TEXAS INSTRUMENTS

HF Antenna Design Notes

Technical Application Report

11-08-26-003 Sept 2003

Radio Frequency Identification Systems

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Edition 3 – September 2003

This is the third edition of the **HF Antenna Design Notes**.

It describes the designing and tuning of HF Antennas for use with the following products:

All Tag-it™ inlays, the S6000, S6500 Readers and any third party reader.

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PREFACE

Read This First

About this Manual

This application note (**11-08-26-003)** is written for the sole use by TI-RFID Customers who are engineers experienced with TI-RFID and Radio Frequency Identification Devices (RFID).

Conventions

Certain conventions are used in order to display important information in this manual, these conventions are:

WARNING:

A warning is used where care must be taken or a certain procedure must be followed, in order to prevent injury or harm to your health.

CAUTION:

This indicates information on conditions, which must be met, or a procedure, which must be followed, which if not heeded could cause permanent damage to the system.

Note:

Indicates conditions, which must be met, or procedures, which must be followed, to ensure proper functioning of any hardware or software.

Information:

Information about setting up and procedures, that make the use of the equipment or software easier, but is not detremental to its operation.

If You Need Assistance

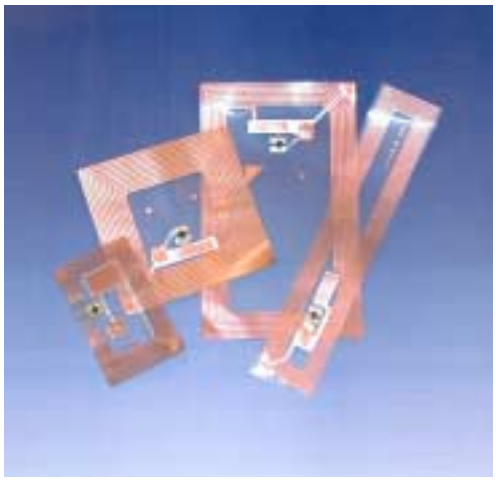
For more information, please contact the sales office or distributor nearest you. This contact information can be found on our web site at: **http://www.ti-rfid.com**.

HF Antenna Design Notes

Allan Goulbourne

ABSTRACT

This document describes how HF (13.56 MHz) antennas can be built and tuned so that their characteristics match the requirements of the Texas Instruments' high performance S6000 and S6500 readers and third party RF modules. This third edition places greater emphasis on antennas for the higher power readers.



Tag-it™ Inlays

In general, the distance at which a Tag-it™ transponder inlay (tag) can be read is related to the size of the Reader's antenna system and its associated magnetic field strength – the larger the antenna – the greater the range. However, as the antenna size increases other issues emerge:

- The Signal to Noise (S/N) ratio will reduce.
- Shielding may be required to remain within regulatory legal limits.
- Magnetic flux holes may develop where the inlay stops being read.
- Matching the antenna to the reader will become more difficult and, if the inductance gets too high, may prove impossible.

1 Reader Requirements

Texas Instruments' Tag-it™ system operates in the High Frequency band at 13.56 MHz and antennas utilize the magnetic (H) field to transfer power to the battery-less inlay (tag) during reading, writing or locking operations. (The associated electrical (E) field is not used). The reader expects an antenna to be tuned to a centre frequency of 13.56 MHz, have 50Ω impedance and when connected to a reader have a (loaded) Q factor of less than 20. For optimum performance, the reader matching should have a VSWR ratio of less than 1:1.2.

2 Tools Required

For antenna development, the following equipment is recommended:

- VSWR meter
- Antenna Analyzer
- Twin Channel Oscilloscope
- Charge level Indicator

2.1 VSWR Meter

The **V**oltage **S**tanding **W**ave **R**atio (VSWR) meter, see Figure 1, is used in-line between the reader and the antenna and indicates the efficiency of the matching by showing the ratio of the forward signal against a reflection. If the antenna is matched correctly then the VSWR should read 1:1, i.e. no reflections or return loss (VSWR is sometimes expressed as the Return Loss. See Appendix A). The VSWR meter can also indicate the output power in Watts. The VSWR meter should:

- Have a full scale ranges of 5 Watts and 20 Watts
- Operate at < 1 Watt
- Indicate power output.

Figure 1. VSWR Meter

2.2 Antenna Analyzer

An antenna analyzer can determine the characteristics of an antenna without having to have a reader connected. It is a variable frequency signal generator that shows the matching – frequency, impedance and VSWR - of the connected antenna. It can be used, together with an oscilloscope to calculate the loaded quality (Q) factor of the antenna under test.

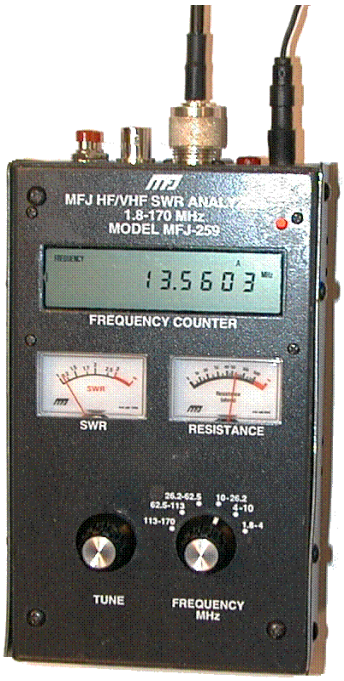


Figure 2. Antenna Analyzer

2.3 Oscilloscope

The oscilloscope is used in conjunction with the antenna analyzer to allow the Quality Factor (Q) of an antenna to be calculated. It is also used in multi-antenna systems to check for minimum coupling between adjacent antennas. It should have:

1) 20 MHz (min) Bandwidth
2) Dual channel

2.4 Charge Level Indicator

This tool can be made from a Tag-it™ inlay and a few components and is used to show the charge-level, at any point in a reader antenna system.

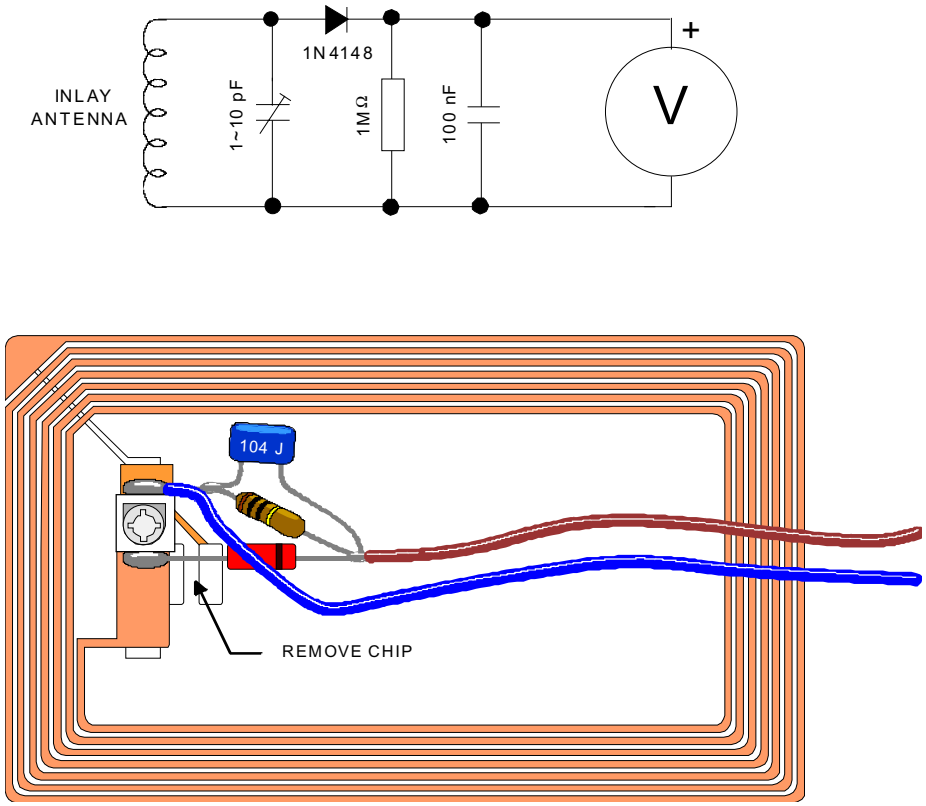


Figure 3. Charge Level Indicator

2.5 Software Tools

A software application can be used to determine antenna characteristics:

'ADP.exe' can be used to calculate the inductance of antennas. For tube antennas it will also give the capacitance values to tune the antenna to resonance. This program can be down loaded from the web site **http://www.ti-rfid.com**

3 Antenna Design Considerations

A number of questions need answers before the design of an antenna can begin:

3.1 What is the Read Distance Required?

A single antenna 500-mm x 500-mm has a reading range of about 600-mm at 4W with the large HF-I inlay. A pair of similar antennas (connected to the same reader) can cover distances greater than 1m. With larger antennas and greater power outputs, longer reading distances can be achieved. Integrators are advised though, that they should always build a margin of safety into their designs when specifying maximum read performance

HF-I inlays will Read and Write at the same distance but the original HF inlays will only Write at around 70% of the reading distance.

3.2 What is the Inlay Orientation?

Inlays receive power by magnetic coupling with the antenna and will receive maximum power when in their best orientation.

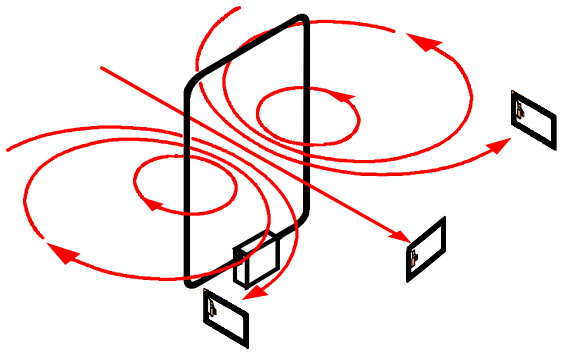


Figure 4. Inlay Coupling

Figure 4 shows the magnetic field lines associated with an antenna and how, when these lines are orthogonal to the inlay, best coupling results. Thus when an inlay is facing an antenna it reads well but move the inlay to the side of the antenna where the lines are now at right angles to the inlay and no coupling results. In this location the inlay will read when at right angles to the antenna. These reading zones are shown in Figure 5.

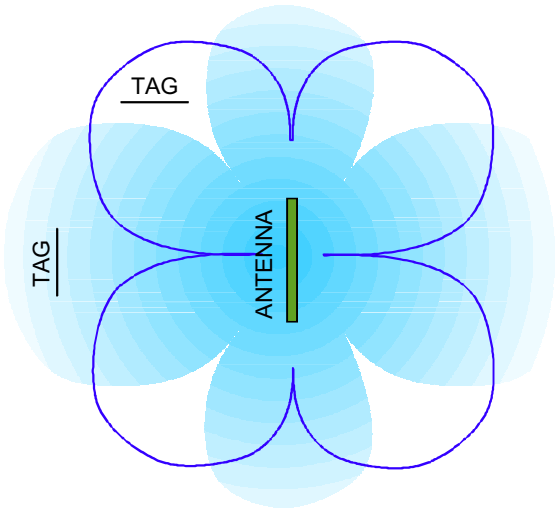


Figure 5. Inlay Reading Zones

In practice, the inlay can be rotated around ± 40º either side of its optimal position and will still be read

3.3 At What Speed is the Inlay Traveling?

At a baud rate of 115,200 the S6500 Reader will read a single block, approximately 60 times a second. Writing, reading multiple blocks and Simultaneous Identification, have different timings and the designer must ensure that, whatever speed the inlay is moving at, it is in the magnetic field long enough for the complete transaction to take place. High-speed operations may require a lengthened antenna.

3.4 What is the Inlay Separation?

The ability to read closely separated inlays depends on the width of the antenna but is closely tied in with inlay reading speed. When multiple inlays are likely to be in the field at the same time and simultaneous identification is used, more time will be required than when reading singulated inlays.

3.5 How Much Data is Required?

The more data that is required from the inlay, the greater the time the inlay must be within the field of an antenna, which in turn will be related to the speed the inlay is traveling.

4 Environmental issues

4.1 What are the Governmental (PTT/FCC) limits?

Systems Integrators should consult their local Governmental Agencies / Test houses to determine the legal limits for the RF field generated from an antenna. The system is approved in both Europe and USA using 4W into the standard 300-mm x 300-mm antenna but where larger antennas are required; they may need to be shielded to meet local regulations.

ETSI Regulations can be found in EN 300 330 or FCC Regulations can be found in FCC CFR47 Part 15.

4.2 Is there Electrical Noise?

Problems with electrical noise are rare but it is wise to perform a site survey before commencing antenna design, than struggle to solve a problem later. In general electrical noise tends to influence the receive performance and results in reduced reading ranges. Slight changes in antenna orientation to the noise source, additional grounding or shielding can all help to reduce the effects. If the problem is common mode noise, fitting a BAlanced UNbalanced (BALUN) transformer will help.

4.3 Is there Metal in the Environment?

The presence of metal close to an antenna will reduce its performance to some extent. As the antenna size increases, so does the minimum separation distance from metal before de-tuning effects are noticed. Much of the effect can be 'Tuned out' but when the metal is close, e.g. less than 200-m, the metal will absorb some power and the read distance will drop. Antennas should always to be tuned in their final positions.

4.4 Proximity of other Antennas

The presence of other antennas will alter the way a system performs because of coupling between the antennas. In some cases, e.g. reflective passive antennas (covered later), the coupling will be deliberate but in most cases, this effect will have to be minimized and will be covered in a later section.

5 Materials

Whilst antennas can be made from almost any conductive material, the use of copper tube or tape offers good results. Aluminum is a suitable alternative to copper but is more difficult to join. For larger antennas, where the inductance may be getting high, 22- mm (¾") copper tube can provide a self-supporting antenna. Smaller antennas can be made with 15-mm (½") tube. Wide copper strip (30 to 50-mm) is a suitable alternative to 22-mm tube but if the antenna is small, RG405 rigid coax (use the outer copper sheath) is all that is required. Capacitors should be mica or NP0 ceramic devices.

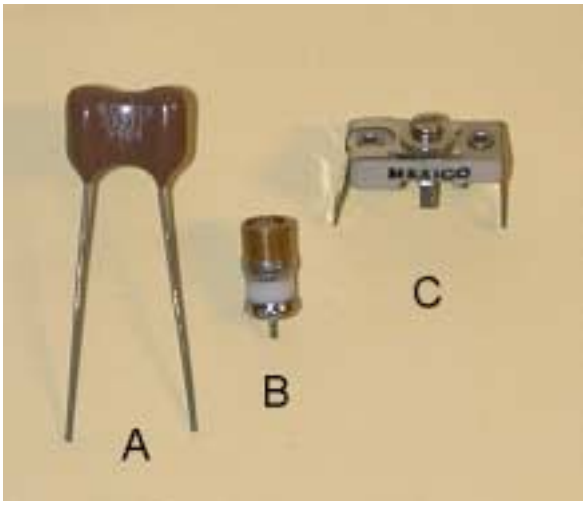


Figure 6. Capacitor Types

In Figure 6, above, three types of capacitor are illustrated. A) Is a fixed value silvered mica capacitor. This type of capacitor is readily available and exhibits high stability for use in RF circuits. B) Is a multi-turn air-gap and is used for fine-tuning and C) is another variable mica type and is available in wide ranges e.g. 12 to 80 pF.

One important consideration when selecting capacitors is that their voltage rating should be suitable for the high voltages of the resonant loop antennas.

The resistor type used to damp the Q of antennas very much depends on the output power of the reader and its operation mode. The S6000 reader has a maximum recommended output of 1.1 W and turns off its transmitter after each command. For this reader, 2W carbon film resistors are adequate but for the S6500, which keeps its transmitter on and can output up to 10W, thick film resistors should be used. Figure 7 show three resistors. A) Is a 2 W carbon film resistor, B) is a 20 W thick film resistor and C) is a 50 W thick film resistor. The last two types should be bolted to the antenna tube or tape to transfer away the heat. Examples can be seen in figures 15 and 19

Figure 7. Resistor Types

6 Loop Antennas

Loop antennas are recommended as the most suitable for generating the magnetic (H) field that is required to transfer energy to the battery-less inlay.

The field strength is a measure of the output power and for the original HF inlay to operate successfully, a magnetic field strength of 100mA/m (or 152dBµA/m) is required. The HF-I inlay is more efficient and only requires a field strength of 93 dBµA/m (144 dBµV/m). The following graphs (Figures 8 and 9) illustrate how small sized antennas have higher field strengths closer to the antenna than larger sizes but this falls-off more quickly. Antennas much larger than 1.3m will start to have reduced reading ranges.

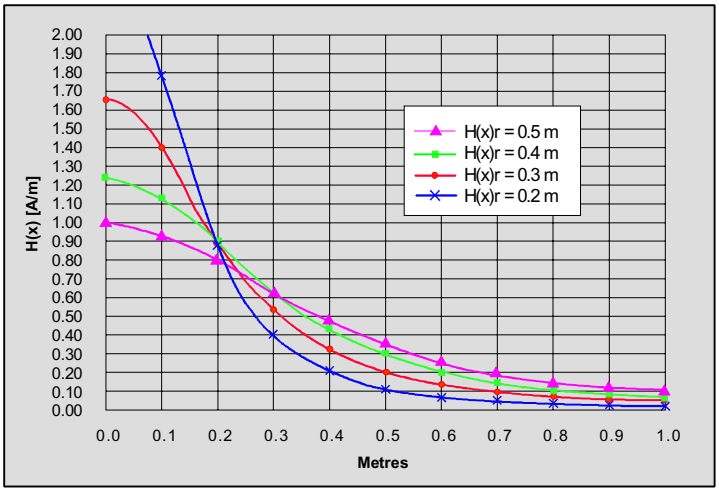


Figure 8. Field Densities for different sized antennas vs. distance

Note: H(x) is the field strength generated by a loop antenna. H(x)r equates to the radius of the loop antenna whose field strength is being measured.

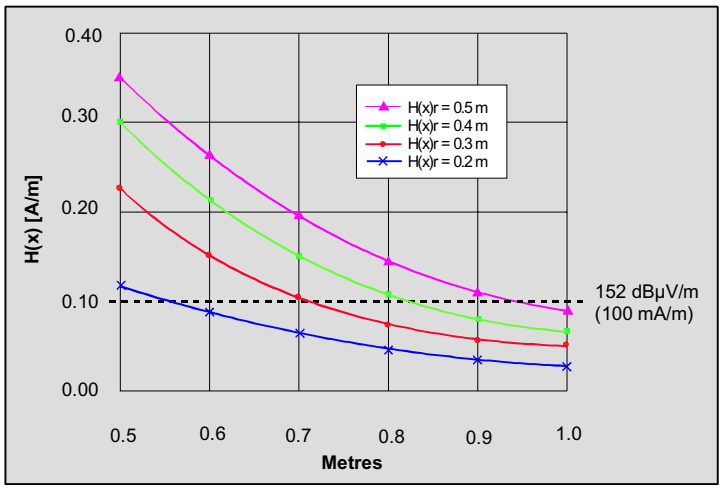


Figure 9. Close-up of Figure 8 showing Theoretical Read Distances

6.1 Loop Antenna Resonant Theory

A loop antenna is a tuned LC circuit and for a particular frequency, when the inductive impedance (X_L) is equal to the capacitive impedance (X_C) the antenna will be at resonance. This relationship is expressed as follows:

$$f = \frac{1}{2\pi\sqrt{LC}} \qquad [1]$$

As can be seen from the equation, the relative values of the inductance (L) and capacitance (C) are interrelated. For this frequency though, if the antennas are made too large, the inductance rises to a point were very small capacitor values are required. Once the inductance exceeds 5 µH, capacitance matching becomes problematic. Two techniques can help to limit the rise of inductance:

1. Use low resistance copper tube in place of wire.
2. Connect two antennas in parallel thus halving the inductance.

6.2 Inductance Measurement

Fundamental to many of the equations used in the design process is the accurate measurement of the inductance of a loop (L). This can be done in a number of ways:

6.2.1 Calculation

This is the least accurate way and although equations may be accurate for round antennas, they are an approximation for rectangular designs.

The formula below is reasonably accurate for square antennas made from tube:

$$L_{\mu H} = \text{Side} \times 0.008 \left[\text{LN}\left(\frac{\text{Side} \times 1.414}{2 \times \text{Diameter}} \right) + 0.379 \right] \qquad [2]$$

Where

Side = Centre to centre length of antenna side (cm)

Diameter = Tube diameter (cm)

Example: 50-cm x 50-cm loop, 15-mm diameter copper tube

$$L_{\mu H} = 48.5 \times 0.008 \left[\text{LN}\left(\frac{48.5 \times 1.414}{2 \times 1.5} \right) + 0.379 \right]$$

$$= 1.36\ \mu H$$

Information:

The program “ADU.EXE” is recommended for inductance calculation.

6.2.2 Measurement at 1 kHz (LCR Meter)

Using an LCR meter is again an approximation but accurate enough for calculating the resonating capacitor.

6.2.3 Accurate measurement of LCR parameters.

Using an Impedance Analyzer, for example HP4192A or Agilent Technologies 4294A you can set the desired frequency, in this case 13.56 MHz and the instrument will measure the Capacitance, Resistance and Inductance of the Antenna. This will allow the correct tuning components to be selected for the antenna.

6.2.4 Resonance Capacitance

Equation [1] can be rearranged to calculate the capacitance needed to bring an antenna to resonance at 13.56 MHz:

$$C_{RES} = \frac{1}{\omega^2 L} \qquad [3]$$

Where: $\omega = 2\pi f$

Example: 50-cm x 50-cm Antenna, 15-mm Tube, L = 1.36µH, f = 13.56 MHz

$$C_{(Res)} = \frac{1}{(2 \times \pi \times 13560000)^2 \times 0.00000136} = 1.01 \times 10^{-10} \text{ (101 pF)}$$

6.3 Determining the Q

The performance of an antenna is related with its Quality (Q) factor.

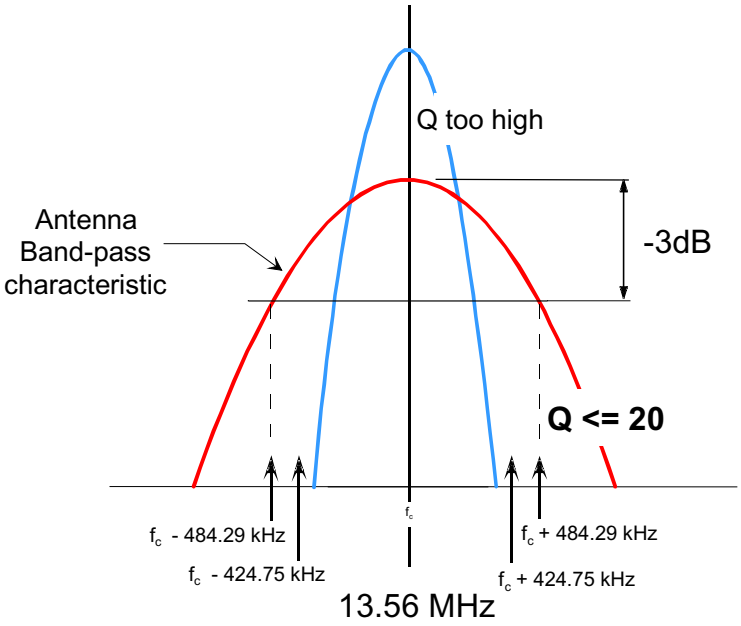
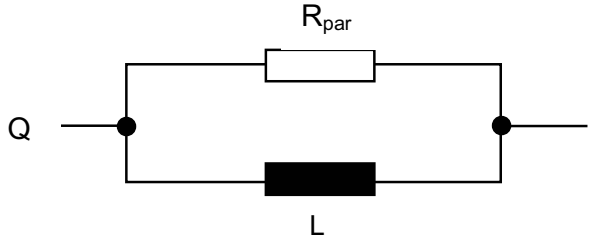


Figure 10. Antenna Q

In general, the higher the Q, the higher the power output for a particular sized antenna. Unfortunately, too high a Q may conflict with the band-pass characteristics of the reader and the increased ringing could create problems in the protocol bit timing. For these reasons the Q or the antenna when connected to a 50-Ohm load (i.e. the reader) should be 20 or less.

The total ac resistance at resonance is difficult to calculate or measure without sophisticated equipment. It is easier to assume a Q value and work backwards.



$$Q = \frac{R_{par}}{2\pi f L} \qquad [4$$

First it is necessary to calculate the total parallel resistance of the finished antenna, having the required Q of 20.

$$R_{par} = 2\pi f L Q \qquad [5$$

Example if L = 1.36µH, f = 13.56 MHz & Q = 20

R_{par} = 2 × 3.142 × 13560000 × 0.00000136 × 20

= 2,317 Ohms

Then assume a value for the present Q (say 50) and repeat the calculation

e.g. L = 1.36µH, f = 13.56 MHz, Q = 50

$R_{par,\ antenna}$ = 2 × 3.142 × 13560000 × 0.00000136 × 50

= 5,793 Ohms

The required resistance can be calculated using formula [6]

$$R = \frac{1}{\frac{1}{R_{par}} - \frac{1}{R_{par,\ antenna}}} \qquad [6]$$

e.g. R_{par} = 2317, $R_{par,\ antenna}$ = 5793

$\underline{R = 3861\ \Omega}$ (use 4.7 kOhms)

Then when you measure the Q and it needs changing, it is relatively easy to adjust the resistor value (R_{par}) to give the required Q by using formula [7].

$$R_{par} = \frac{Q_{present} \times Q_{required} \times 2\pi f L}{Q_{present} - Q_{required}} \qquad [7]$$

6.4 Measuring the Quality Factor

The Quality factor (loaded) of an antenna can be readily measured if you have an instrument capable of generating frequencies between 13 MHz and 14 MHz. (e.g. MFJ-259B Analyzer, refer to page 37 for supplier details) and a spectrum analyzer or oscilloscope.

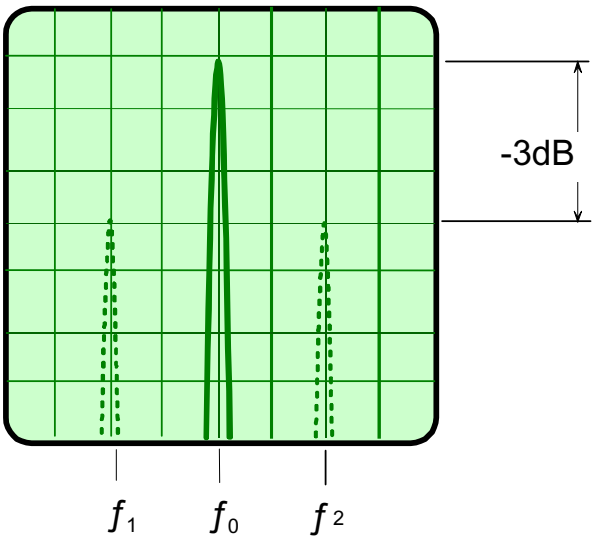


Figure 11. Spectrum Analyzer screen

The MFJ meter is connected to the antenna under test and a pick-up loop, connected to the spectrum analyzer, is positioned about 300 mm away from the antenna

The spectrum analyzer should be set to the 1dB/div scale and the MFJ's frequency is adjusted until the maximum amplitude of the signal is seen. By lowering and raising the frequency, the upper and lower -3dB points can be found and recorded.

The three frequencies (f_1, f_0, f_2) from Figure 10 can be used in the following formula:

$$Q = \frac{f_0}{f_2 - f_1} \qquad [8]$$

e.g. $Q = \frac{13.56}{13.91 - 13.20} = 19$

If an oscilloscope is used the method is slightly different. In this case the maximum voltage is recorded as the frequency is adjusted and this value multiplied by 0.707 in order to obtain the equivalent -3dB value. The frequency is then raised and lowered to get the f_1 and f_2 values.

7 Antenna Matching

For optimum performance, the antenna and its feeder coaxial cable must have impedance of 50 Ohms. Matching changes the impedance of a resonant loop to 50 Ohms and the accuracy of the matching is checked by the Voltage Standing Wave Ratio (< 1:1.2) on the VSWR meter.

There are numerous matching techniques but this document will detail only four methods:

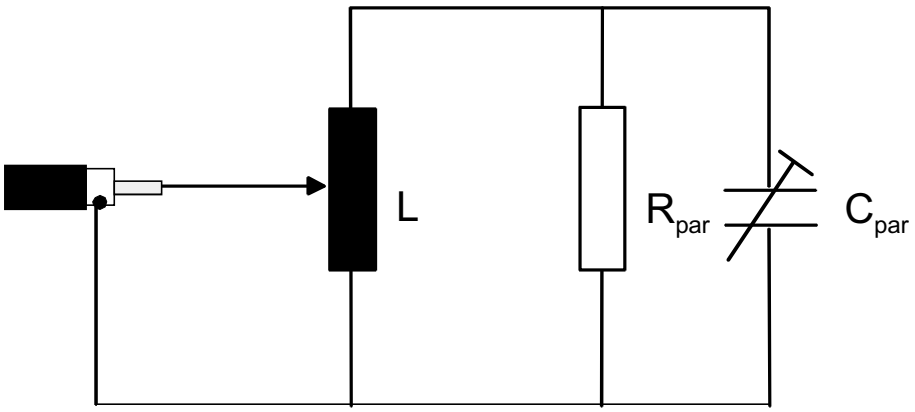
- Gamma Matching / T-Matching
- Transformer Matching
- Capacitance Matching

WARNING:

High voltages exist at the **antenna terminals** due to the resonance behaviour. You should **not** modify the matching circuits with the equipment switched on.

7.1 Gamma Matching

This method must be the easiest and cheapest method. The equivalent circuit is shown in Figure 12.



Where L is the Inductance, C_{par} is the parallel capacitance
R_{par} is the damping resistance.

Figure 12. Gamma Matching Circuit

Note:

Figure 12 shows an unbalanced system. If a 1:1 BALUN is used before the coax cable, then the system will once again be in balance.

Once the Inductance of the antenna has been determined, the resonant capacitor is calculated and fixed across the open ends of the loop. The coax cable shield is connected to the centre of the antenna, opposite the capacitor position, with the coax centre wire attached to the matching tube, which is in turn connected to the main loop at the correct impedance point.

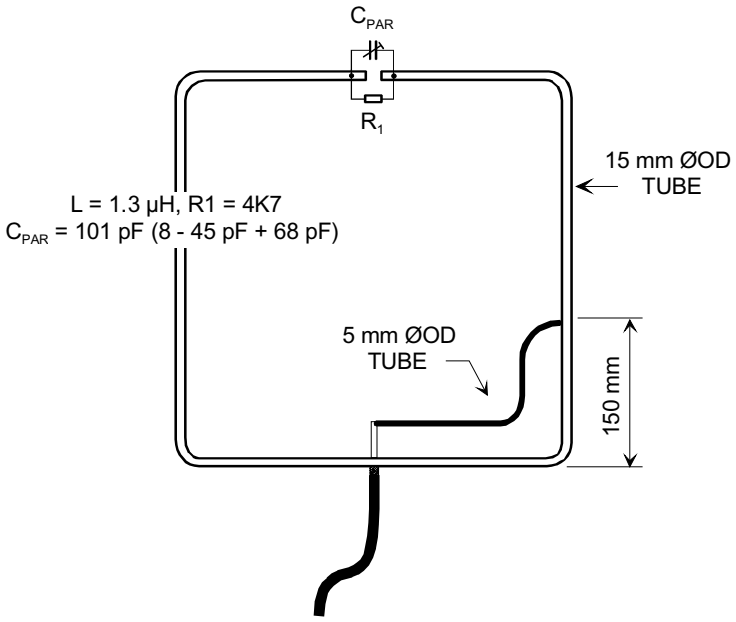


Figure 13. A Gamma Matched Antenna

Figures 13 & 14 show a 50-cm x 50-cm square loop antenna, constructed from 15-mm copper pipe. The matching tap is made from 5-mm copper / nickel brake pipe.

A 4K7 resistor is fixed in parallel with the capacitor to reduce the Q.

The point on the loop's perimeter where the matching tap is fixed depends on the Q of the antenna - the higher the Q - the closer the tapping point moves to the centre.

Note:

In practice a variable capacitor with a large range e.g. 12 – 80pF is used to achieve the desired range. Once matching has been achieved, it is removed and measured and a larger fixed capacitor is used, together with a smaller variable capacitor, to allow for fine tuning.

Figure 14. Gamma Matched Antenna

Figure 15. Joining the Loop & Attaching components

Figure 14 shows a completed antenna. The SMA bulkhead connector is bolted to the tube and the center pin (the red wire) is connected to the matching arm. In figure 15 you can see how the components are attached.

7.2 T-Matching

This method, like the Gamma-matching, taps the antenna loop for the matching points. Figure 16 shows the equivalent circuit.

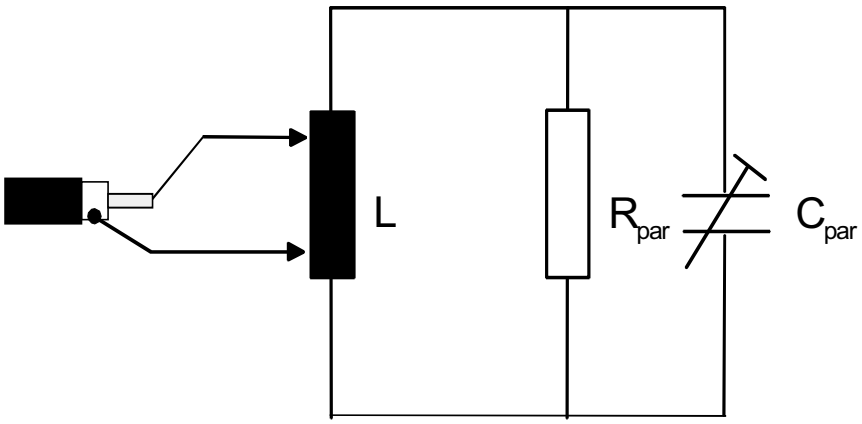


Figure 16. T-Matching Circuit

This type of matching is 'balanced' as both screen and centre core of the coax cable are tapped and not, as in Gamma matching, just the core. Once again, as for Gamma matching, the tapping can be external or internal to the loop. Figure 17 shows how the antenna analyzer can be used to find the tapping points.

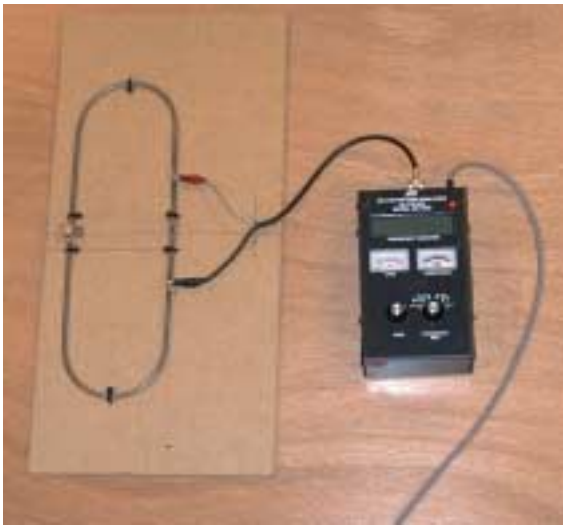


Figure 17. Using the Analyzer to Determine the Matching Points

As for Gamma matching, the matching arms need to have at least 40-mm separation from the loop to prevent capacitive coupling. The exact matching points will vary with the Q - the higher the Q, the closer together the matching points are - the lower the Q, the farther apart the matching points are.

Figure 18 shows part of a large T-matched antenna made from 50-mm wide copper tape.

Figure 18. T-Matched Tape Antenna

The resonance capacitance and Q reducing resistor arrangement for the same antenna are shown in Figure 19

Figure 19. Resonance Adjustment and Q Damping

The proportions between the size of the main loop and the matching arms should be approximately (3:1). In this case the loop is 50-mm wide tape and the matching arms 12-mm wide.

7.3 Transformer Matching

The equivalent circuit for transformer matching is shown in Figure 20. With transformer matching, the galvanic de-coupling means that the antenna inductor has no DC connection to the reader. This can sometimes be required or help to overcome grounding problems

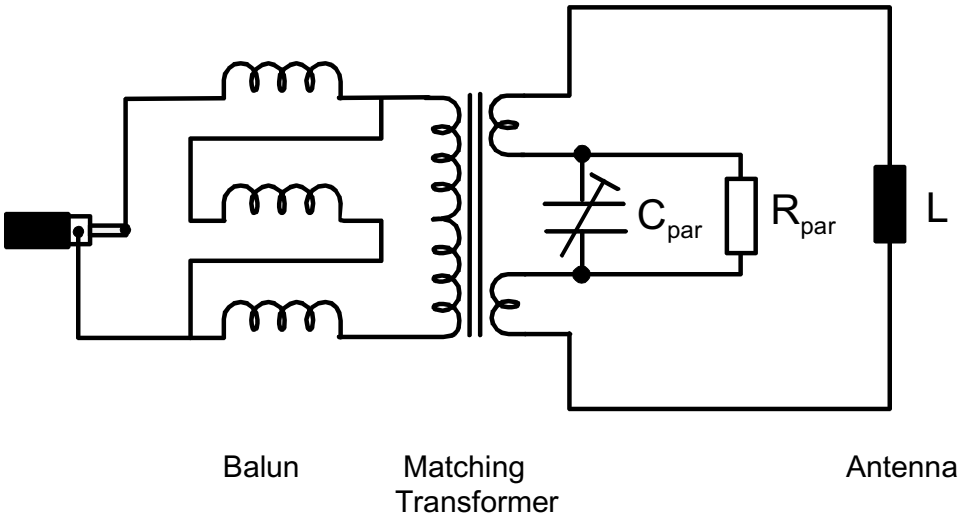


Figure 20. Transformer Matching

The transformer matching circuit comprises two elements

- The matching transformer.
- A **Bal**anced / **Un**balanced (Balun) transformer.

Determining the matching is very similar to that of the Gamma matched antenna:

Measure or calculate the inductance of the antenna loop (L)
Calculate the value of the parallel resonant capacitor (C_{par})
Determine the parallel resistor (R_{par}) necessary for Q

7.4 Matching Transformer

It is now necessary to calculate the turns ratio for the matching transformer using formula [9] below, with the value for R_{par} from formula [5] with Q = 20.

$$\left(\frac{n}{m}\right)^2 = \frac{R_{in} \times R_{par}}{(2\pi f L)^2} \qquad [9]$$

Where n/m is the transformer ratio (set m = 2 initially)
R_{in} is 50 Ohms

Example: R_{par} = 2317 Ohms, R_{in} = 50 Ohms, L = 1.36µH, m = 2

$$n = m \times \sqrt{\frac{R_{in} \times R_{par}}{(2\pi f L)^2}}$$

$$\underline{n = 6} \ (5.8)$$

Note:

This formula is not exact. In practice, the number of windings depends on the Q; the higher the Q, the more turns required. The actual windings ratios of the examples (Figure 24 A/B) are 3:10 (m=3, n=10) and 2:6 (m=2, n=6)

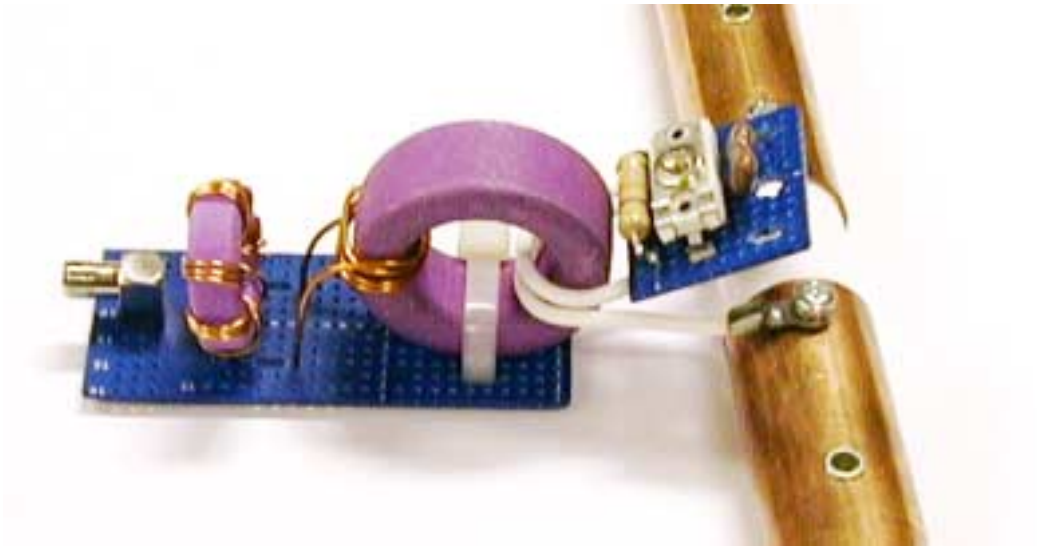


Figure 21. Toroid Matching Transformer

Figure 21 shows a 5:2 matching transformer. The ferrite toroid must be the correct grade for this frequency and we recommend the FerroxCube (Philips) 4C65 grade. Part number: RCC 23/7 4322 020 9719.

7.5 Baluns

The Balun converts an unbalanced load to a balanced load and is primarily used to remove common mode noise problems associated with multiple antennas that have different ground potentials. It is also used to connect balanced antennas to (unbalanced) coax. These differences may set up common mode currents that can disturb the receive circuits.

The Balun is a trifilar winding of 1:1 ratio and it is important to keep the three wires tight together but the sets of three wires can be evenly spaced around the toroid.

Again the correct grade of ferrite is important and we again recommend the Ferroxcube (Philips) 4C65 grade (or the equivalent Siemens K1). Figure 20 shows a schematic of the windings.

Note:

It is important to note that although ferrite manufacturers data state a Ferroxcube equivalent, in practice this could be incorrect. Build a 'Golden' Balun using Ferroxcube 4C65 grade ferrite and test others against this.

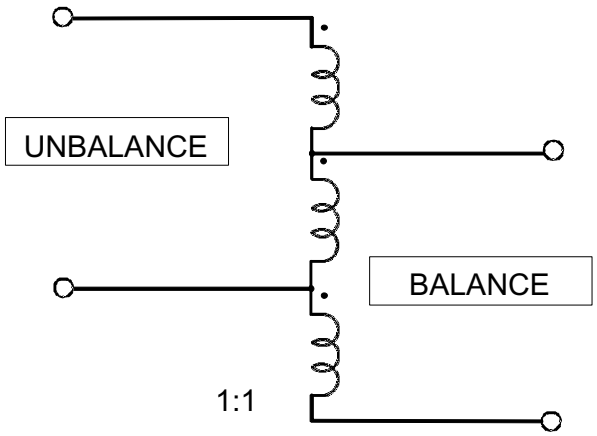


Figure 22. 1:1 BALUN

Figure 23 uses 3 colors to indicate how a toroidal Balun is wound. In practice 0.8-mm polyurethane insulated transformer wire is used.

Figure 23. Toroid BALUN

The coax core is connected to 'A' and 'B' to the coax screen. Wires 'C' and 'D' are not polarized and connect to the antenna / matching circuit. It is also possible to use 'Pig's Noses' (twin holed ferrites) to produce the Baluns.

Integrators are advised to check the winding of their Baluns before use. Connect the Balun to a reader via an SWR meter and terminate wires 'B' and 'D' with 50 Ohms. The VSWR meter should show around 1:1.3.

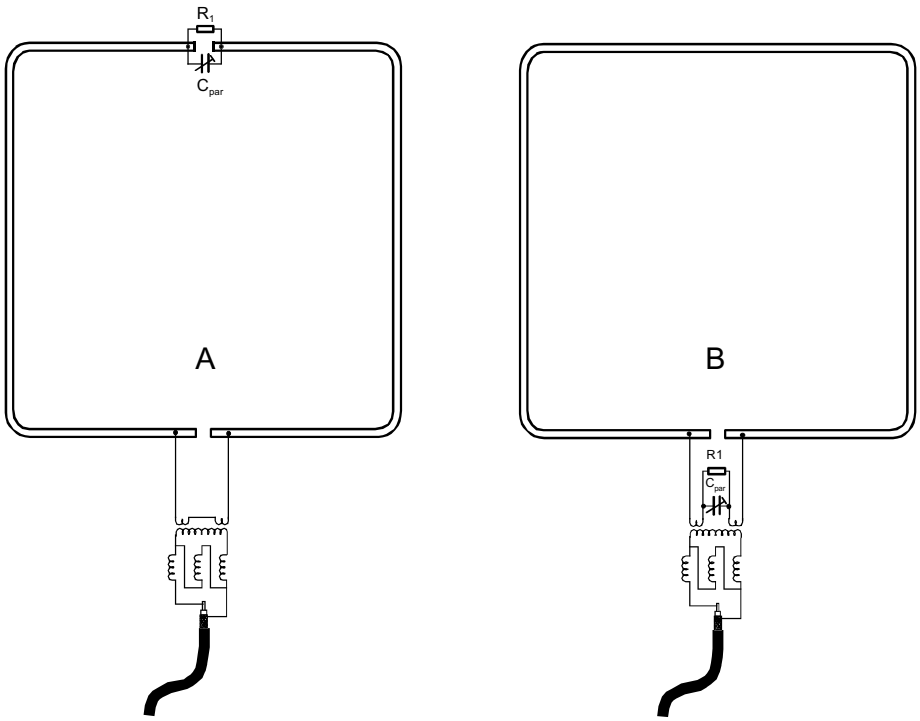


Figure 24. Transformer matched Examples

A …… L = 1.36 µH, Cpar = 65 pF (2~12 pF + 56 pF)

R1 = 10 K, Q = 26, turns ratio = 3:10

B …….. L = 1.36 µH, Cpar = 80 pF (2~12 pF + 69 pF)

R1 = 6K (2 × 12K in parallel), Q = 21, Turns ratio = 2:6

There is no such thing as 'half a turn' on a transformer. If the exact tuning falls between two windings e.g.2:6 and 2:5, increase the primary winding to three and add more secondary turns (see A above).

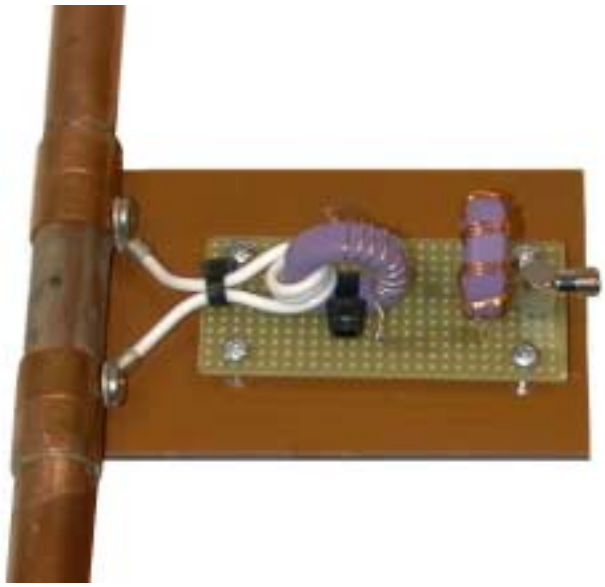


Figure 25. Transformer circuit for Example A

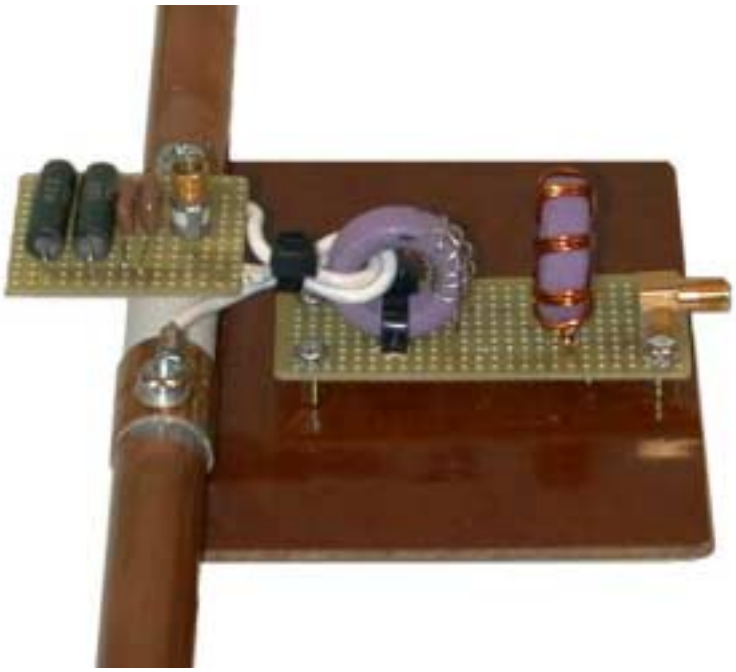


Figure 26. Transformer Circuit for Example B

7.6 Capacitance Matching

Capacitance matching is perhaps the most difficult of the three methods of antenna matching to develop. Small changes in capacitance can make large differences to the matching, so it is easy to miss the 'window' when using trial and error methods. This is particularly the case with larger antennas where only small Pico Farad capacitance values are required for matching. The formulas are also inexact as there are many variables involved e.g. changing the length of the legs of a capacitor. They are a starting point for trial and error work with your antenna analyzer

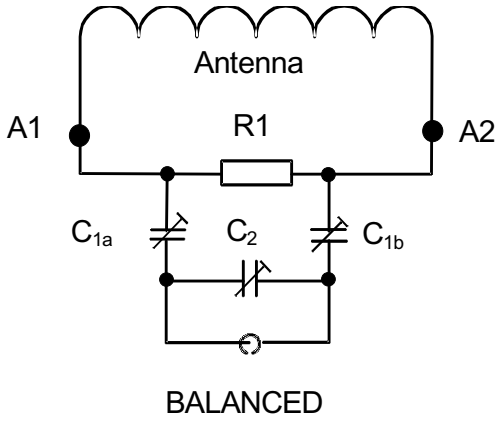


Figure 27. Balanced Capacitor Matching Circuit

Figure 27 shows the series-parallel capacitance matching circuit used in Texas Instrument's demonstration antenna from its S6000 reader/antenna set. The equivalent unbalanced circuit is shown in Figure 28

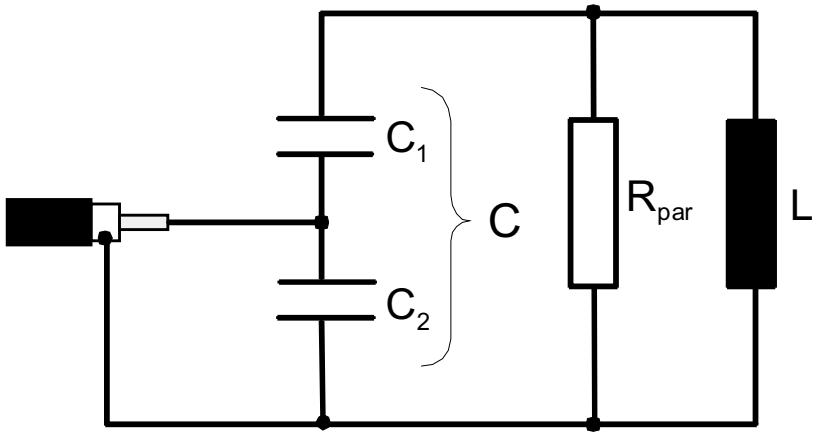


Figure 28. Unbalanced Parallel-Series Capacitor matching circuit

To calculate the required capacitance:

1. Calculate or measure the Inductance (**L**) [2] e.g. 1.36µH
2. Calculate the total resonant capacitance (**C**) [3] e.g. 101pF

3. Calculate the equivalent resistance ($\mathbf{R_{par}}$) [5] e.g. 2317 Ohms for Q =20

4. From the total capacitance [3], calculate C_2

$$C_2 = C \times \sqrt{\frac{Z_{out}}{Z_{in}}} \qquad [10]$$

Where Z_{out} = Total parallel resistance [5] e.g. 2317 Ohms
Z_{in} = 50 Ohms
C = Total Capacitance [3] e.g. 101 pF

Thus

C_2 = 101 × Sq Root (2317/50) = 687.5 pF

5. Calculate C_1

$$C_1 = \frac{1}{\frac{1}{C} - \frac{1}{C_2}} \qquad [11]$$

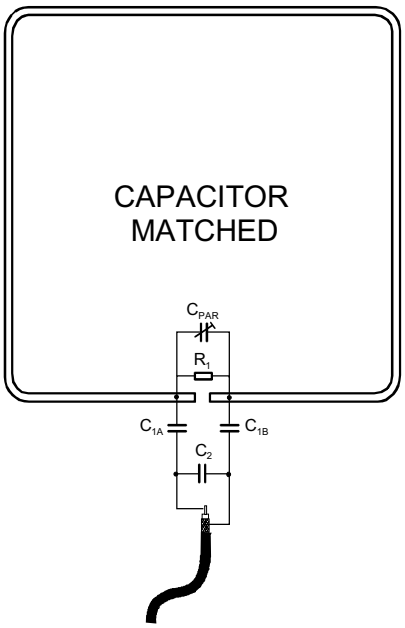
Where C = 101, C_2 =687.5

C1 = 1/((1/101)-(1/687.5)) = 118 pF

For balanced capacitance matching, the value of C_1 is doubled and added to both sides, so:

C_{1A} = 236 pF, C_2 = 680 pF and C_{1B} = 236 pF

These values are **only the starting point** as the equations are not very accurate. Figure 29 is the same 50-cm x 50-cm antenna but this time capacitance matched.



L = 1.36, R_{par} = 4K7, Q = 20
C_{par} = 2 ~ 75 pF, C_{1A} / C_{1B} = 230 pF, C_2 = 560 pF

Figure 29. 50-cm x 50-cm Capacitor matched Antenna

The actual matching circuit for the antenna above is shown in Figure 30.

Figure 30. Capacitance matching

One big advantage of capacitance matching is that for small antennas, the voltages are low enough for surface mount components to be used which can significantly reduce the matching circuit size.

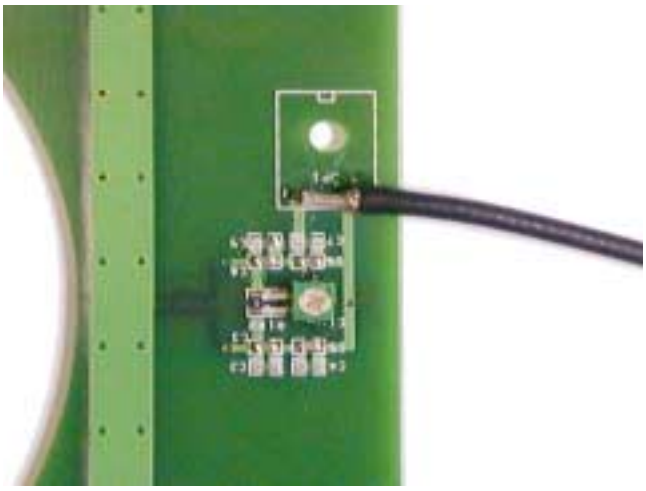


Figure 31. Miniature Capacitance Matching Circuit

8 Coupling between Antennas

Where multiple antennas are operating close to one another, the coupling between antennas can enhance or degrade the performance of individual antennas.

8.1 Nulling Adjacent Antennas

For adjacent antennas (on individual readers) to operate at maximum efficiency, interaction between antennas should be minimal. The degree of coupling between antennas depends on the distance apart and the angle between them. An antenna that is exactly 90º to its neighbor should display minimal coupling. The exact null point can only be found by injecting a signal into one antenna (e.g. using the MFJ analyzer) and monitoring the voltage induced in the second (use a 'scope), as it is moved relative to the first antenna.

The minumum point may not be where you expect it, as the magnetic field of an antenna is not uniform. i.e. the voltage in an antenna is greatest at the opposite side from the feed point.

8.2 Reflective Antennas

If a matched (but unconnected) antenna is positioned opposite a driven antenna, the performance of the driven antenna is enhanced. Such an antenna is sometimes called a reflective antenna, which suggests how it helps to increase the range. This type of coupling can be face-to-face or with the side lobes of the driven loop powering the reflective loop.

8.3 Two Antennas on a Splitter (in Phase)

More than one antenna can be connected to the same reader by means of a splitter

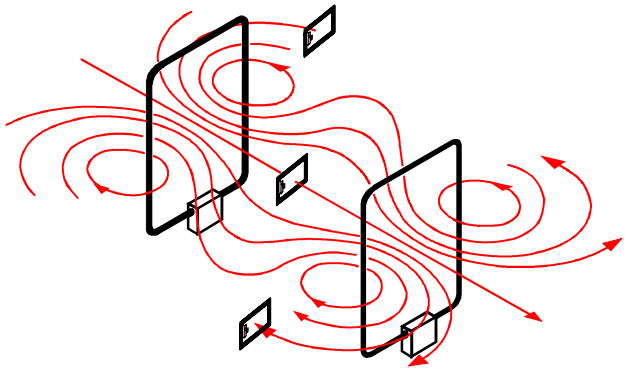


Figure 32. Antennas on a Splitter In-Phase

(see Appendix C for suppliers). Although splitters introduce losses, the reading distance of two opposing driven antennas can be greater than double that of single antenna and are particularly effective when writing to inlays. With a single antenna the field strength drops off with distance but when two opposing antennas are used, the field is 'fed' from both sides, allowing writing at greater distances. This arrangement is also useful when detecting items traveling on a conveyor, when the inlay can be on either side of the item.

8.4 Two Antennas on a Splitter (Out-of-Phase)

When two opposing antennas are out-of-phase with each other, the magnetic field pattern changes. An inlay parallel to the antennas will now have a reading hole in the middle but an inlay at 90º to the antennas will read all the way across at the front and rear of the antenna (Figure 33).

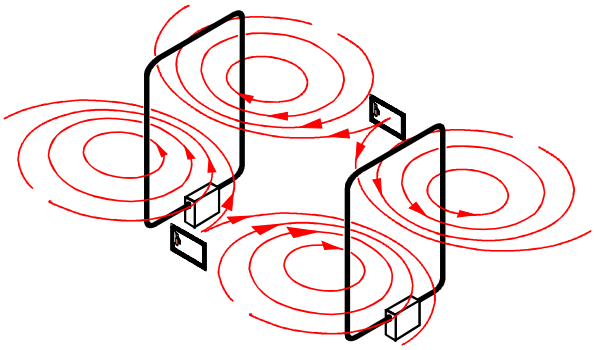


Figure 33. Out-of-phase Magnetic Field Pattern

8.5 Rotating Field Antennas

By using different feeder cable lengths, a pair of antennas can be used to produce a rotating field. The typical arrangement is a pair of antennas in a crossed arrangement.

The included angle of the antennas should be 90º and one feeder cable after the splitter, should be a quarter wavelength longer than the other to give a 90º-phase shift.

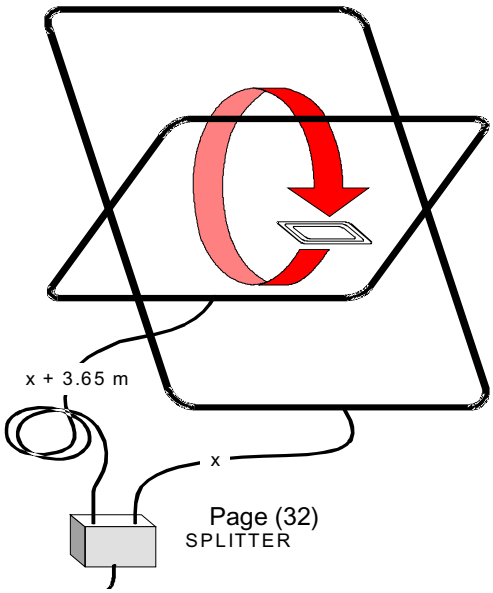


Figure 34. Rotating Field Antennas

Because the signal travels slower through the coax cable than free air, the cable will actually be shorter than ¼ wavelength. In this case you multiply a quarter of 22m x 0.66 (the velocity factor for RG58 coax cable), so the actual length needs to be 3.66m longer than the other feeder.

The effect is to 'rotate' the field' and inlays will read in any position indicated by the arrow in Figure 34.

8.6 Complementary Antennas

This method can be used with the S6500 and S6550 readers that have an additional receive (X1) only antenna port. The 'Basic' transmit/receive is connected to X2 and the 'Complementary' antenna is positioned parallel to, and opposite from, the basic antenna. If the complementary antenna is tuned to exactly 90º Out-of-Phase to the opposing driven antenna, the RF field will alternate between In-Phase and Out-of-Phase at twice the transmitter frequency. This means that it will read all inlays passing between the two antennas for all vertical orientations.

Although it will also read inlays that are horizontal at the top and bottom of the RF envelope, a hole always exists at the centre.

For such a system to function correctly, a number of points are important:

1. The opposing antennas should be the same shape and size.
2. They must be exactly at 90º to each other.
3. The 'Complementary' RX antenna must be tuned to exactly 90º Out-of-Phase to the TX/RX antenna.
4. The voltages in the two antenna should be the same (balanced)

To achieve the correct tuning and balance, a scope and two (self-build) pick-up loops are required.

Figure 35. Pick-up Loop

The pick-ups are wire loops connected to 1.5-m coax cables terminated with BNC connectors for connecting to the twin channel scope.

The antennas will always have to be tuned as a pair, as they will influence each other. The distance between the antennas is related to the size of the antennas; if they are too far apart the complementary antenna will not couple correctly with the driven antenna (and the voltages will be very different).

As a rough guide, the distance apart of the antennas should not be greater than twice the smallest diension of the antennas. e.g. If the antennas are 500-mm x 400-mm, the distance apart could be 800-mm

Once the two antennas have been tuned, both pick-up loops are positioned at the centre of the 'Basic' antenna and the two channels of the 'scope adjusted so that the sine wave signals are superimposed over each other (i.e. in-phase and the same amplitude)

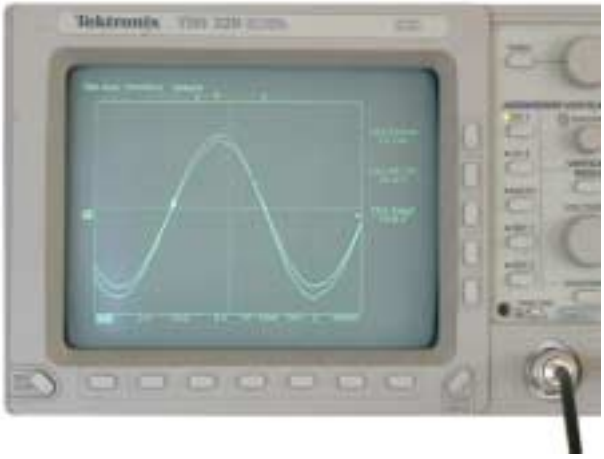


Figure 36. Calibrating both Loops

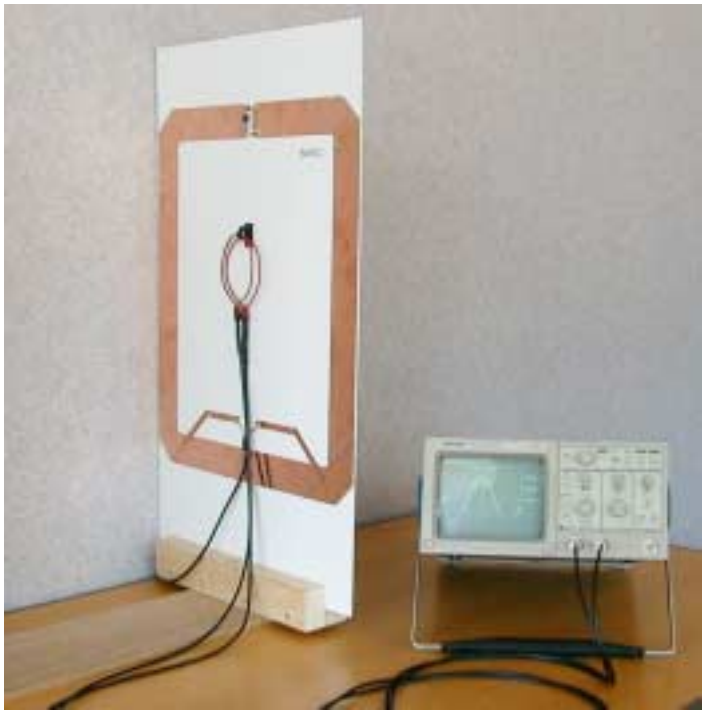


Figure 37. Both Pick-up Loops on the Basic Antenna

One loop is then transferred to the 'Complementary' antenna, ensuring that the orientation of the pick-up loop is maintained and the tuning adjusted to give the 90º offset.

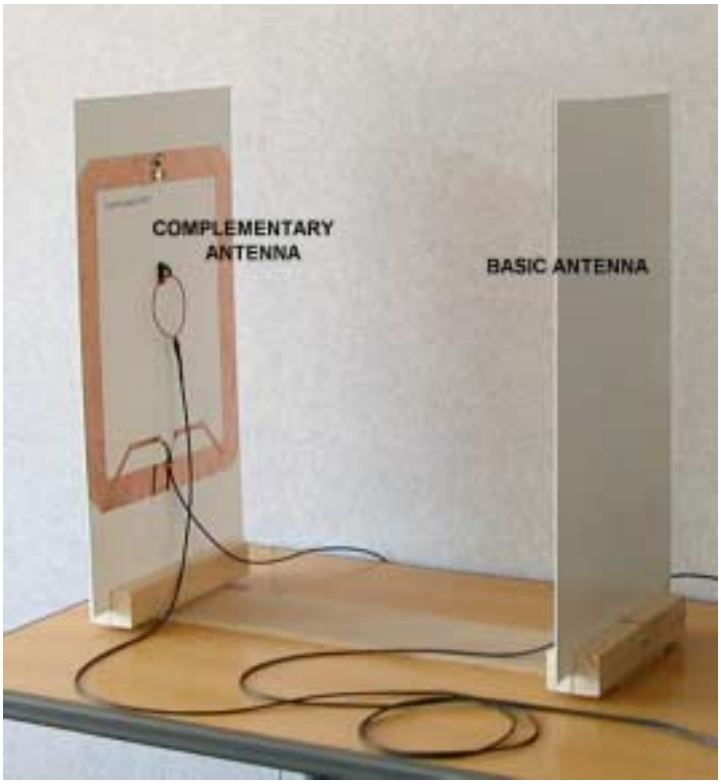


Figure 38. Pick-up Loops Separated

This tuning is changed at the complementary antenna until the sine waves have exactly 18.4 ns separation and are roughly the same amplitude. If you are attempting to separate the antennas too far, the voltage level in the complementary antenna will be much lower than the basic antenna. One method of attempting to balance the voltages is the increase the Q in the complementary antenna.

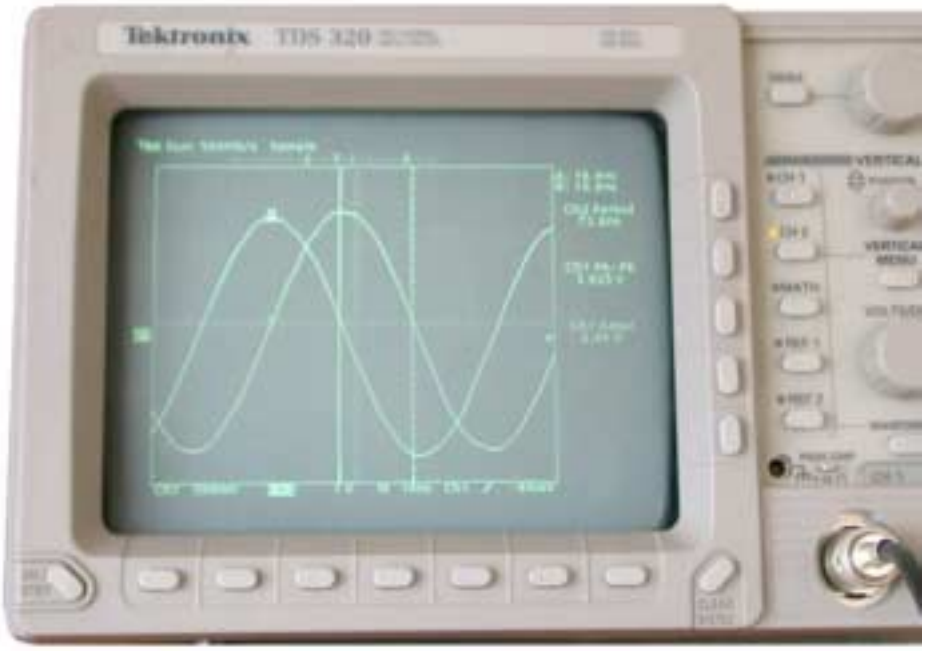


Figure 39. Scope Screen Showing the 18.4ns Offset

As a rough guide to the balance of the two antennas, an inlay should be able to be read the same distance from the back of both basic and complementary antennas

8.7 All Orientations (360º) Detection

There are a number of ways in which an antenna system can be developed to read inlays passing through a system in any orientation. We have already seen how Basic and Complementary antennas can detect inlays in all vertical orientations but for horizontal inlays, a hole always exists at centre height between the two antennas.

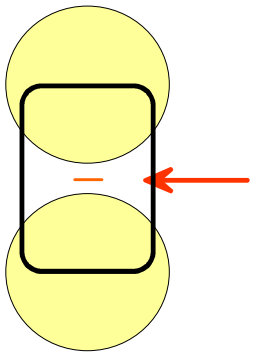


Figure 40. Reading Hole for Horizontal Inlays

If horizontal inlays need to be read, two approaches are commonly used. The first (A) is to connect a second Basic antenna (TX/RX) using a splitter and position that antenna underneath or over the conveyor system further up the track. The second (B) approach is to connect a second set of Basic and Complementary antennas using two splitters but positioned with the second set covering the hole.

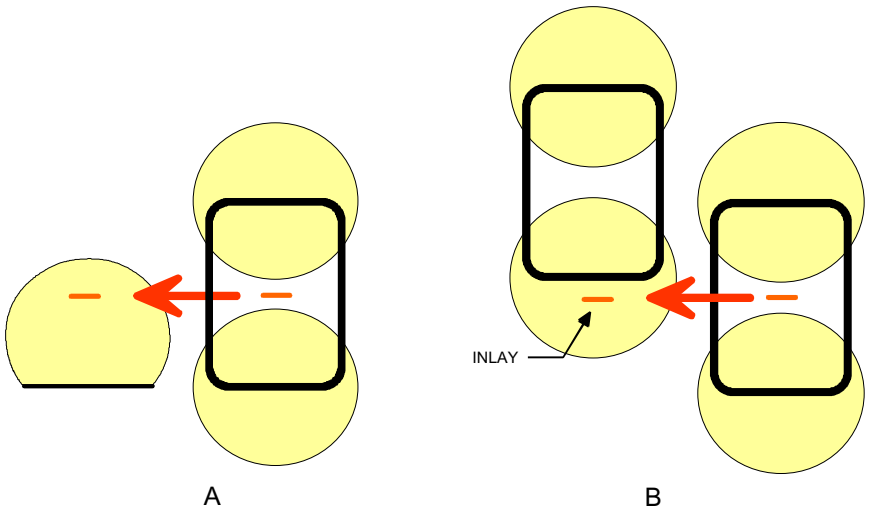


Figure 41. Removing the Reading Hole

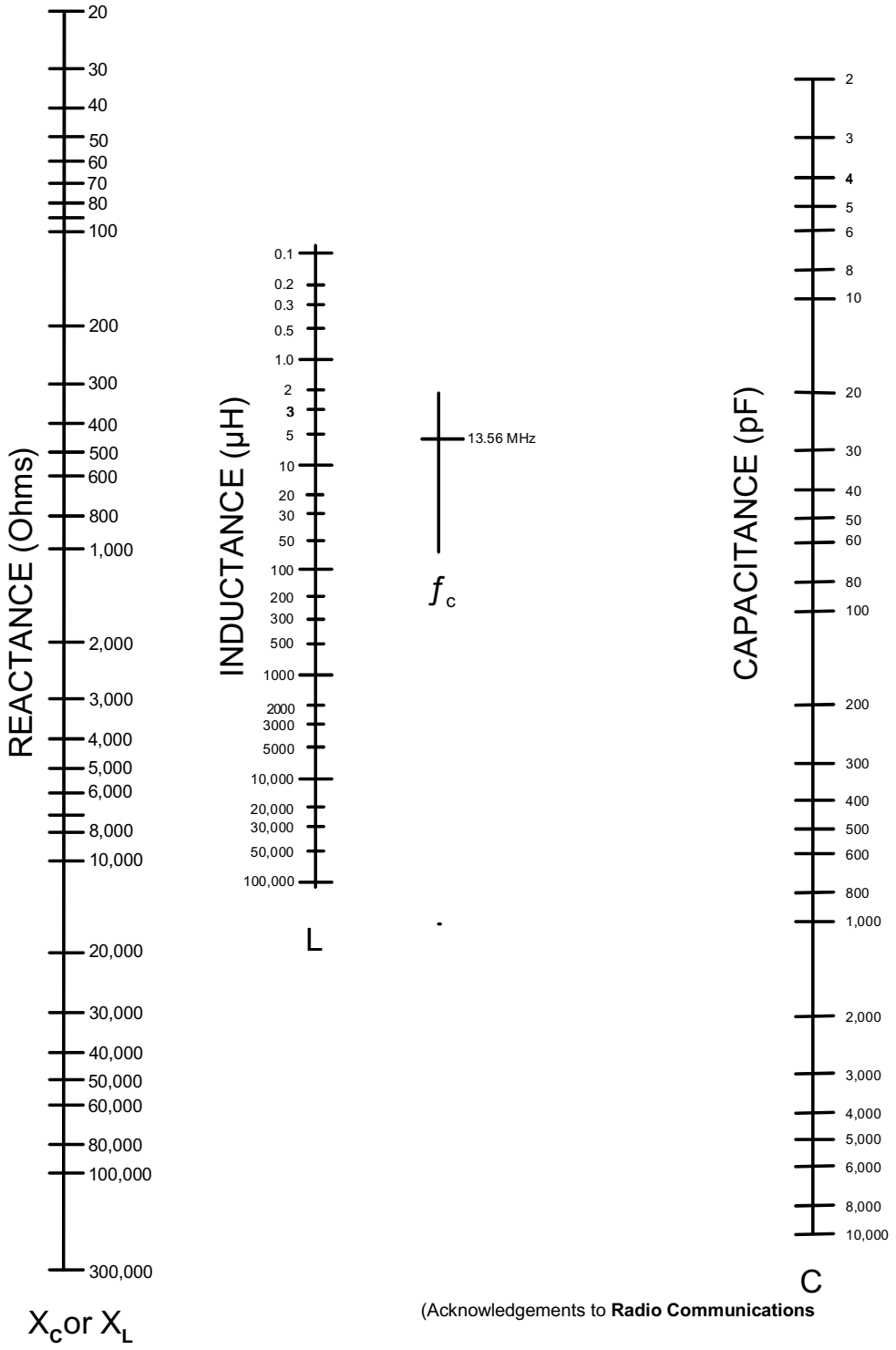
The additional antennas must be outside the RF field of the first set of antennas or the rotating effect will be destroyed

Appendix A Return Loss

Return Loss (dB)	Linear	VSWR	Transmission
40	0.010	1.020	0.000432
30	0.032	1.065	0.00432
25	0.056	1.119	0.0137
20	0.100	1.222	0.0432
18	0.126	1.288	0.0683
16	0.158	1.377	0.108
15	0.178	1.433	0.135
14	0.200	1.499	0.169
13	0.224	1.577	0.212
12	0.251	1.671	0.266
11	0.282	1.785	0.332
10	0.316	1.925	0.414
9	0.355	2.100	0.515
8	0.398	2.323	0.639
7	0.447	2.615	0.790
6	0.501	3.000	0.973
5	0.562	3.570	1.193
4	0.631	4.419	1.455
3	0.708	5.829	1.764
2	0.794	8.724	2.124
1	0.891	17.390	2.539

Table 1. Return Loss Figures

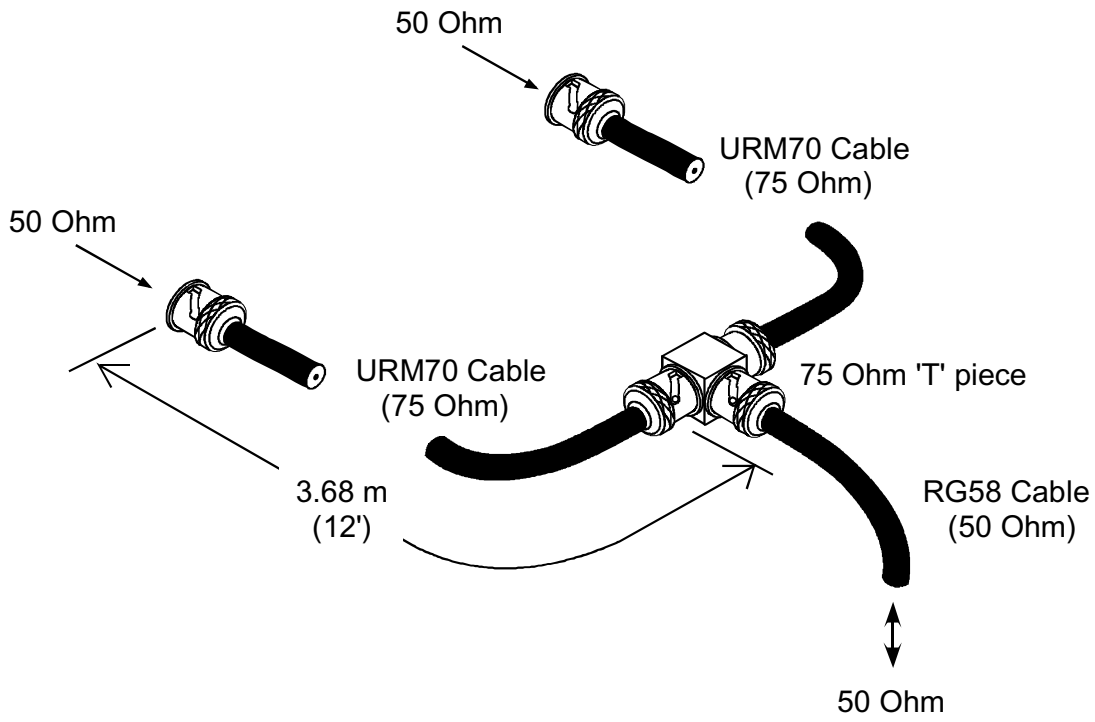
Appendix B Reactance & Resonance Chart



X_C or X_L

(Acknowledgements to **Radio Communications Handbook)**

Appendix C Coax-cable Splitter



Appendix D Component Suppliers

Component Suppliers

Capacitors

- § ARCO Electronics http://www.arco-electronics.com/
  Mica capacitors - fixed and variable.
  (UK Stockist - Mainline Electronics, +44 116 286 5373)

- § Tronser http://www.tronser.com
  Produce small value multi-turn air-gap trimmers.
  (UK Distributor - Willow Technologies, +44 1342 835234)

Thick Film Resistors

- § Vishay Intertechnology. http://www.vishay.com/products/resistors/
- § Meggitt Components http://www.meggittelectronics.com/

Ferrites

- § Ferroxcube (Philips) http://www.ferroxcube.com/
  (UK Distributor - Deltron Hawnt, +44 121 7643501

Splitters

- § **Minicircuits** http://www.minicircuits.com/products.htm

  Produce splitters for multiple antennas and rotating field antennas

Meters

- § **MFJ Enterprises** http://www.mfjenterprises.com/index.htm
  Make a range of low cost RF equipment including the MFJ-259B
  (UK distributor: - Waters & Stanton, +44 1702 206835

- § **RF Parts** http://www.rfparts.com/diamond/index.html
  Produce a range of VSWR meters including the Diamond 200
  (UK distributor: - Waters & Stanton, +44 1702 206835