Tuning Aids for the 136kHz and 500kHz Bands

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Figure 1 Resistive SWR bridge (Left), LF tuning meter (Centre), "Scopematch" (Right)

When adjusting the tuning and matching components of an LF or MF antenna, tuning for maximum output does not guarantee the transmitter is loaded by the design impedance level (usually 50Ω). Many transmitters will actually deliver greater power to a mismatched load; for example, the switching-mode transmitters widely used at LF and MF will often deliver more output power if the load impedance is reduced, but this condition will probably over-stress components in the output stage, sooner or later resulting in damage. Therefore it is essential to have some way of indicating correctly matched impedance at the transmitter output. This article describes a number of devices (Fig 1) that have been used at M0BMU for antenna match adjustment, including:

- Low-power resistive SWR bridge
- "Scopematch" tuning aid (which can also be easily converted to an SWR bridge)
- LF tuning meter

One way of determining if the impedance is correct is to use an SWR bridge, as is usually done at HF. This indicates magnitude of reflection coefficient, effectively the degree of mismatch, so antenna tuning adjustment is a matter of trial and error to reduce the mismatch to a minimum. It would be more helpful to the operator to have an indication of the relative magnitude and phase of the RF voltage and current at the transmitter output. This facilitates adjusting the antenna loading coil to resonance (voltage and current in phase), and the matching transformer ratio or loading coil tapping point can then be adjusted so that V/I = 50Ω. The first method used to do this at M0BMU was what became the "Scopematch", using a dual-trace 'scope to display the voltage and current waveforms (I think it was given this name by G3KAU). This makes tuning the antenna very quick and straightforward to do, but does need an oscilloscope; OK if you have one in the shack anyway, but not very convenient for /P operation! The LF tuning meter was conceived to perform the same function, but to be a simple, self-contained unit requiring no additional power supply. The tuning meter contains two meters; An RF voltmeter and ammeter, and a phase meter. The voltmeter/ammeter is used to determine the magnitude of the load impedance (V/I), while the phase meter indicates if the load is resonant (voltage and current in phase), inductive (+ve phase; voltage leads current), or capacitive (-ve phase, voltage lags current).

Low Power Resistive SWR Bridge

This is probably the simplest impedance mismatch indicator, and has the advantages that it requires no test equipment or calibration, yet indicates a matched condition quite accurately. It is also usable over a wide frequency range from VLF to HF. The main drawback is that the resistive bridge dissipates most of the transmitter power, so the bridge has to be taken out of circuit after tuning has been completed, and the TX power level has to be limited to a few 10s of watts if the resistors are not to become rather bulky. The basic circuit is the resistive bridge shown in Fig. 2(a). If the resistor values R1,2,3,4 are made equal to 50Ω, the RF voltage V_{out} is proportional to the reflection coefficient ρ:

$$\frac{V_{out}}{V_{in}} = \frac{1}{8}\frac{(Z_L - R)}{(Z_L + R)} = \frac{\rho}{8}$$

When $Z_L = R$, the antenna is matched, $\rho = 0$ and $V_{out} = 0$. Since a zero indication corresponds to a perfect match, the accuracy and linearity of the voltmeter are unimportant, so a simple diode voltmeter can be used to measure V_{out}. The power dissipated in the bridge resistors varies depending on what Z_L is. The maximum power dissipation in each resistor as a fraction of the total transmitter output power P_{TX} is, in theory:

$$R1: \tfrac{1}{4}\,P_{TX}$$
$$R2, R3: \tfrac{9}{16}\,P_{TX}$$
$$R4: \tfrac{1}{16}\,P_{TX}$$

Actually, the power dissipated depends somewhat on the actual transmitter output impedance, but the above is a good guide. In the circuit of Fig 2(b), 3W power metal oxide resistors are used. These are non-inductive, and can withstand considerable short-term overload. The continuous power rating of the complete bridge is 16W, and the diode voltmeter gives a usable indication to less than 1W. The meter movement is a cheap "S-meter" from Maplin (Stock number LB80B). It would be possible to add another switch to bypass the bridge when not in use, however, I felt I was more likely to forget to switch the bridge out of circuit than physically unplug the unit after tuning! Fig 3 shows the prototype.
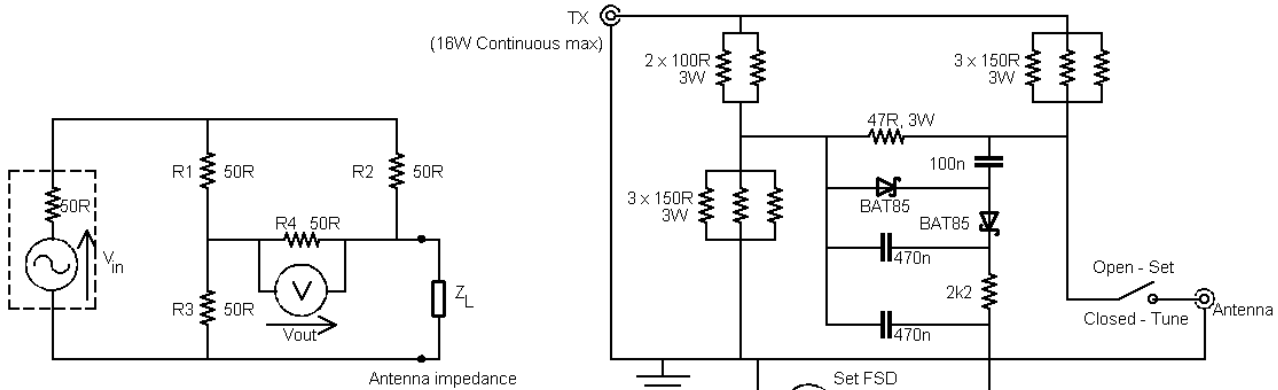

Figure 2(a)
50Ω Resistive SWR Bridge

Figure 2(b)
Practical Circuit

In use, the Set/Tune switch is first opened, a few watts of transmitter power applied, and the pot adjusted to give full-scale deflection of the meter. The Set/Tune switch is then closed to connect the antenna, and the tuning adjusted for a minimum meter reading. A meter reading of about 10% of full scale corresponds to reflection coefficient magnitude of 0.1, or an SWR of about 1.2:1, which is good enough for most practical purposes. The meter scale could be calibrated to read |ρ| or SWR, but this is not especially useful in practice. This SWR bridge is quite handy when the antenna tuner is some distance from the transmitter. The bridge can be connected in the feeder at the ATU end, and the transmitter set to produce a continuous low-power carrier while the operator goes to the ATU and makes adjustments. When taps need to be changed in the "hot" parts of the ATU, the TX power can be interrupted by switching to "Set". Because the bridge behaves effectively as a 6dB attenuator pad, the maximum mismatch that the transmitter is subject to is a reflection coefficient of 0.25 or an SWR of about 1.7:1, which is unlikely to be a problem for the transmitter, even if the antenna is grossly mismatched during tuning.
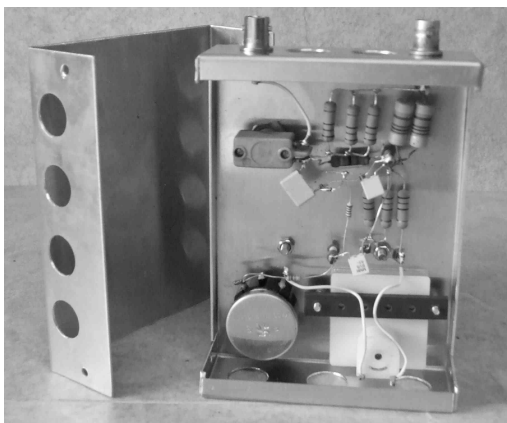

Figure 3 - Resistive SWR Bridge construction – note ventilation holes

The "Scopematch" Tuning Aid

For the first LF transmissions from M0BMU, no antenna matching indicator was to hand, so I used an oscilloscope in the improvised set-up of Fig 4(a). The 10:1 scope probe displays the voltage waveform, while the toroidal transformer current probe displays the current waveform at the TX output. For a resistive load, voltage and current waveforms are in phase. If the load is reactive, a phase shift is visible. The magnitude of voltage and current read from the screen enable the magnitude of the impedance to be calculated; correct matching has been achieved when V/I = 50Ω and phase shift is

zero. Transmitter output power can also be determined by multiplying V and I. This arrangement proved convenient and easy to use, so it was made more permanent by building voltage and current probes into a box that could be left connected in the antenna feeder. The unit was originally built for 136kHz, but also works fine on 500kHz.
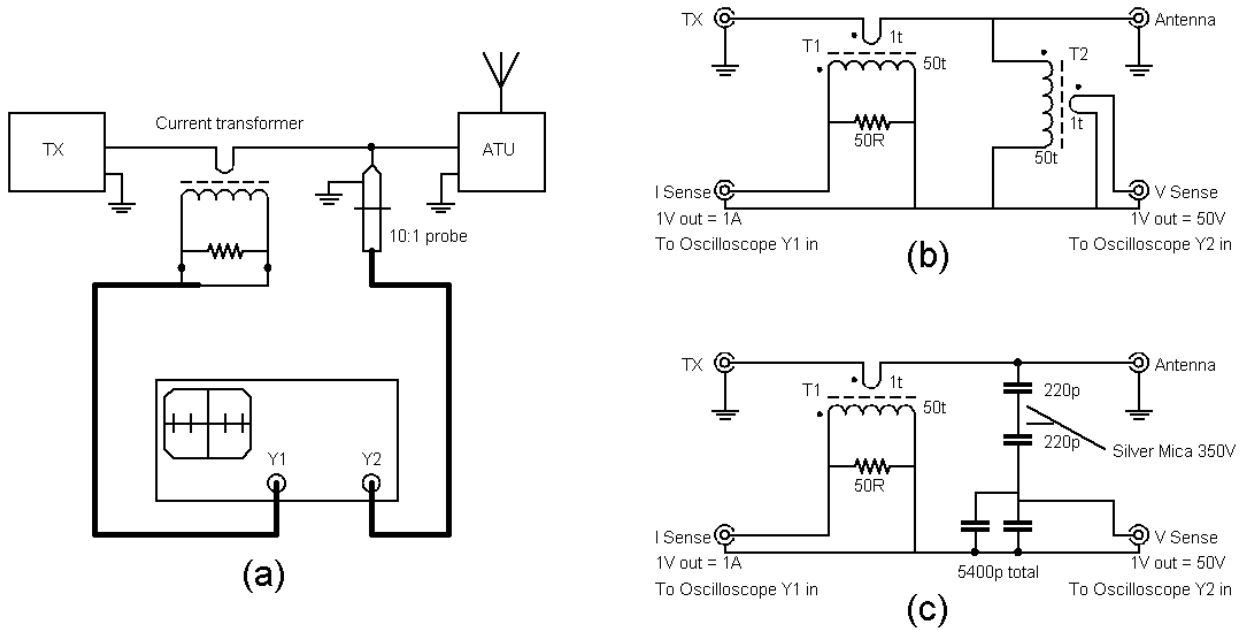

Figure 4(a) improvised antenna tuning indicator
(b) Scopematch with voltage divider transformer; (c) with capacitive voltage divider

Figs 4(b) and (c) shows details of the "Scopematch" box. The primary of the current transformer T1 is a single turn consisting of an insulated wire passing through a toroidal core. The multi-turn secondary must have enough turns to make the impedance of the winding much larger than the load resistance at the operating frequency. Any toroid core onto which the winding will fit, and with A_L greater than a few hundred nH/turn should be OK for T1. The prototype used an 18mm diameter core with μ about 5000, and A_L about 4uH/turn. The output voltage to the 'scope input from the current transformer is $V = I.R/N$, where I is the feed line current, R is the current transformer load resistor, and N is the number of secondary turns. It is convenient to make $R = 50\Omega$, and $N = 50$ turns, giving a scale factor of 1V = 1A. If the division ratio of the voltage divider is now made 50:1, then with a 50W load and the same volts/division setting on each 'scope channel, the voltage and current output waveforms will have the same amplitude. This makes it very easy to see if the antenna load resistance is correct; voltage waveform larger than current waveform means impedance >50Ω, voltage smaller than current means impedance <50Ω.

Two types of voltage divider have been used, an additional 50:1 transformer T2 (Fig 4(b)), or a capacitive divider (Fig 4(c)). For relatively low powers, a similar toroidal core and winding as T1 can be used for T2 in Fig 4(b), except now the 50 turn winding is connected between the feed line and ground, and the voltage output is taken from a single wire looped through the core. For higher powers, greater than 100W say, care is required in the transformer design, because the full RF voltage is applied to the 50 turn winding. As well as requiring good insulation of the winding, the applied voltage can lead to high flux density and large losses in the core. The peak flux density B_{pk} is given by:

$$B_{pk} = \frac{V_{RMS}}{4.44\,fNA_e}$$

Where f is frequency in Hertz, N is the number of turns and A_e is the effective cross-sectional area of the core (in *square metres*, ie area in mm^2 x 10^{-6}). B_{pk} is inversely proportional to frequency for a given inductor, so operation at 136kHz, which also tends to require higher power and therefore higher voltage, will normally be the limiting factor. A maximum flux density of about 100mT will keep the temperature rise reasonably low. For transmitters in the 1 - 2kW range, over 300V RMS could be present. Using a 50 turn winding, a cross-sectional area of about 100mm^2 is needed, which requires a rather large toroid core. It would be possible to reduce the flux by increasing the number of turns (say 100:2 turns), but this is tedious to wind and requires a bigger core anyway. A better solution is to use a pot core for T2; an RM10 core in a "power" grade of ferrite has a cross-sectional area of about 96mm^2 and is easier to wind. Practically all RM10-sized cores intended for power applications (with no air gap and no tuning slug) are a suitable grade of ferrite (3C85, N87, etc.). I used kynar-insulated wire-wrapping wire for the 50 turn primary as this has quite good insulation compared to normal enamelled wire.

A simpler solution is to use a 50:1 capacitive voltage divider. Although the output impedance is high compared to the transformer, in practice it will only be loaded by the oscilloscope input, and the stray capacitance associated with the

connecting cable, about 100pf for a 1m long cable. The capacitive divider in Fig 4(c) uses two capacitors in series in the high potential leg, due to the fairly high RF voltage present.
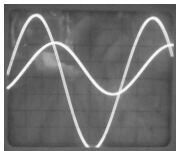
Examples of oscilloscope displays seen using the Scopematch
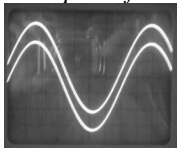
 Load 50Ω, resistive – V (upper) and I (lower) waveforms are in phase and equal magnitude
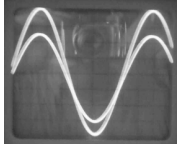
 Resistive Load; load is resonant, but V greater than I, so resistance >50Ω (about 80Ω here)

 I > V, and V lags I in phase, so a capacitive load of magnitude < 50Ω (about 20Ω here)

Converting the "Scopematch" to an SWR bridge

The Scopematch has an obvious resemblance to the Bruene-type SWR bridge with the detectors omitted. A diode detector can easily be added, as shown in Fig 5. Compared to the resistive bridge described above, this circuit has the advantage that it dissipates very little power, and so can be left in line to monitor antenna matching during transmission. With the switch set to "FWD", and a carrier output from the TX, the meter is set 100% FSD. The switch is then set to "REV" to read reflection coefficient while the antenna tuner is adjusted. A breadboard version of the circuit in Fig 5 had sufficient adjustment range for powers between about 10W and 800W. With a fixed meter resistor, it would be possible to calibrate the meter to read TX output power in the "FWD" position. For lower power levels, it would be an advantage to change the voltage divider and current transformer ratios to 20:1, to provide more RF drive for the diode detector.
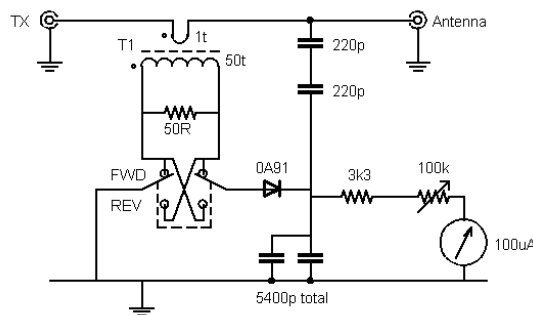

Figure 5: Bruene-type SWR bridge using "Scopematch" components

LF Tuning Meter

The LF tuning meter was designed to provide similar functionality to the "Scopematch", but in a compact, stand-alone unit. It has two meters, one indicating phase, while the other can be switched between measuring RF voltage and current, allowing the magnitude of the load impedance and the TX output power to be determined. The circuit diagram is shown in Fig 6.

RF Voltmeter / Ammeter section

The RF voltage is measured by a simple diode rectifier voltmeter (D11, D12), driven from a divide-by-21 capacitive voltage divider. A toroidal current transformer T3 is used with another rectifier (D7 – D10) to measure current. "Hi" (300V, 6A) and "Lo" (100V, 2A) voltage and current ranges are provided, which makes the meter usable over a range of about 20W to 200W(Lo range) or 200W to 1.8kW(Hi range) transmitter power. The voltage and current scales are chosen so that the voltage scale is 50 times the current scale FSD. Therefore, with a 50Ω load connected, the same deflection is seen on the meter scale when the meter is switched between voltage and current measurement. In a similar way to the "Scopematch", this means the operator can immediately see if the load is matched to 50Ω (V/A readings equal deflection), greater than 50Ω (V>A), or less than 50Ω (V<A), without performing any mental arithmetic, and also without requiring any additional device to calculate and display the resistance.

Phase Meter section

A classic technique to measure the phase difference between two signals is first to phase shift one signal by 90^0, then clip the signals to a constant amplitude square wave (to make the measurement independent of signal amplitude) and apply the signals to the inputs of a balanced mixer. With square wave signals applied to the mixer, the output consists of

a DC level with a voltage proportional to the phase difference over the range -90^0 to $+90^0$. For the tuning meter, one input signal is a sample of the transmitter output voltage from a potential divider. The other input is a sample of the transmitter output current from a current transformer. This system provides a nice phase measurement, but gets quite complicated. However, in practice we only need to determine if the phase is zero, positive or negative, so we can accept reduced measurement accuracy in exchange for drastically reduced complexity. In this circuit, the voltage is sampled by the network consisting of 2 x 470pF capacitors and the 82 ohm resistor shunted by a pair of back-to-back Schottky diodes, D1,D2. This provides a reasonably square waveform of fairly constant amplitude over a wide power range, phase shifted by 90^0. This signal is applied to a balanced diode mixer (D3 – D6), which is driven by a sample of the load current obtained from the current transformer T1. Although the current driving the mixer varies widely, it is sufficient to saturate the mixer over a wide range also, so quite a wide variation of transmitter power does not affect the mixer gain greatly. The DC output from the mixer is measured by a centre-zero meter to indicate the phase. Since the mixer output is zero when voltage and current are in phase, there is very little error in the indication of zero phase shift over a wide power range – in the prototype unit, zero degrees phase was accurately indicated with transmitter powers between 20W and 1200W – at power levels below about 20W, there is a substantial reduction in meter deflection when the load impedance is inductive or capacitive, but the sign of the phase reading is still correct, which is all that is required for tuning an antenna. At 1W level, the zero phase reading is still only in error by a few degrees.
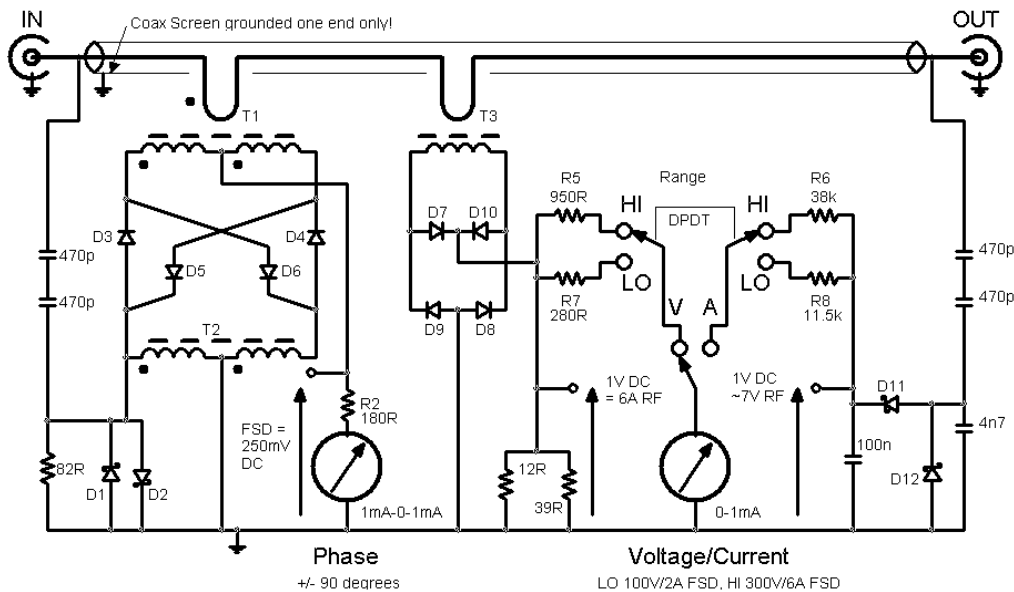

Figure 6: Tuning meter circuit diagram

Components and Construction
The prototype tuning meter is shown in Figure 7; the part numbering below corresponds to the circuit diagram in Figure 6. The clipping diodes D1, D2 are BAT85 Schottky switching diodes, and limit the input signal to about 500mV pk-pk, i.e. less than the forward voltage drop of the junction diodes used in the mixer. 1N5819 small Schottky rectifier diodes also worked well, with slightly lower V_f, which reduces the DC output from the mixer somewhat. RF-type Schottky and germanium diodes will not work well in this application – their current-carrying capability is too small.

The mixer diodes D3 – D6 are a matched quad of 1N4148s. Matching is critical so that a significant error does not occur in the zero-phase reading. Fortunately, this can be easily done using the "diode check" range on most digital multimeters. Pick several diodes from the same production batch – usually if you buy some diodes, they come on tape "bandoliers", and you can be pretty certain they come from the same batch. Check the forward voltage drop of each diode with the multimeter, taking care that they are all at an equal temperature by only touching them with the meter leads, and doing the job reasonably quickly. Pick the 4 diodes with the closest matching V_f, which should be within a few millivolts of each other. Diodes selected at random can easily have V_f differing by 50mV or more, which will result in large phase measurement errors. I tried this matching procedure with batches of 1N4148, 1N914 and 1S44 switching diodes, all with satisfactory results in the phase meter circuit. D7 – D10 can also be 1N4148 or other small switching diodes – matching is not critical. D11 and D12 are BAT85 Schottky diodes for low forward voltage drop – germanium signal diodes should also work well. Note that D3-D6 are connected as a "rat-race", but D7-D10 are in a bridge rectifier connection.

The 470pF capacitors must be stable and withstand the full RF output voltage from the transmitter. Silver-mica units were used. The 4.7nF was polystyrene. The transformers are all wound on some high-permeability ferrite cores about 22mm diameter of unknown origin, probably from a pulse transformer in a SMPS. They have A_L of about 4000nH/t, and permeability is about 5000. The RS components 232-9561, 212-0910 and numerous others should be suitable. Power handling is not important, but if lower permeability material is used, the reduced inductance could cause problems with unwanted phase shifts. The winding details are as follows:

T1: Primary is RG58 coax passing through core. Secondary 2 x 25t Bifilar 0.3mm enamelled Cu .
T2: 2 x 50t bifilar 0.25mm enamelled Cu.
T3: Primary is RG58 coax passing through core. Secondary 50t 0.5mm enamelled Cu.

The coax links the input and output sockets, and T1 and T3 are threaded on to the coax in the usual SWR-bridge style. Make sure you ground one end only of the coax braid!
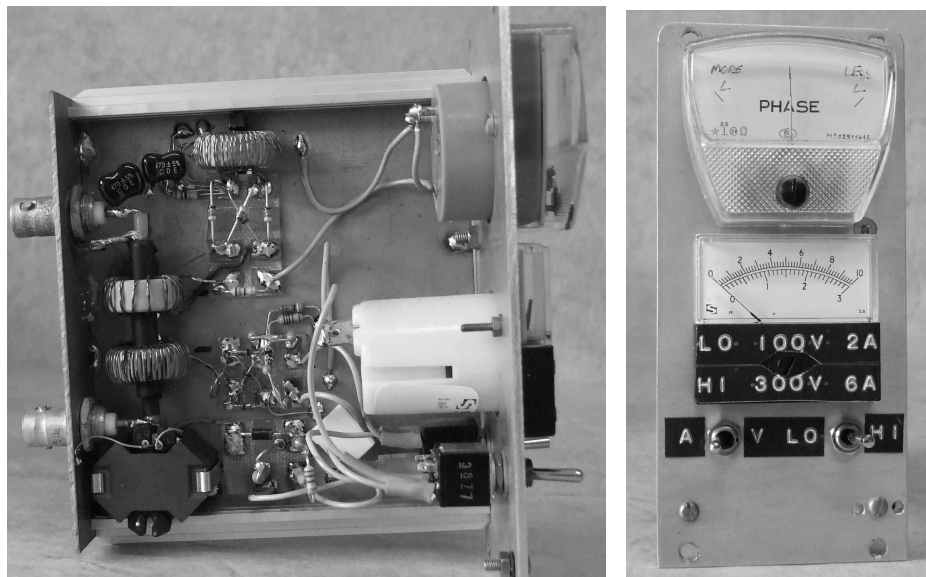

Figure 7: LF tuning meter – this version incorporates the modifications described below for dual-band 136kHz/500kHz operation

The meters and range-setting resistors will depend on what you have in the junk box, and what transmitter power is to be used. I had a 1mA-0-1mA meter marked "phase", so I used it for the phase meter... meters of higher sensitivity can also be used by increasing the value of R2. The resistor value should give full-scale deflection of the meter with a mixer output of around 250mV, but this will vary slightly with different diodes and so on – accuracy is not critical, however, since we are mainly just interested in the sign of the phase. Similarly, for the voltmeter/ammeter section, I had a 1mA meter with 0-3 and 0-10 scales available, so the voltage and current scales used reflect this and the range of transmitted power I expect to be using. R5 and R7 set the current scales, and can be calculated from $R = (I_{RF}/I_M)/6$, where I_{RF} is the full-scale RF current, I_M is the full-scale meter current in amps. The meter coil resistance must be subtracted from this (50Ω for the particular meter used). The voltage range resistors R6 and R8 are given approximately by $R = (0.134 \times V_{RF} - 1)/I_M$, where V_{RF} is the full-scale RF voltage. If facilities are available to calibrate the voltage and current ranges, presets could be used instead of fixed range setting resistors. "Hi" and "Lo" ranges were provided to extend the useful power range of the unit; this is obviously not necessary if a fixed transmitter power is to be used. The rectifiers, particularly the voltage-sensing rectifier, become less accurate at low power levels due to the effect of finite diode forward voltage drop, but at the 20W level, the error in the prototype was less than 5%. If the unit were to be used with a QRP transmitter, it would be a good idea to change the division ratio of the capacitive potential divider to supply a higher signal voltage to the rectifier.

Testing and Use
With the unit connected between a transmitter and non-reactive dummy load, the phase meter should read zero within a few percent of FSD for power levels of a few watts or greater. Small errors can be trimmed out using the mechanical zero adjustment on the meter. With the transmitter set to a low power output, connect a capacitor of about 22nF in place of the dummy load. With about 30V or more RF voltage from the transmitter (but with output kept low enough not to damage transmitter or capacitor!), the phase meter should read close to negative full scale – adjust R2 if required. If the meter reads positive instead of negative phase, this can be corrected by reversing the connections of the secondary of T1, or by reversing the meter connections. The voltage and current ranges can also be checked and adjusted – it is not vital that the readings have high absolute accuracy, but the range setting resistors should be adjusted so that the meter deflection is the same when the meter is switched between V and A with a 50Ω load connected, since this makes it easy to tell whether the antenna is correctly matched, as explained previously.

In use, select the "Hi" or "Lo" range to suit the power level in use. Apply some transmitter power to the antenna, and note the phase meter reading. If the phase is negative (capacitive), increase the loading coil inductance, and reduce the inductance if the phase is positive (inductive). When zero phase is obtained, switch between "V" and "A" ranges. The ratio V/I is the resistance – if it is greater or less than 50Ω, as indicated by the meter deflections not being equal, adjust the matching transformer, loading coil or whatever matching system you are using as appropriate. If the "V" deflection

is greater than the "A" deflection, adjust to give a reduced load resistance; if "V" is less than "A", adjust for a higher load resistance. The transmitter output power when the load is resistive is VxA.

Operation on the 500kHz Band

When the 500kHz band was introduced, I was quite pleased to find that the original 136kHz tuning meter design actually worked fairly well on 500kHz without modification. The phase meter has a zero offset equivalent to a couple of degrees, but this is not practically important. The voltmeter was reading high by about 10% on 500kHz. Also, there was significant non-linearity at low voltages, which was unimportant on 136k due to the higher power levels used, but which was more noticeable with lower powers on 500kHz. Investigation showed both these effects were due to loading of the voltmeter diode detector by the 1mA meter movement. One solution would be to substitute a more sensitive meter movement (50 or 100µA) and increase the values of the scale-setting resistors suitably. However, I wanted to retain the existing meter. Instead, the voltage level at which the diode detector operates was increased, allowing the use of a higher impedance meter circuit, and the source impedance of the voltage divider reduced. This was achieved (Fig 8) by replacing the 21:1 capacitive voltage divider with an auto-transformer with about 3:1 ratio, and using a 600V "ultra-fast" rectifier diode instead of the original switching diodes D11, D12. The maximum DC output of the voltmeter rectifier is now about 150V, and the scale factor approximately 1V DC = 2V RMS RF. The modified voltmeter circuit shows almost no variation between 136kHz and 500kHz bands. It would also be possible to connect a diode rectifier directly to the feed line, but at the maximum power level, the rectified DC voltage is inconveniently high at several hundred volts. For power levels below a few hundred watts however, this approach would eliminate the transformer.
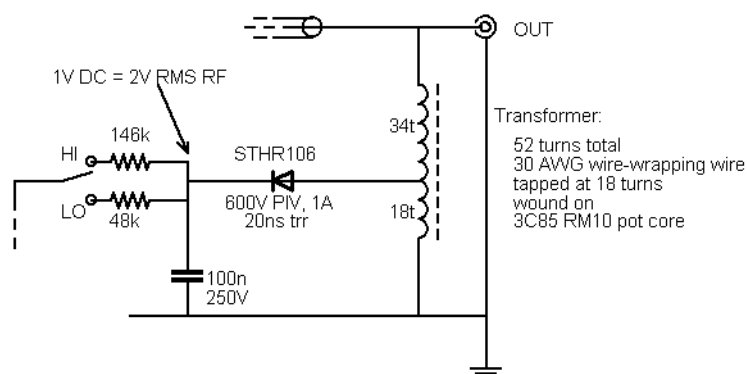

Fig 8: Modification to LF tuning meter to improve voltmeter accuracy for 136kHz/500kHz use

8th July 2009 - Version 2. Expanded to include:
      Operation of LF tuning meter on 500kHz band
      Additional sections on SWR bridges and "Scopematch"

Originally titled "LF Tuning Meter for the 136kHz Band", 29 April 2003