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Portable Receivers for Digital Radio Mondiale: A Look at Antennas and Sensitivities

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Abstract

Although Digital Radio Mondiale (DRM) services have been broadcast since 2003, it is only recently that domestic portable receivers have entered the market. The sensitivity of this early equipment has proved slightly disappointing, but were the expectations realistic?

A typical portable receiver uses a ferrite rod antenna for LF/MF reception, and a telescopic whip for HF. The HF whip may drive an untuned low-noise amplifier. This paper shows how to calculate the sensitivity of such a receiver, and compares the theoretical values with practical measurements. Some of the pitfalls in making these measurements are also described.

The conclusion is that calculated and measured sensitivities agree well, but unfortunately this performance falls short of that proposed for DRM. An improvement would be possible on HF by tuning the input circuitry.

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Portable Receivers for DRM: A Look at Antennas and Sensitivities

Ranulph Poole

1 Introduction

Although Digital Radio Mondiale (DRM) services have been broadcast since 2003, it is only recently that domestic portable receivers have entered the market. Staff at Kingswood Warren are assisting the manufacturers with the testing and debugging of this early equipment, since the success of DRM depends on attractive and affordable radios being available to the general public. As might be expected, problems have arisen through the combination of very sensitive RF input circuitry and large amounts of digital signal processing: self-interference can 'deafen' an otherwise good receiver.

Once any self-interference has been cured, there is still the question of whether the basic sensitivity is adequate. The two important factors are firstly the ability of the antenna to convert field-strength (in volts/metre) into signal (in volts or perhaps dBm) and, secondly, intrinsic thermal noise. Thermal noise arises in both the electronic circuitry and the antenna itself, and is unavoidable. For reception to be possible, the wanted signal must be appreciably greater than the noise — perhaps by as much as 20 dB.

Portable AM receivers have been available for a very long time, and have given adequate reception without great sophistication. Typically they use ferrite rod antennas for LF and MF, and telescopic rod antennas for HF. Since the antennas are physically small (compared with the wavelength of the signal), their efficiency is poor. Fortunately, for AM reception, the demands are not great: the BBC quotes a field-strength of 66 $dB_{\mu V/m}$ for the limit of an MF service area. Performance for DRM needs to be much better, and the aim is to achieve reception at 40 $dB_{\mu V/m}$ on MF.[1] Another difficulty facing receiver designers is that tuned front-ends are out of favour, at least on HF.[2] Tuning is very helpful in providing noise-free amplification.

The question then arises as to what the ultimate sensitivity of a 'blameless' receiver is. There is no point in trying to make a receiver meet an unattainable specification. This report shows how to calculate the possible sensitivity and compares this with practical measurements. Some of the pitfalls in making these measurements are also discussed.

2 The Radio to Be Tested

A typical receiver is sketched overleaf, in order to illustrate the important details. It is shown as it would appear from the back with the rear panel removed. Although the sketch is based on an actual receiver, some uncritical details have been changed to preserve anonymity.

The HF telescopic antenna retracts into the case when not in use, and extends to a total length of about 0.8 m. A large ferrite rod antenna is provided for LF and MF reception. This is mounted internally, and cannot be used remotely in the manner favoured by some manufacturers. A 9 V mains adaptor provides the power. Although it is not possible to run the receiver off internal batteries, an external battery pack was made up for use during tests.

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1 The philosophy is that reception should be limited by noise in the environment rather than by the receiver itself. Another important factor is that an AM signal is still intelligible when the signal-to-noise is poor, whereas DRM does not work at all below a certain threshold.

2 One reason for this is that HF receivers are now expected to cover 3 MHz to 27 MHz continuously — nearly a decade. Older 'short wave' receivers were generally restricted to a band of 6 MHz to 20 MHz.

Internally, the RF electronic circuitry is built into a small module, which is then mounted on a larger motherboard containing more prosaic things such as the power supply regulators and the audio amplifier. The motherboard sits 'piggy-back' on a further board, which provides the user interface — the display, knobs and pushbuttons. There is an earth-plane on this user interface board, which helps screen the antenna from the digital activity there. A sheet of bent tinplate covers much of the base of the receiver, providing a counterpoise to the antenna. The base of the antenna is clamped to the counterpoise with the help of an insulating sleeve.

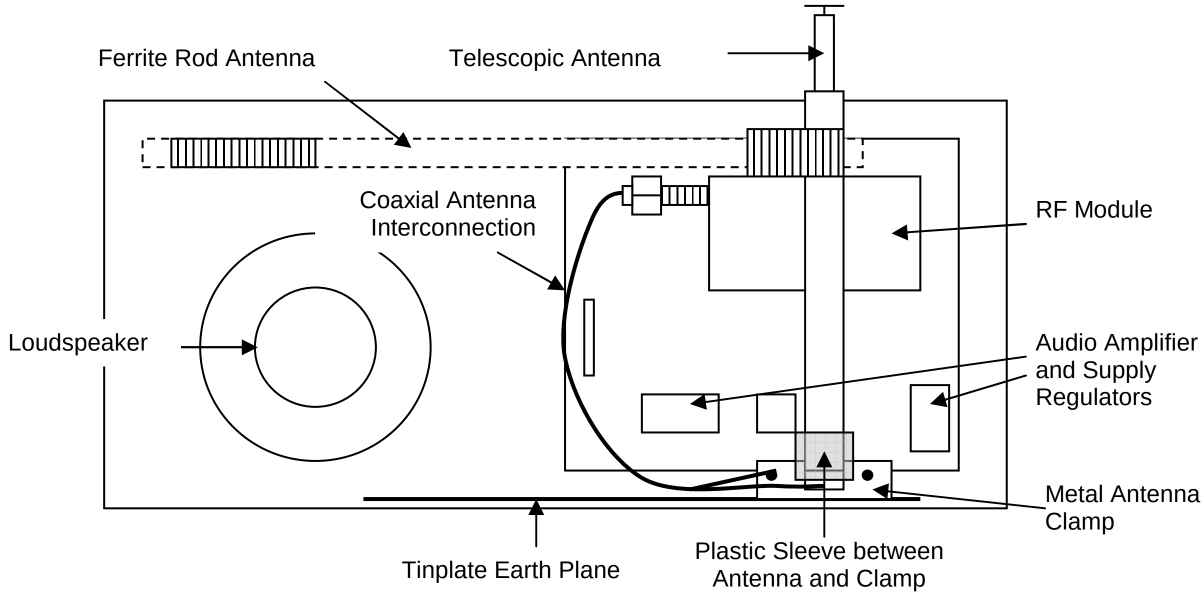

Figure 2.1: Sketch of the Receiver as Viewed from the Rear

Separate RF circuitry is used for the LF/MF, HF and VHF/FM bands. Both the HF and VHF/FM circuits are connected to the telescopic antenna, and are isolated by means of a simple trap. The LF/MF circuit can only be used with the ferrite rod antenna.

Part 1: The Performance on HF

3 The Input Circuitry

The antenna system and its associated input circuitry are illustrated below. The system comprises a simple telescopic whip of overall length 0.8 m, and an earth-plane, or counterpoise, placed at the bottom of the cabinet. C1 represents the 'dead' capacitance that exists when the antenna is fully retracted, whereas C2 is the additional 'active' capacitance when the antenna is extended. C2 in particular will be greater if there are earthed objects nearby. C4 represents the capacitive load presented by the VHF front-end. L1 is the isolating trap mentioned in the previous paragraph.

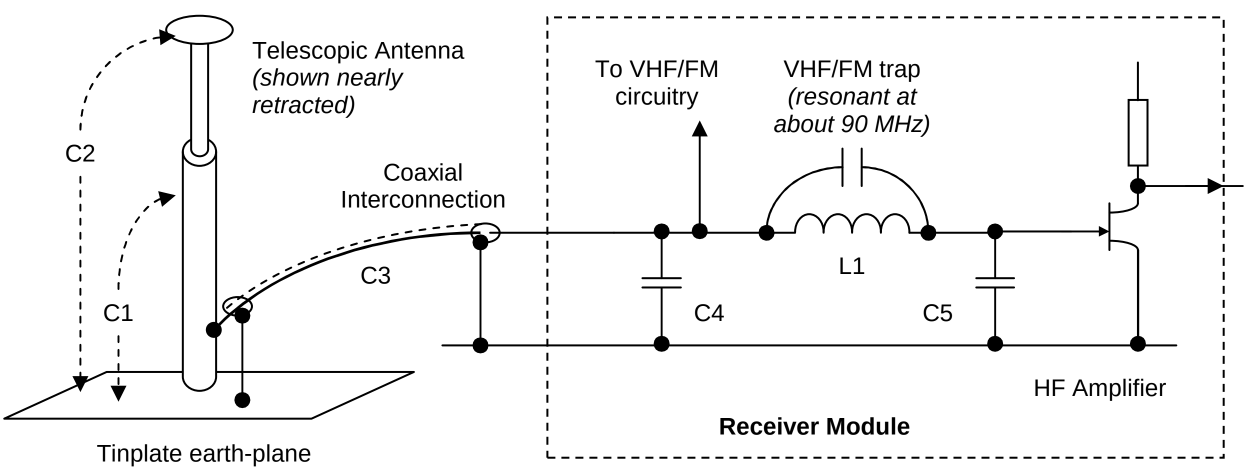

Figure 3.1: Telescopic Antenna and Its Associated Circuitry

The HF amplifier is a simple common-source FET stage. According to the device's manufacturers, its gate-source and drain-gate capacitances are 10 pF and 1.9 pF respectively. The second component is more significant than it looks, as it gives rise to a much greater Miller capacitance when the amplifier is powered. The value of C5 therefore depends on how — and whether — the HF amplifier is being used.

Values for C1 to C5 are presented below. How the capacitances were measured will be described in the next section. For the moment, note how tiny the active antenna capacitance C2 is when compared with the overall input capacitance. This does not bode well for the sensitivity of the receiver.

Capacitance	Value (pF)	Description
C1	19.3	Capacitance of antenna when retracted
C2	0.85	Additional capacitance of antenna when extended
C3	12.4	Capacitance of coaxial interconnection
C4 + C5	46.3	Total capacitance of input circuitry
C5	12	Estimated contribution of HF amplifier, ignoring any additional Miller capacitance

Table 3.1: Capacitances Associated with the Antenna and Input Circuitry

4 Determining the Capacitance Values

Capacitance values were measured with the help of an HP4192A component bridge. Apart from offering a good degree of accuracy, this equipment allows a wide choice of test-oscillator frequencies (to 13 MHz maximum) and levels. It might be thought that measurement would be a simple matter, but there were several problems:

- The receiver possesses an attenuator at the input of the HF amplifier, as part of the AGC system. Even at the minimum test-oscillator level, the attenuator comes into operation, hence causing erroneous measurements of C4 + C5.
- The bridge is provided with two terminals apparently isolated from earth. The isolation is not complete, however, and any stray capacitance between the antenna system and the metalwork of the bridge gives rise to some very strange effects.
- The input impedance of the RF circuitry cannot necessarily be represented by a pure capacitance, particularly at higher frequencies.

To overcome the AGC attenuator annoyance, the receiver was deliberately tuned to MF while measuring C4 + C5. The HF amplifier was then disabled, along with its AGC. Under these conditions, C5 does not include the amplifier's Miller capacitance — a factor that will be discussed later.

A 'strange effect' resulting from the incompletely isolated bridge terminals is shown overleaf, where the plots relate to impedance at the receiver's input with the antenna extended. There is evidently a series resonance at 10 MHz, since the input reactance becomes inductive above this frequency. To minimise the effect, the receiver was kept at least a metre away from the bridge. Allowance was then made for the additional capacitance of the interconnections (about 3 pF).

Measurements beyond 13 MHz were not possible with the HP4192A bridge. For the purposes of the following calculations, the total capacitance (C1–5) was simply taken as its low-frequency value of 72 pF, and the input conductance ignored. This approach was felt to be reasonable, as the measured sensitivity of the receiver was known to be sensibly constant over the HF band.[3]

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[3] There was actually a resonance at 23 MHz, but this will be discussed.

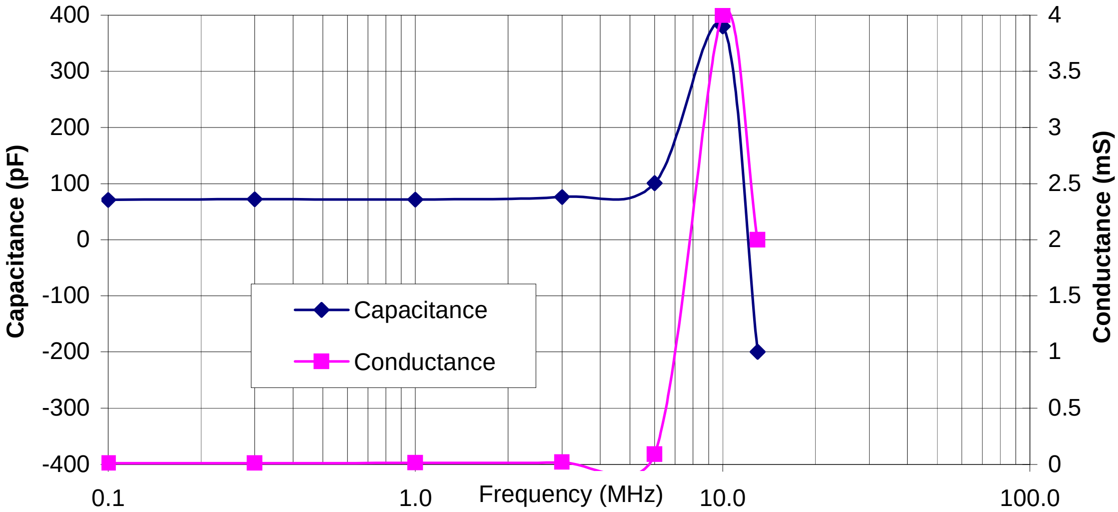

Figure 4.1: 'Strange Effect' Noted when Measuring Total Input Capacitance

5 The Receiver Sensitivity

It is now possible to estimate the sensitivity that should be achieved by the receiver. Firstly, what is the signal level that needs to be applied directly to the input of the receiver module?

FET datasheets always seem coy about equivalent noise input voltages. In the case of the device used here, the manufacturers quote 0.8 nV/√Hz at 100 kHz. This figure is probably pessimistic for higher frequencies, as there could be a significant flicker noise component at 100 kHz.[4] The classic FET noise model gives a mean-square noise current of

$$\overline{i_d^{\,2}} = 4kT\left(\frac{2}{3}g_m\right) + K_2\left(\frac{I_D^a}{f}\right) \qquad \text{in unit bandwidth.}$$

g_m is the common-source mutual conductance, and the right-hand term represents the flicker noise.

Ignoring the flicker noise, and translating the output noise current into an input noise voltage, gives

$$\overline{v_{gs}^{\,2}} = 4kT\left(\frac{2}{3}\frac{g_m}{g_m^{\,2}}\right) = 8kT/3g_m \qquad \text{since } \overline{v_{gs}^{\,2}} = \overline{i_d^{\,2}}\big/g_m^{\,2}\,.$$

Taking g_m as 45 mS from the manufacturer's data, and the bandwidth as 10 kHz, results in an RMS input noise voltage of 0.0495 µV.[5] If a signal-to-noise ratio of 17.5 dB is needed, the minimum usable signal voltage becomes 0.37 µV, or –115.6 dBm.[6]

Some practical sensitivity measurements are shown on the next page, and agreement with the theoretical value is reasonable at the 'best frequency' of 15 MHz. Possible sources of error are uncertainty in the g_m of the FET, loading of the signal generator by the input circuitry (C1–C5), and noise introduced subsequent to the RF amplifier. The slowly worsening performance at lower frequencies could be the tail-end of the FET's flicker noise contribution, whereas the VHF isolation circuitry could be causing some damage at higher frequencies. The important point is that no amount of work could greatly improve the sensitivity of the receiver module.

Finally, it remains to reconcile the above 'direct injection' sensitivity to the sensitivity obtained when using the normal antenna. The model for calculating this is illustrated in Figure 5.2.

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4 Flicker noise is a low frequency phenomenon of slightly obscure origins. It is a noise contribution whose power spectral density is inversely proportional to frequency; i.e. it increases by 3 dB per halving of frequency.

5 According to the manufacturer's data, the figure would be 0.08 µV at 100 kHz.

6 Signal levels are quoted here in dBm, because measuring instruments such as spectrum analysers are calibrated in that way. Strictly, the figure refers to power in a 50 Ω system, and not a voltage. During practical measurements, an external 50 Ω termination was applied to the input of the receiver.

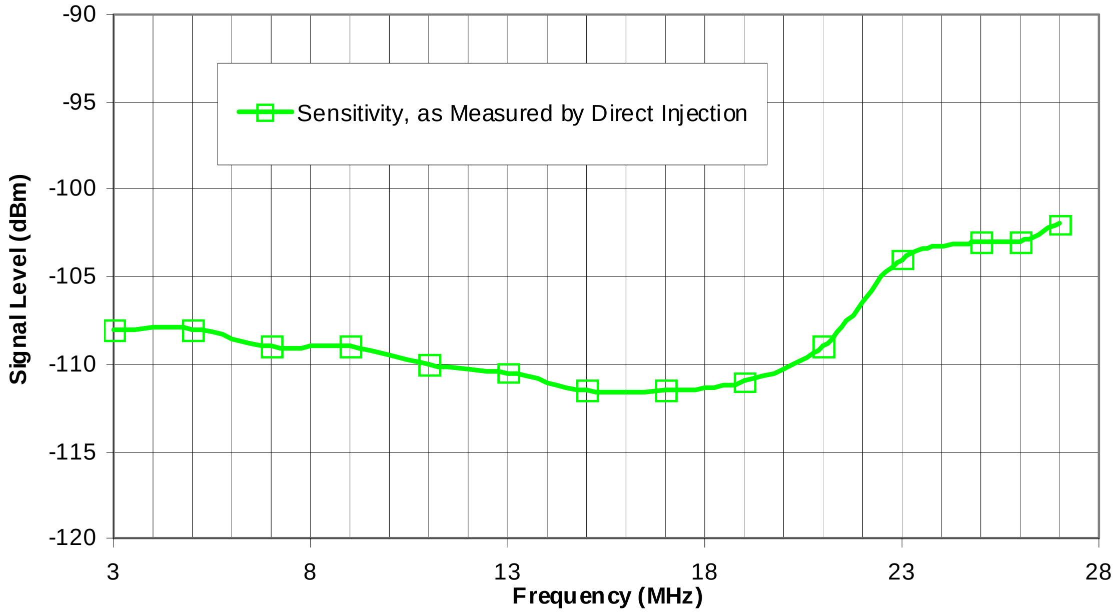

Figure 5.1: Sensitivity Measured by Means of Direct Injection

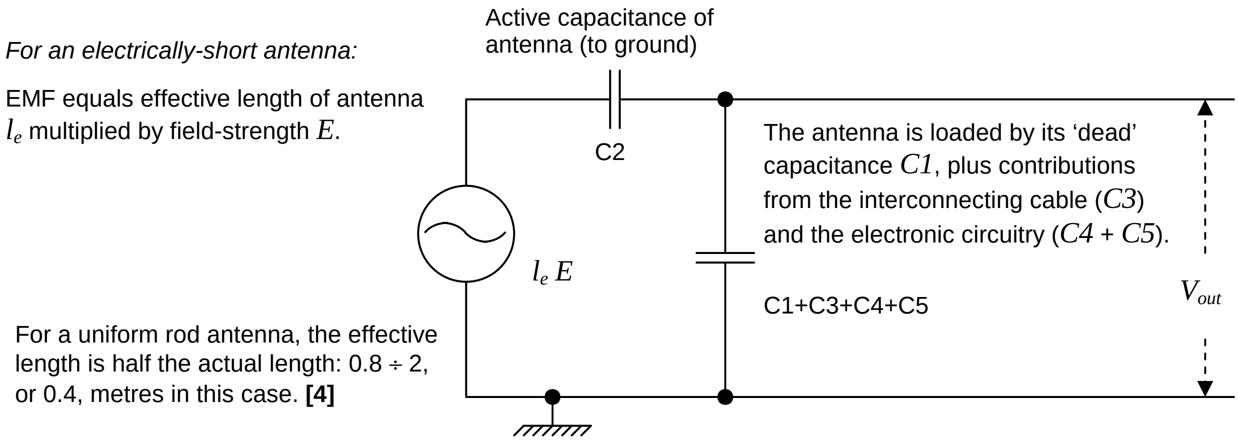

Figure 5.2: Model for Calculating the Antenna Sensitivity

Inspection of Figure 5.2 shows that the output voltage is given by

$$V_{out} = l_e E\left(\frac{C2}{C1+C2+C3+C4+C5}\right) = 0.4 \cdot E\left(\frac{0.85}{78.85}\right).$$

In other words, the output voltage equals the field-strength in volts/metre divided by 232.

If the minimum usable signal level at the input to the module is taken as –112 dBm, or 0.56 µV, the corresponding field-strength is 130 µV/m, or 42 $dB_{\mu V/m}$. This is in good agreement with the figures of about 40 $dB_{\mu V/m}$ obtained during measurements on the 'unimproved' receiver[7] in the Kingswood pseudo TEM-cell **[1]**; some typical plots are shown overleaf. The most likely sources of error lie in the calibration of the pseudo TEM-cell and in the measurement of the very small effective antenna capacitance.

Once again, the evidence is that the receiver is working in a 'blameless' manner: self-interference is not degrading the sensitivity appreciably. On the other hand, improvements would be possible by using a bigger antenna, or by incorporating the various stray capacitances into a tuned circuit.

7 That is, without enhancements such as an external ground plane or antenna capacity hat. As can been seen from the plot labels, some minor changes were tried — without much effect.

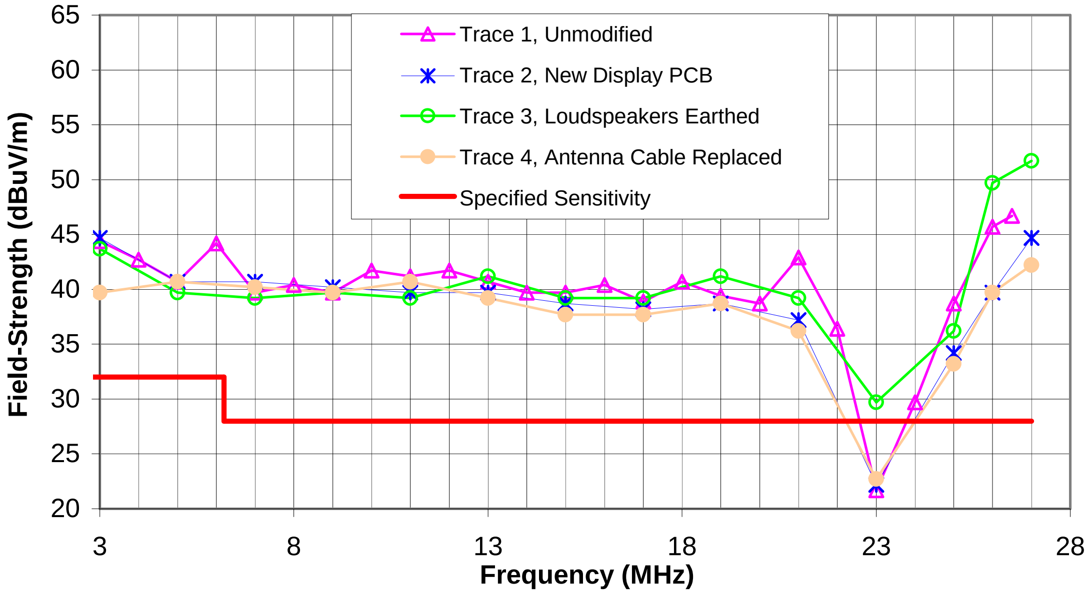

Figure 5.3: Typical Sensitivity Measurement Runs

6 The Sensitivity Peak at 23 MHz

One mystery to explain is the strange peak in off-air sensitivity at about 23 MHz in the plots above. Typically, there is an improvement of some 10 dB at this 'sweet spot', even though the sensitivity, as measured by direct injection, falls away at the top end of the band.

Without destructive intervention, it is difficult to determine the exact mechanism responsible. However, it is plausible that the VHF/FM trap is involved:

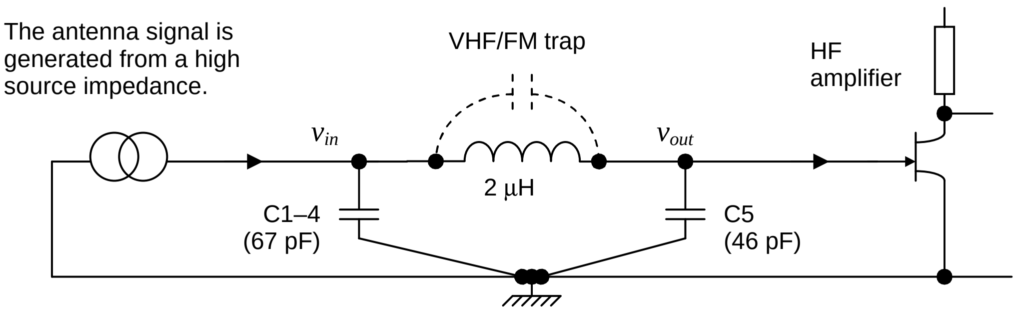

Figure 6.1: The VHF/FM Trap and Its Equivalent Circuit

The trap is evidently part of a tuned circuit whose resonant frequency is determined by the 2 µH inductor and C5 in series with C1–4.[8] C1–4 total about 67 pF, as previously measured. However, C5 is not simply the gate-source capacitance of the FET, but must include the Miller contribution from the gate-drain capacitance of 1.9 pF. The gain of the HF stage was calculated as ×18, giving a Miller capacitance of 1.9 pF × 18 to be added to the existing 12 pF. Hence C5, in this context, is about 46 pF.[9] The resonant frequency of the tuned circuit is then determined by 46 pF in series with 67 pF (27 pF) and 2 µH, giving an encouraging figure of 21.5 MHz. Unfortunately, without knowing the Q of the inductor and the other circuit elements, it is not possible to calculate the magnitude of the resonance.

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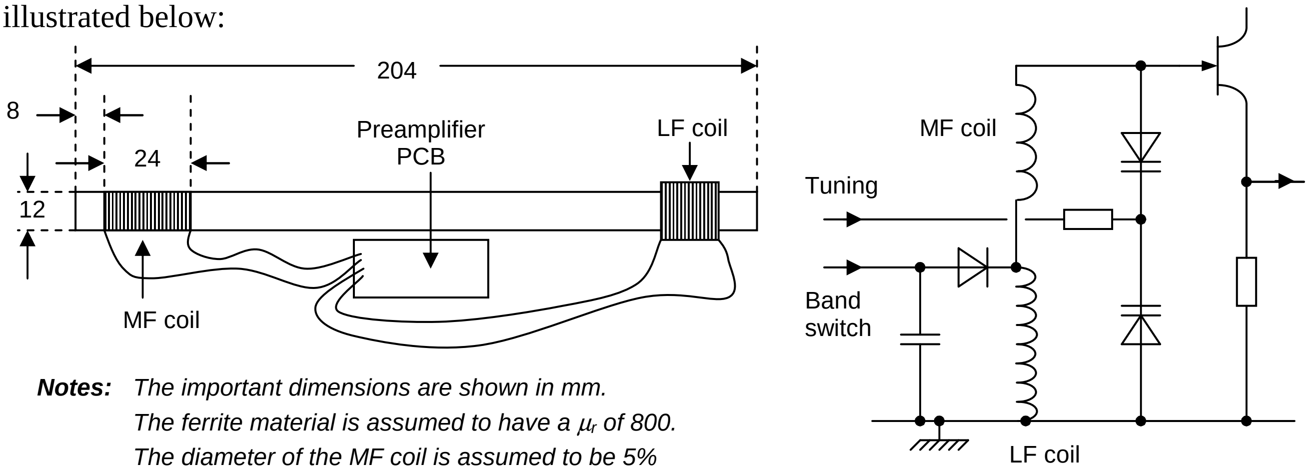
[8] The capacitance shown in parallel with the inductor is negligible in comparison with C1–4 and C5.

[9] The Miller capacitance does not necessarily have an adverse effect on signal-to-noise ratios: the negative feedback introduced by the Miller effect reduces both the wanted signal and the equivalent input noise in proportion. Hence the Miller contribution was ignored during the earlier calculations of sensitivity.

Part 2: The Performance on MF

7 The LF/MF Antenna Arrangement

The LF/MF antenna comprises a long ferrite rod, mounted on the rear panel of the receiver, with the LF and MF coils at opposite ends. In conventional manner, the MF coil is wound as a single layer, whereas the LF coil is pile-wound. A preamplifier board, containing the tuning diodes and a source-follower stage, is attached to the rod, so allowing the high impedance interconnections to be kept short. The two coils are connected in series for LF operation. On MF, the coils remain in series, but a short is placed across the LF coil by means of a switching diode. The arrangement is illustrated below:



Notes: *The important dimensions are shown in mm.*
The ferrite material is assumed to have a μ_r of 800.
The diameter of the MF coil is assumed to be 5% greater than the rod diameter.
The MF coil has 67 turns.

Figure 7.1: The LF/MF Antenna Arrangement

For the present investigation, measurements were confined to 999 kHz, but previous work showed that the results were similar elsewhere in the MF band. On other occasions, the sensitivity figures lay between 44 and 48.5 $dB_{\mu V/m}$, depending on whether the rear panel was in place, and on how the internal wiring had been dressed.[10] The target value for DRM reception is 40 $dB_{\mu V/m}$.

8 Some Measurements and Calculations

There are two spreadsheets available for calculating the signal and noise outputs of a ferrite-rod antenna, both of which are introduced in White Paper 091. **[2]** 'Spreadsheet 1' was developed by the author, and allows entry of the various parameters and dimensions, as given in Figure 7.1. In return, it gives useful information such as the output voltage for a given field-strength, the self-inductance and the noise voltage. Its main limitation is that it assumes the coil to be centrally placed on the rod — patently not the case here. The second spreadsheet, entitled 'Mummrod', is more sophisticated, and uses the 'method of moments' to calculate correction factors for coil position and geometry. It is available over the internet. **[3]**

Two factors need to be determined before putting the spreadsheets to work. Firstly, the permeability of the ferrite material: A figure of 800 is a reasonable assumption for MF rods, although this varies with sample and temperature. Fortunately, the value is not critical, as the permeability is heavily diluted by what amounts to the large air-gap in the magnetic circuit: the geometry is the overriding factor.

Secondly the Q must be measured: The rod itself is nearly lossless at these frequencies, and the losses in the coil and its environment are difficult to calculate — hence the need for measurement. A good method is to plot the response as a function of frequency, and then to find a theoretical response that gives the best fit, as shown overleaf.

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10 In other words, how close the antenna and its connections were to internal sources of interference.

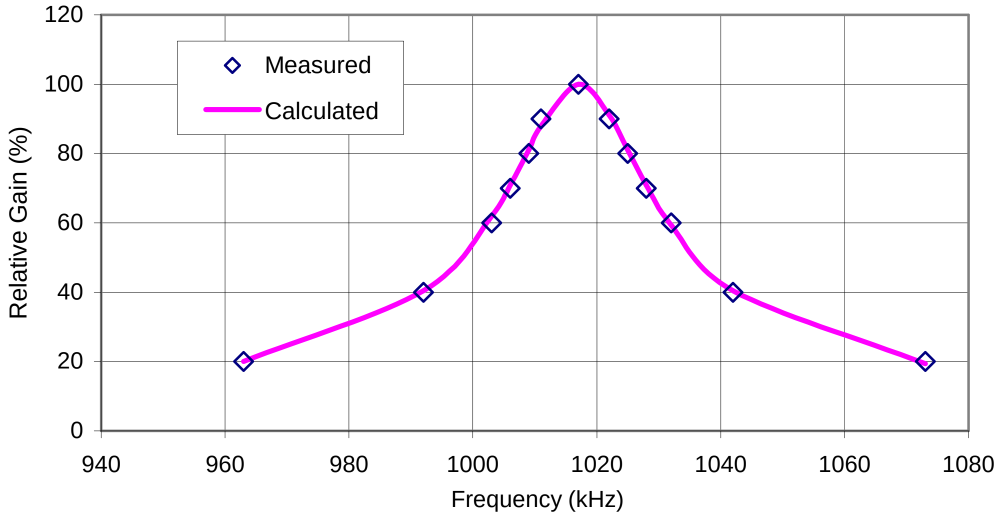

Figure 8.1: Response of the MF Antenna, as Found

The 'calculated response' above is based on the formula

$$|A| = 1\Big/\sqrt{1 + 4Q^2 (f - f_0)^2 / f_0^{\,2}}\ ,$$

where f_0 is the resonant frequency.[11] In this case, Q is a modest 46 and f_0 is 1,017 kHz (18 kHz higher than the nominal 999 kHz). It is possible that some of the detuning was caused by the experimental arrangements.

Assuming that the coil is correctly tuned, Spreadsheet 1 indicates that a field-strength of 40 $dB_{\mu V/m}$ should result in a usable signal-to-noise ratio (S/N) of 22.9 dB. It is interesting that the noise of about 5 µV is almost entirely associated with the 168 kΩ dynamic impedance of the tuned circuit: the contribution of the FET would only be about a hundredth of this.

However, Spreadsheet 1 is only valid for a centrally placed coil whose diameter is exactly equal to that of the rod. Mummrod must be used to give correction factors for the actual coil. These are 0.452 for the position and 0.907 for the diameter, corresponding to a total of –7.7 dB. The S/N has now fallen to 15.2 dB at 40 $dB_{\mu V/m}$. In other words, 42.3 $dB_{\mu V/m}$ is needed to achieve a just-usable S/N of 17.5 dB.

Fortunately, no further correction is needed for the coil being off-tune. Both S and N are reduced by the same amount — about 6 dB, in this case.[12] Of course, if S falls by too much, noise in the following amplifier stages becomes significant.

The sensitivity as just calculated agrees reasonably with the best experimental figures of 44 $dB_{\mu V/m}$. However, it is not yet known what difference the short-circuited LF coil makes.

9 The Effect of the LF Coil

It seems reasonable to attribute the low Q of the antenna to the presence of the short-circuited LF coil, but could the coil also reduce the effective length of the rod? To find out, the LF coil was disconnected and the response of the MF coil plotted in the same way as before. Following that, the output level was measured for a known field-strength, with the LF coil in and out of circuit.

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[11] The FET preamplifier stage made life easy. A CW signal was injected into the antenna by means of a Meguro loop and the output of the preamplifier measured with a CRO and probe. There was no need to worry about the probe loading or detuning the antenna. However, to prevent the AGC from attenuating the signal, it was necessary to disconnect the preamplifier from the following circuitry.

As the preamplifier comprised a source follower, its voltage gain could be taken as unity.

[12] A consequence of this is that the antenna cannot be set up by adjusting its tuning for optimum sensitivity.

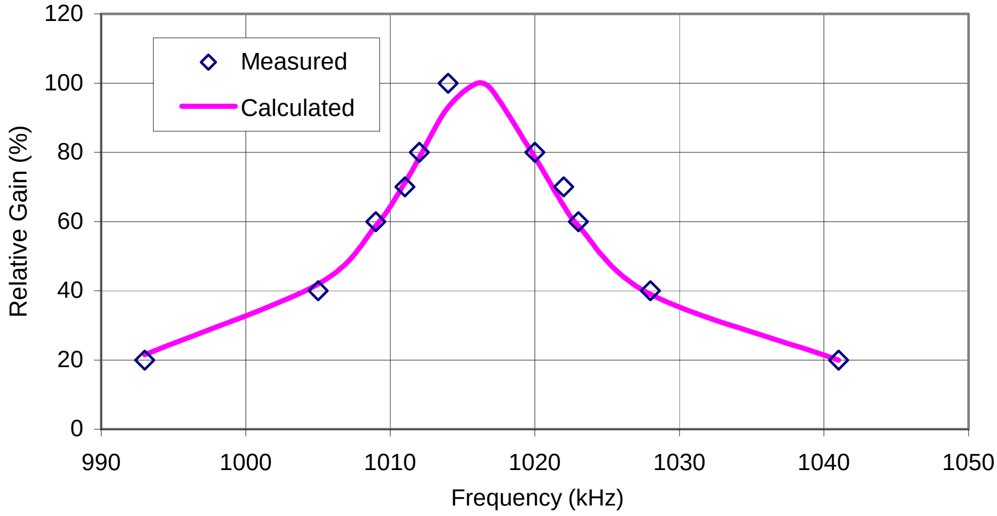

Figure 9.1: Response of the MF Antenna, with LF Coil out of Circuit

The plot indicates a Q of 100. According to Spreadsheet 1, the expected output level is 299 mV, or 123 mV once the Mummrod corrections have been applied, whereas the measured output level was 103 mV.[13] This is good agreement, bearing in mind measurement uncertainties.

With the LF coil connected, the output fell to 38 mV RMS — a factor of 2.7. The loss of Q would account for a factor of 100/46, or 2.2, so presumably the remaining factor of 1.24 is attributable to a reduction in effective length of the rod. This would reduce the sensitivity of the receiver by nearly 2 dB, giving good agreement between calculated and measured sensitivity.

10 Conclusion

The work just described has sought to account for the HF and MF sensitivities of a domestic DRM receiver. Some points to emerge are as follows:

- For both HF and MF, the measured sensitivities are in reasonable agreement with the calculated values. The implication is that, for this receiver, self-interference is not degrading the performance significantly.
- The HF performance is limited by the small self-capacitance of the antenna and the high input capacitance of the following circuitry. Resonating out the input capacitance could provide a useful improvement in sensitivity.
- The above point is demonstrated accidentally by a spurious resonance of the VHF/FM trap.
- The MF performance is limited by the ferrite rod antenna: a longer rod would be needed to achieve a significant improvement in sensitivity. It would, of course, need to be placed away from sources of interference.

A final point to make is that, because small antennas are limited in performance, receivers should be provided with a socket for an external antenna.

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[13] The experimental arrangements were as described in **[2]**, and used a Meguro loop to generate the known field. In this case, the loop was fed with a signal level of +13 dBm, and was placed 600 mm from the ferrite rod.

With the higher Q, the tuning becomes rather touchy. To reduce errors resulting from this touchiness, it was helpful to plot the theoretical response curve, and to choose its centre frequency and Q for a best fit to the experimental figures.

11 References

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