this (slow) wave is propagating *from the outside of the ferrite inwards towards its middle.* In contrast the speed at which the flux (the H vector) flows down the *length* of the ferrite will be close to the speed of light.
For confirmation of the above, resonant effects have been reported in the literature across the width of magnetic circuits. For instance Snelling says (p18) 'at high frequencies or with large cross-sections dimensional resonance can occur', and 'the cross-sectional dimension should be much less than $\lambda/2$ if dimensional resonance is to be avoided'. In contrast there are no reported instances of resonance down the length of the rod since they are never long enough, or the frequency high enough.
The situation is analogous to the propagation on a wire dipole. Here the velocity down the wire is close to c, but *into* the wire it is very much slower, and leads to skin effect.
So the resonant length of a magnetic dipole is the same as an electric dipole.

12. Discussion

It seems incredible that for over 50 years, all major antenna textbooks and all respected papers on ferrite antennas have quoted an equation for μ_{rod} which is so inaccurate.
The author has read most of the significant references on ferrite antennas and the reasons seem to be twofold : firstly, the original experimenters produced an inaccurate analysis, and secondly, subsequent measurements by other experimenters erroneously confirmed this analysis. Taking these in turn :
Much of the early work on ferrites was carried-out by Mullard Laboratories in the UK and Phillips in the Netherlands and this work resulted in the magnificent book on ferrites by Snelling (ref 1) which has become a standard reference. The main applications were transformers, inductors, CRT scanning yokes, and permanent magnets. Most probably Snelling et al were *not* antenna engineers, so when they discovered that a radio signal could be enhanced with a ferrite rod they turned to their understanding of demagnetisation to explain the reducing improvement as the rod was made longer.
When *antenna* engineers became interested in ferrites they presumably would not have been totally convinced by the demagnetisation theory, and needed to make measurements at RF preferably of the far field. But far-field measurements are difficult to do accurately and very time consuming, and so they turned to the much easier near-field measurements, believing that these could be accurately related to the far-field by well established theory for loop antennas. This theory seemed to be relevant since the accepted view was that the ferrite antenna *was* a loop antenna, with the ferrite merely increasing the effective area. Their near-field measurements confirmed the demagnetisation theory, and from then-on other researchers accepted this without question.
But it now seems that the ferrite antenna is a magnetic *dipole* and the wire loop around it is merely a method of detecting the magnetic field. The theory linking the far field to the near field of a loop was therefore not applicable to ferrites antennas, unless they were infinitely thin.

13. Summary

When a ferrite rod is introduced into a receiving coil, the signal strength increases by a large factor and this is currently calculated according to demagnetisation theory. However experiment shows this to be in error by up to 10dB or more.

A new theory is given, which agrees well with experiment, and this shows that the ferrite rod is a magnetic dipole rather than a loop antenna, and the coil is merely a device for detecting its flux. With the new theory the radiation resistance is proportional to $(l/\lambda)^2$, exactly the same as a conventional electric dipole. The radiation resistance is also proportional to (A/λ^2), and so for a given amount of ferrite it is therefore better to use the material long and thin, but this requires the highest permeability to achieve its full potential.

14. Appendix 1 Demagnetisation

14.1. Demagnetisation

The effective permeability of the rod, μ_{rod} , is less than that of the ferrite, and in the conventional theory this is explained by demagnetisation. This was developed for permanent magnets, and explains why it is easier to magnetise a long thin bar down its length rather than across its width. The key idea is that when a ferromagnet forms an open magnetic circuit such as a bar magnet, the field *within* the material works against the magnetising field. So imagine a bar magnet with N pole at one end and S pole at the other. The field *inside* the bar due these magnetic poles is in the *opposite* direction to the field which set them up, and to the field outside the bar. This internal field is known as the demagnetising field, and for a long thin object it is weak because the poles are well separated. For a field across a squat flat object the demagnetising field is large because the poles are closer together, which explains why it is difficult to magnetise a bar across its width.

Knowing the demagnetisation D the current theory calculates μ_{rod} from (see Snelling ref 1, section 4.3):

$$\mu_{rod} = \mu_f / [1+ D (\mu_f - 1)] \qquad 14.1.1$$

where μ_f is the relative permeability of the ferrite.

So we now need to look at the calculation of D.

14.2. Ellipsoidal Demagnetisation and μ_{rod}

The demagnetisation of a cylinder (such as a ferrite rod) cannot be deduced exactly, and the closest geometrical shape which can be is the ellipsoid. In some of the published work on ferrite antennas the ellipsoid was used as an approximation to the cylinder, and so we start with this. For instance Devore and Bohley (ref 2, eq A16a) quote the demagnetisation for an ellipsoid as :

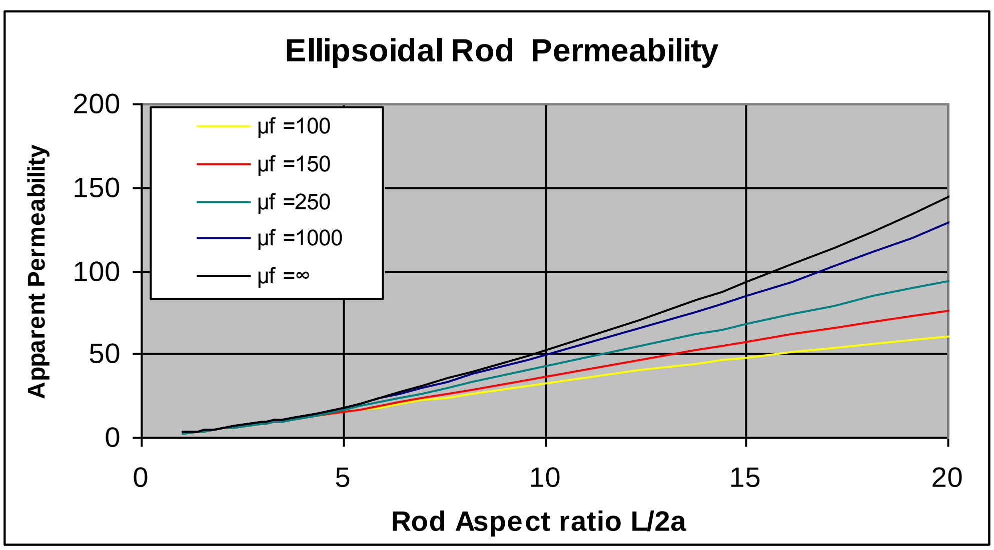
$$D= 0.5 (2 a / l)^2 . (1 /e^3). [\mathrm{Ln} (1+e)/(1-e) - 2e] \qquad 14.2.1$$

Where $e^2 = 1- (2a / l)^2$

a and l are the radius and the length of the ferrite rod

This equation is valid for $e^2 > 0$ ie $l/2a > 1$.

Inserting 3.2.1 into 3.1.1 we get the following for μ_{rod} for the ellipsoid, for various values of ferrite permeability μ_f :



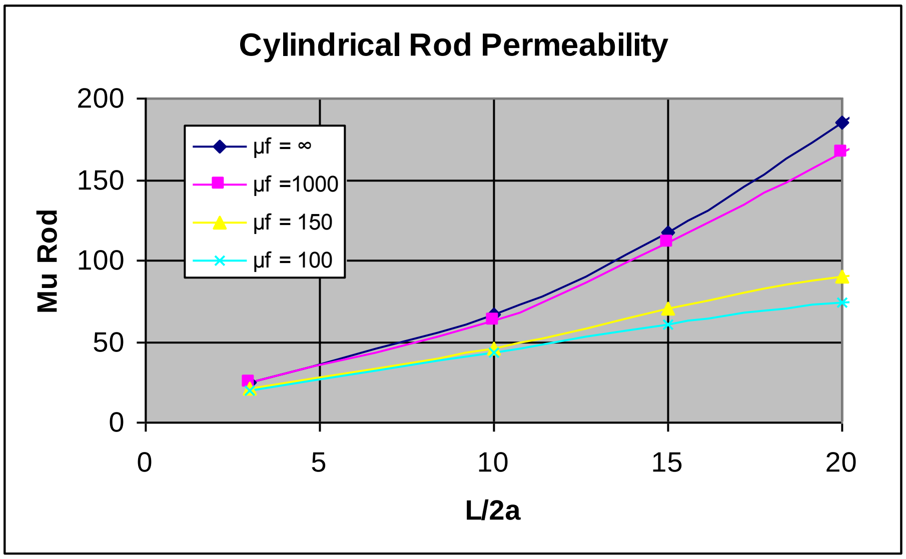
So we see that to get the largest signal enhancement the rod should be as long as possible for a given radius (assumed equal to that of the coil), and to have a high intrinsic permeability.

When the ferrite permeability is infinite, an empirical equation which matches the above data to ±5% for (l/2a) from 0 to 95 is :

$$\mu_{rod\,\infty} \text{ for ellipsoid} = 1.1\,(l\,/\,2a)^{1.65} + 2 \qquad 14.2.2$$

14.3. Cylinder Demagnetisation and μ_{rod}

Since ferrite rods are cylindrical we ideally need the demagnetisation of a cylinder, but no easy closed equation has been found by the author. Bozorth & Chapin (ref 3), give curves of the demagnetisation factor for a cylinder and from these the author has generated the following curves, using Equation 14.1.1



An empirical equation (based on an equation by Poole, ref 6) which matches the above to within about ±5% for (l/2a) from 3 to 30 is:

$$\mu_{rod\,cyl} \approx x\;1.2\,\mu_f\,/\,(x + 1.2\,\mu_f) \qquad 14.3.1$$

$$\text{where } x = 2\,(l\,/\,2a)^{1.5} + 2$$

When the ferrite permeability is infinite this reduces to :

$$\mu_{rod\,\infty} = 2(l\,/\,2a)^{1.5} + 2 \qquad 14.3.2$$

The cylindrical μ_{rod} is greater than the ellipsoidal. For instance at l/2a =15 and μ_f = 150, $\mu_{rod\,cyl}$ = 70 whereas $\mu_{rod\,elipse}$ = 58, a factor of 1.22.

15. Appendix 2 Field Equations

15.1. Classical Field Theory

In the accepted ferrite rod theory it is assumed that the coil is the antenna, having an area enhanced by the ferrite. So researchers felt safe in using the field equations for the loop antenna, since these were known to be accurate. These equations are given by Jasik p2-4 using the following coordinate system:

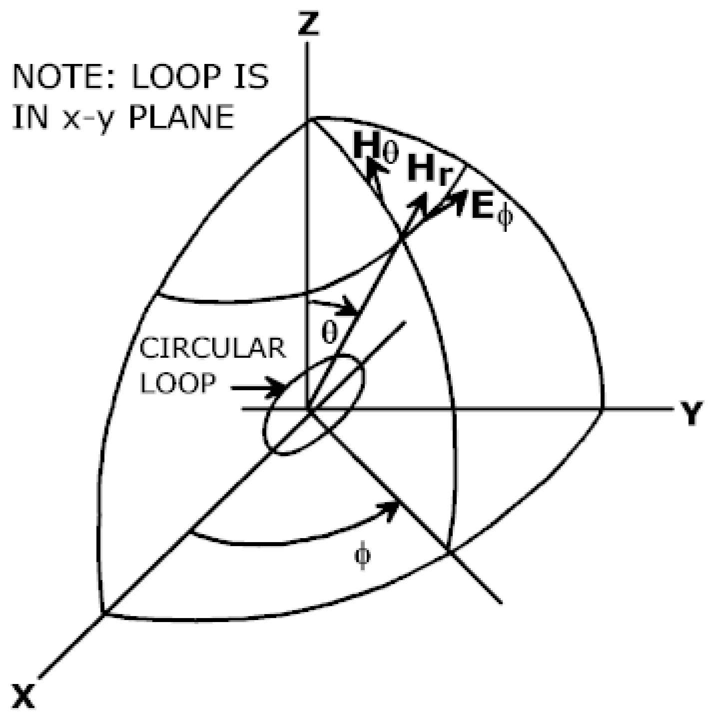


Figure 1 Coordinate System for Loop

For the loop antenna there are two electric fields and two magnetic fields, H_r and H_θ, and we need consider here only the magnetic fields.

The field H_θ contains the radiation component, and so we will consider this first. Jasik gives :

$$H_\theta = [m/(4\pi)] \; [\; \beta^2/r \; - \; j\beta/r^2 \; - \; 1/r^3 \,] \; \mathrm{Sin}\,\theta \; e^{-j\beta r} \qquad 15.1.1$$

Where $\beta = 2\pi/\lambda$
θ is the angle with respect to the coil axis

The factor m is the differential magnetic dipole moment, and for the normal loop is given by m= I_o N A (see Johnson & Jasik p 5-1). For the ferrite antenna the accepted view is that this increases to m = $I_o\mu_{rod}$NA, and this is what the experiments were aiming to prove.

We see that there are three fields, in β^2/ r, $j\beta /r^2$, and $1/r^3$, and at a sufficiently large radius, r, the first term dominates and the other terms become negligible. So the first term is the radiated field.
Notice that all three are proportional to the magnetic dipole moment m, so a measurement of any one of the three fields will give the dipole moment and therefore the value of all three. If we measure the field at a very low frequency (large wavelength) the first two terms will become negligible compared with the last and this will dominate, and this we can then measure.
Notice also that the Sine function means that the H_θ fields peak at an angle of 90^0 to the axis of the loop, as is well known for the radiation field, and the fields are zero along the axis of the loop.
So it would be reasonable to measure at low frequencies the H_θ field in a direction normal to the axis of the coil. However, in practice this has not been done, and experimenters have measured the H_r field in a direction along the axis of the coil. So we now need to look at the H_r field.

Jasik (ref 9, p 2-4) gives the equation for the H_r field (sometimes called H_z) as :

$$H_r = [m /(2\pi)] \; [j\beta /r^2 \; - \; 1/r^3] \, \mathrm{Cos}\, \theta \, e^{-j\beta r} \qquad 15.1.2$$

Notice that the fields are similar to the H_θ fields, *except that the radiation term in 1/r is absent*, and the magnitude is twice at $m/(2\pi)$, so making measurement easier. Also the Cosine function shows that it peaks along the axis of the coil, and is zero normal to the coil, where the radiation is a maximum. However, since it is the moment m which we are trying to measure it seems that H_r is equally good. At a sufficiently low frequency, and along the axis, it becomes (for a coil only):

$$H_r = I_o N b^2/(2r^3) \qquad 15.1.3$$

Here we have assumed a circular coil of radius b so that $A = \pi b^2$
Often experimenters have used an exciting coil which has a relatively large radius b compared with r and then this equation needs to be modified to (see Poole p9 and Stewart p45):

$$H_r = I_o N b^2/[2(b^2 + r^2)^{3/2}] \qquad 15.1.4$$

So the theory seems to be reasonable, except when you put it into words : All the published measurements are of a *near-field* component rather than the desired far-field. But not of the near-field component of H_θ, which contains the radiated field, but of H_r which does not. The measurements are then in a direction for which the *radiated* field is zero.
So clearly there has been enormous faith in the accuracy of these equations, and in their applicability to this problem. This is the next aspect to be investigated.

15.2. Applicability of the Field Equations

It seems that the above equations may not be applicable, and to find the reasons we can look at the large body of knowledge for the electric dipole. This is relevant here because the equations for *its* fields are analogous to those above, except that the magnetic and electric fields are interchanged (see Jasik p 2-4). Also it is shown later that the new equation for the radiation resistance of a ferrite rod antenna is similar to that for an electric dipole. So the following statement by Jordan (ref 10, p359) for a normal electric dipole antenna seems highly relevant here 'It is evident that in computing the reactance of an antenna, its finite diameter will have to be considered. The reason why the approximation of an infinitely thin antenna is valid for computing radiation resistance but not reactance, becomes apparent when it is recalled that the radiated power, which determines radiation resistance, depends only on the distant fields. On the other hand, the reactive power, and hence the reactance of the antenna, depends upon the induction and electrostatic fields close to the antenna. *The strength of these near fields depends to a marked degree upon the shape and thickness of the antenna, whereas these same factors affect the distant field only slightly'* (my italics).

So it appears that the field equations given above are only valid for an infinitely thin ferrite rod. But experimenters have used these to justify their near-field measurements, and to verify the demagnetisation theory and μ_{rod}.

REFERENCES

1. SNELLING E C : 'Soft Ferrites. Properties and Applications' 1969, Illiffe Books London
2. DeVORE R & BOHLEY P : 'The Electrically Small Magnetically Loaded Multiturn Loop Antenna' (IEEE Trans. Ant & Prop, Vol AP-25, No4, July 1977, p 496-505)
3. BOZORTH R M & CHAPIN D M : 'Demagnetisation Factors of Rods' Journal of applied Physics, Vol 13 , p320-326, 1942
4. JOHNSON C J & JASIK H : 'Antenna Engineering Handbook' 2nd Edition, 1984 McGraw-Hill, Inc.
5. BELROSE J S : 'Ferromagnetic Loop Aerials' Wireless Engineer, Feb 1955, Vol 32, p41-46
6. POOLE R H M : 'Ferrite Rod Antennas for HF?' BBC R&D White Paper WHP 091 , July 2004 http://www.bbc.co.uk/rd/pubs/whp/whp091.shtml
7. STEWART J L : ' On Ferrite Loop Antenna Measurements' IRE National Convention Record, 1957, Pt1, p42-48
8. VAN SUCHTELEN H : 'Ferroxcube Aerial Rods' Electronics Application Bulletin, 1952, Vol 13 p88-100.
9. JASIK H : 'Antenna Engineering Handbook', McGraw-Hill Book Company Inc, 1961.
10. JORDAN E C : 'Electromagnetic Waves and Radiating Systems', Prentice-Hall Inc, Second Printing April 1951.
11. PAYNE A N : 'The Inductance of a Single Layer Coil derived from Capacitance' http://g3rbj.co.uk/.
12. PAYNE A N : ' The Inductance of Ferrite Rod Antennas' http://g3rbj.co.uk/

Issue 1 : June 2014

 Enquiries to paynealpayne@aol.com