UHF aerial analysers, and Wheatstone's wonderful bridge

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On the day *Amateur Radio* (May 2005) published my design for a HF aerial analyser, ham friends started asking me for construction details of a VHF/UHF unit. In trying to satisfy these requests, I've had some fun and learnt a lot, and a design has evolved that is startlingly simple and works well. If you have a reasonable junk box, you should have most of the bits already.

Anyone who has done formal electronics training will be familiar with the Wheatstone bridge. Somewhere, early in the course, a diagram is drawn complete with battery and sensitive galvanometer, and it is carefully explained how to measure resistance by "balancing" the bridge. Complex mathematics are used to demonstrate this, and then the whole subject is quickly dropped because "modern" electronics can be used to measure resistance far more conveniently. The quite clear implication which emerges is that, apart from the odd specialist application, this old DC measurement technique belongs in the 19th century and should be forgotten.

In fact, nothing could be further from the truth.

With AC applied to the bridge, and some more complex mathematical analysis (which the author has yet to see in any text), the bridge can be used to measure SWR very accurately over an enormous frequency range; and without any of the problems of frequency and power sensitivity shown by almost any other SWR bridge design. Even better, only readily available components are used.

The Theory

In the circuit shown in Figure 1, imagine that the load is a pure resistance of 50 Ω. The AC voltage appearing at both points A and B (V_A & V_B) will be 0.5 V RMS. After half-wave rectification, V_A becomes V_1 = 707 mV DC. Similarly, V_B becomes V_2 = 707 mV DC, assuming perfect diodes (no turn-on voltage). V_3 is the rectified version of the voltage difference between A and B, and because V_A and V_B are in phase and of equal magnitude, $V_3 = 0$.

Now make the load an open circuit. V_A will still be 0.5 V RMS and V_1 still 707 mV DC. V_B will be 1 V RMS and so V_2 will be 1.414 mV DC. V_3 will be 707 mV DC because the difference between V_A and V_B is now 0.5 V RMS.

Finally, short the load terminals. V_1 will remain at 707 mV DC. V_B will be zero as will V_2, and V_3 will be 707 mV DC because the difference between V_A and V_B is again 0.5 V RMS.

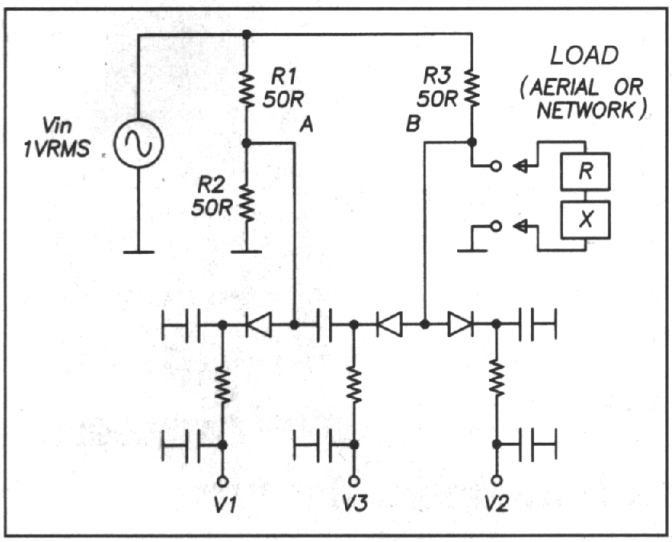

Fig 1 – The Wheatstone bridge for AC.

Summarising, the voltage at A and therefore V_1, did not change with the load. The voltage at B, and therefore V_2, rose from 0 to 1.414 mV as the load was varied from zero to an open circuit. The voltage V_3 dropped from 707 mV (load shorted – SWR infinite) to zero (50 Ω load - SWR=1) and then rose again to 707 mV with an open circuit load (SWR infinite).

What we have just described is how an SWR meter works. V_1 represents forward power, V_2 represents reflected power and V_3 represents the difference between the two, or SWR.

Taking all this a little further it is easy to see that for a known value of input voltage, V_2 can be used to produce a resistance scale on a meter while an SWR scale can be produced from V3.

But so far we have only talked about purely resistive loads. What happens when the load is a complex mixture of resistance and capacitance, resistance and inductance, or pure capacitance or inductance?

To answer these questions requires really heavy-duty mathematics and frankly is beyond the scope of this article.

Suffice to say that the maths clearly shows that, irrespective of whether the load is complex or purely resistive, the indicated SWR will be correct and the SWR scale can simply be produced by using purely resistive calculations.

For those who would like to personally demonstrate this for themselves, I have included two vector diagrams from which the appropriate mathematics can be derived. Figure 2 is for the general case of a complex load, whilst Figure 3 is for the special case of a purely capacitive or inductive load.

The diagrams are constructed as follows. Because Vin is always the hypotenuse and the voltage across the resistive and reactive components must always have a

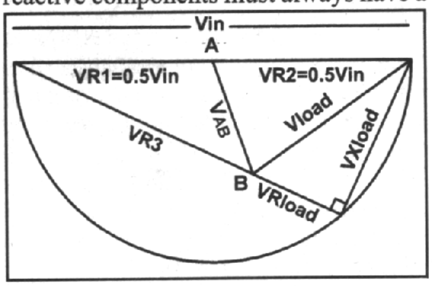

Fig 2 - Vector diagram - general case.

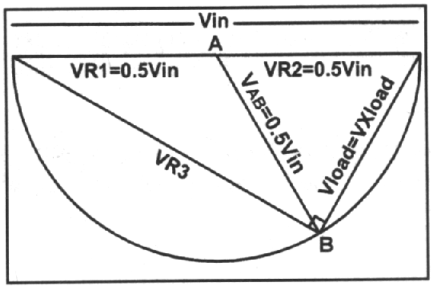

Fig 3 - Vector diagram - pure inductive or capacitive load.

90 degree phase relationship, from simple trigonometry the intersection of the resistive and reactive vectors must always be on a semicircle of a radius Vin/2. In the case of a purely reactive load this leads to the remarkable conclusion that the difference voltage VAB is constant at Vin/2 (irrespective of the size of capacitor or inductor). This is correct, as the SWR for a purely reactive load will always be infinite, which Vin/2 represents.

Not surprisingly, the meter scale produced from V2 for resistance is not accurate for complex loads. But it is also clear that, for any complex load comprising a known value of resistance in series with a reactance, the voltage indicated for this load will always be higher than the voltage indicated for that value of resistance alone, because the overall load impedance is higher. Putting this another way, the indicated voltage will always be minimum when an antenna is at resonance and therefore purely resistive, and the resistance scale then reads correctly. On either side of resonance the voltage will rise because of the reactive term which is introduced. We can use this observation very practically by noting what happens to the indicated resistance as we vary frequency and this idea is covered in greater depth later in this article.

Other conclusions which emerge from studying this circuit are:

(a) The generator never sees an SWR of greater than 2:1 (with an open circuit load) and so there is no chance of doing serious damage to a driving source due to high SWR.

(b) This is a measurement instrument not an SWR meter, because three quarters of the applied power is lost in the measurement network (instead of radiating from the aerial). Furthermore, because of the need to use non-inductive low power resistors, it is a low-power animal (2 watts maximum) and cannot be left permanently connected as a monitor in a transmission line.

(c) In order to make the forward voltage drop of the diodes negligible, fairly large

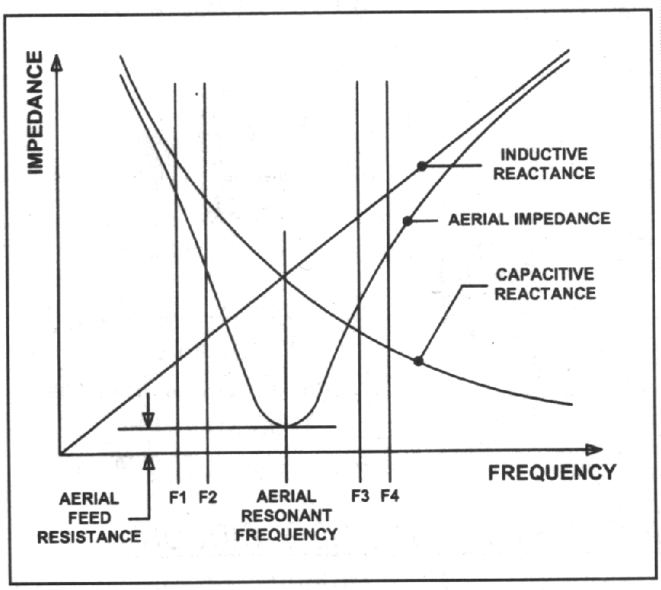

Fig 4 – Impedance, reactance, resonance chart.

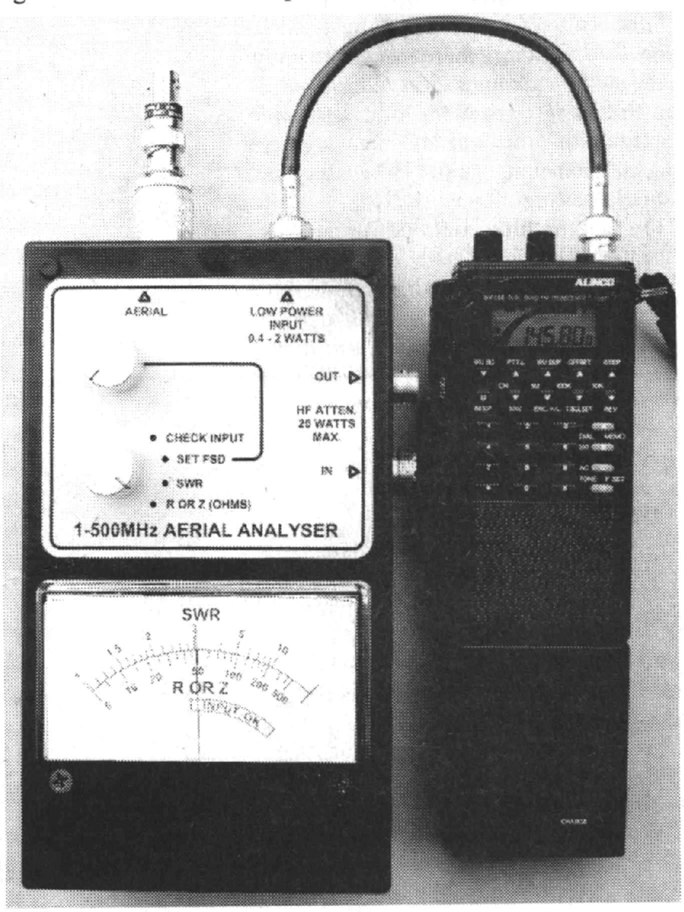

Photo 1 – The analyser with a handheld as signal source.

driving voltages must be used. Further, if the bridge is to function well at 70 cm, only Schottky barrier diodes can be used with their great speed and low forward voltage drop (approx. 200 mV). In fact, the meter scale (see Figure 6) includes the effects of diode forward voltage drop.

The Practical Analyser

Constructors of the previous HF analyser were so happy with its performance that they soon began demanding an instrument that covered 6 and 2 meters, and also hopefully 70 cm. It also had to be cheap and easy to construct! This is a brutal design requirement. After a whole lot of research, two things emerged. First, frequency pre-scaling ICs which work to 500 MHz are not readily available unless you are prepared to order in quantities of at least 1000, and so an LCD frequency display derived via a microprocessor is just not on. Second, the design and construction of a "flat" high-power driving source (say 1 watt from 30-500 MHz) was going to be an expensive nightmare and also (third) very heavy on battery use.

How to overcome these three obstacles? Simple: use the amateur's hand-held radio (with its frequency display) as the driving source. The result is a cheap and basic instrument with no batteries which does all the things an amateur needs to design and tune a resonant aerial system.

The last part of the exercise is designing the test network to be purely resistive. This is not simple because all modern resistor types have built-in inductance due to the laser spiralling used to adjust their value to within tolerance.

Some careful measurements were made on standard ¼ watt metal film resistors with zero lead lengths to establish whether their self-inductance was negligible at 70 cm. Sadly, this is not the case and even placing three units in parallel to reduce the effective inductance by a factor of three (and also increase the power rating), does not help much either. But the technique does work at 2 metres and so two versions of the Analyser have been created.

Version 1 works accurately to 150 MHz and uses standard ¼ watt metal film resistors. It is for those constructors who don't feel confident about using surface mount components. Version 2 uses 1206 type ¼ watt surface mount resistors in the bridge and works to 500 MHz accurately.

Use a type N connector for the aerial circuit if the unit is for UHF applications. SO239/PL259 connectors have high dielectric losses, high capacitance, and poor impedance matching at 450 MHz, and will cause very significant errors on the resistance scale (around 15%) even with no load on the instrument. The much lower capacitance of the type N connector will still cause slight FSD errors on the resistance scale at 70 cm, but this capacitance is swallowed in the 50 Ω line when a load is connected to the Analyser. The losses and mismatch of a SO239/PL259 connector are not! If a SO239 must be used, find one with clear plastic insulation, not light brown bakelite!

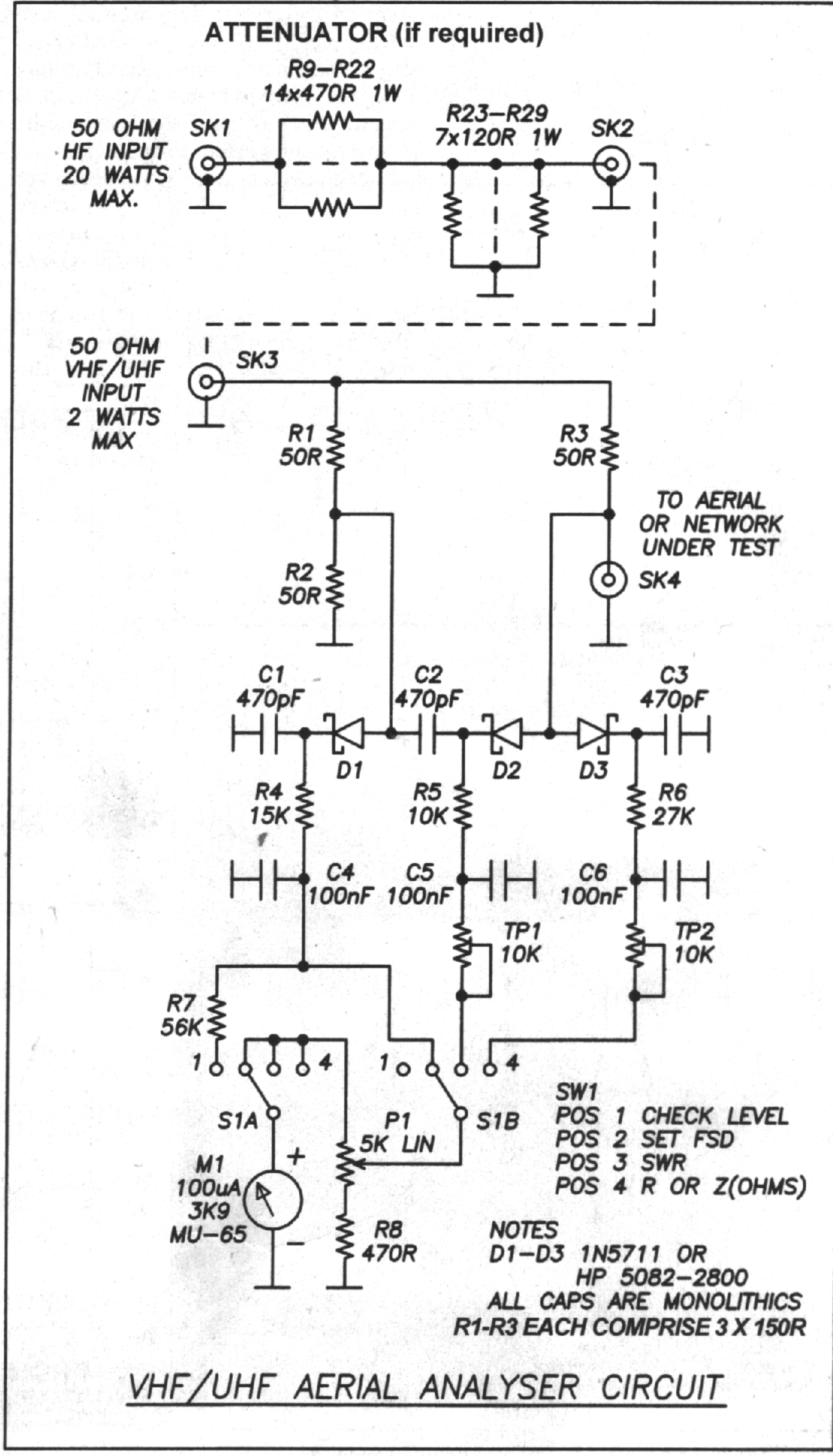

Fig 5 – Aerial analyser schematic.

The final part of the design is a power attenuator so that, for HF measurements, a standard HF transceiver at low power can be used as the signal source. Constructors may wish to omit this feature from the instrument if they have already built, or possess, an HF aerial analyser.

Construction

Make the PCBs first. The steam iron/ clay paper method works well (see *www.users.on.net/~endsodds*). Artwork is included for the connector PCB (Figure 11), the Version 1 or 2 main PCB (Figure 12 or 13), and if required, for the attenuator connectors (Figure 10). Drill all holes and lightly solder-coat the PCB copper surfaces using a neutral paste flux and your soldering iron. Clean all surfaces with methylated spirits.

Complete all mechanical work on the case. In order to mount the PCBs, some of the case reinforcing ribs must be completely removed (a wood chisel is good for this). The front panel drilling details are given in Figure 7. Use the PCB (Figure 11) as a template to mark out the connector holes in the top of the case, and if the attenuator is included, mark out its connector holes in the side from the PCB defined in Figure 10.

Finish the PCBs. If you are using surface mount resistors in the bridge, mount them first. Very lightly coat the area where the resistors will be mounted with a neutral paste flux, and then hold the first resistor across its width with tweezers. Place it in position and lightly tack one end to the PCB using minimum solder. Repeat for all nine resistors. Firmly solder the other ends, allow to cool, and then re-solder the tacked ends using fresh solder. Remove all flux with methylated spirits and blow the PCB dry with hot air (hair dryers are great). Then, following the schematic (Figure 5) and the layout diagram (Figure 9) mount all other components. See, it wasn't really painful.

Solder the brass nuts to the connector PCB using steel screws to temporarily hold the nuts in final position. Mount all connectors, and then solder the connector and component boards together at right

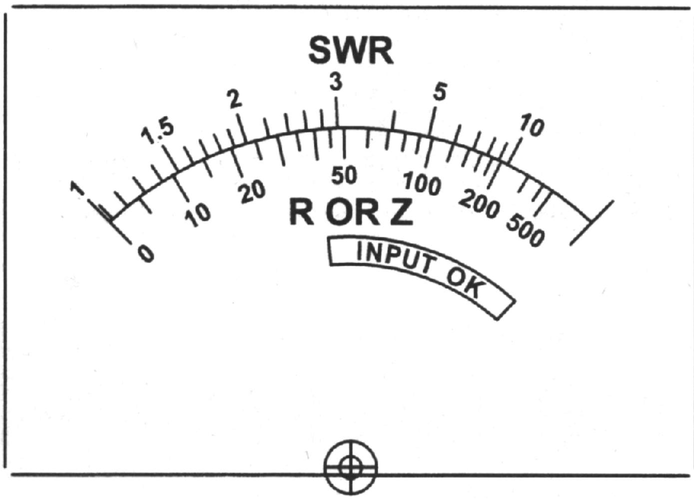

Fig 6 – Meter scale (exact size).

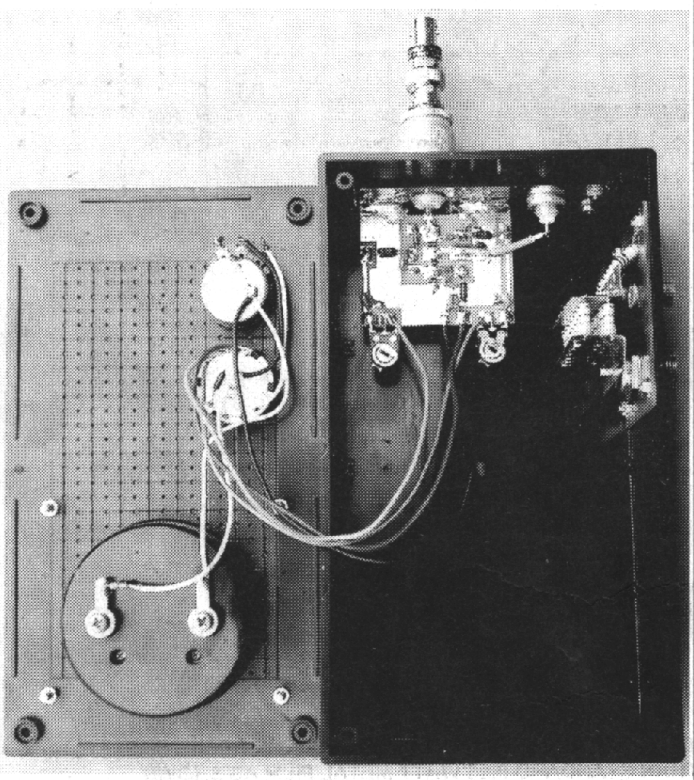

Photo 2 – Construction details with case open.

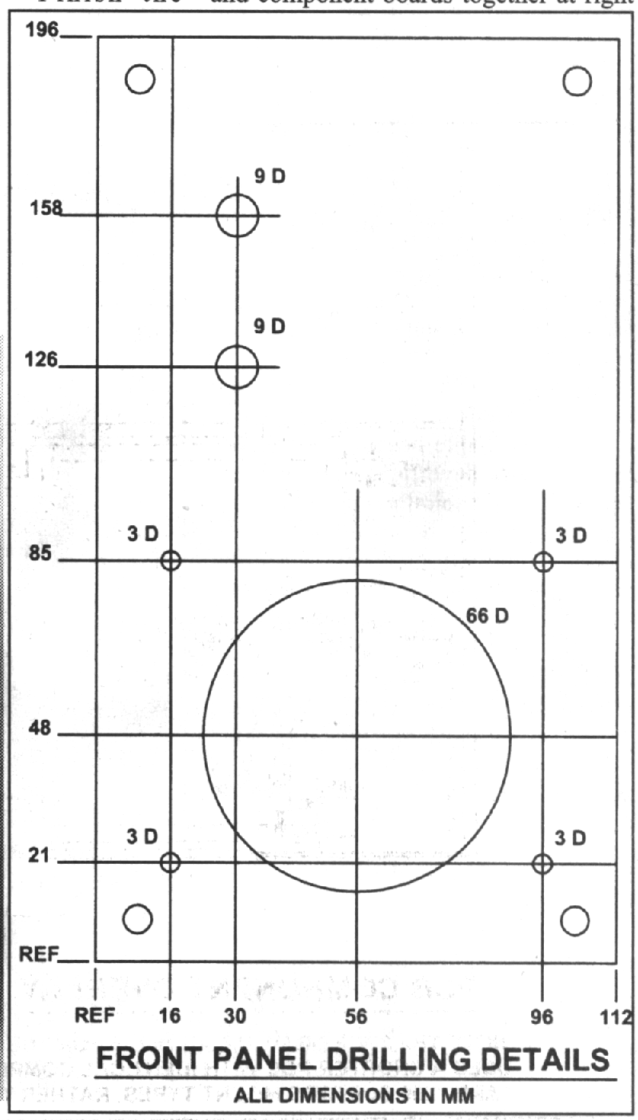

Fig 7 – Front panel drilling template.

angles. The completed assembly is shown in Figure 9. Use plenty of solder in the fillet. Make the final connection between the component board and input BNC connector using Teflon insulated miniature 50 Ω coaxial cable. If the HF attenuator is to be included in the instrument, assemble it as shown in Figure 10. Install everything in the case and complete all other wiring as per Figure 9 and Photo 2.

Then, modify the meter. In a very clean working environment remove the plastic faceplate and the screws which retain the metal scale. Turn the scale over and carefully cover the rear surface with thin double-sided adhesive tape. Photocopy the meter scale (Figure 6) onto heavy-weight glossy paper and carefully cut around its perimeter with a very sharp hobby knife. Stick this scale to the rear of the existing metal scale. Trim up with your hobby knife and reassemble the meter.

The final task is to install the front panel label which is provided in Figure 8. Follow the same procedures as for the meter scale.

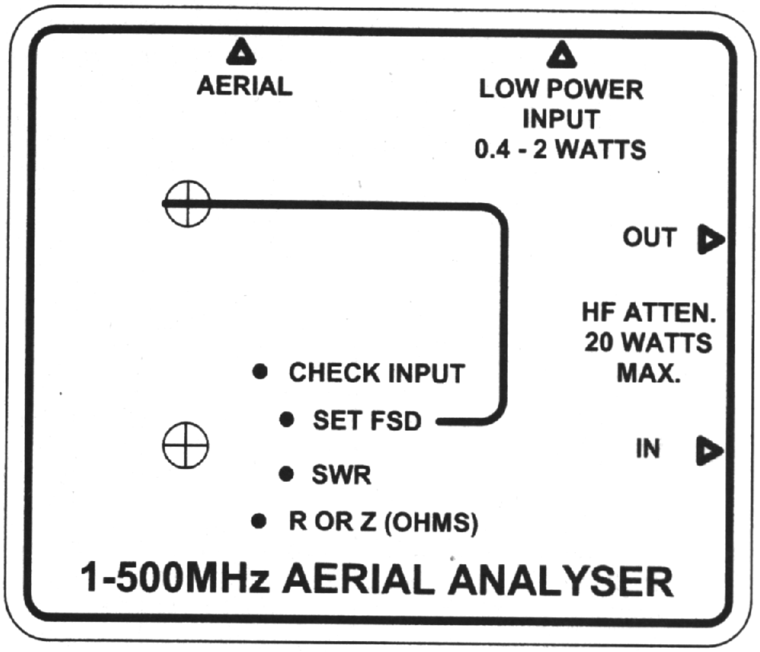

Fig 8 – Front panel label (exact size).

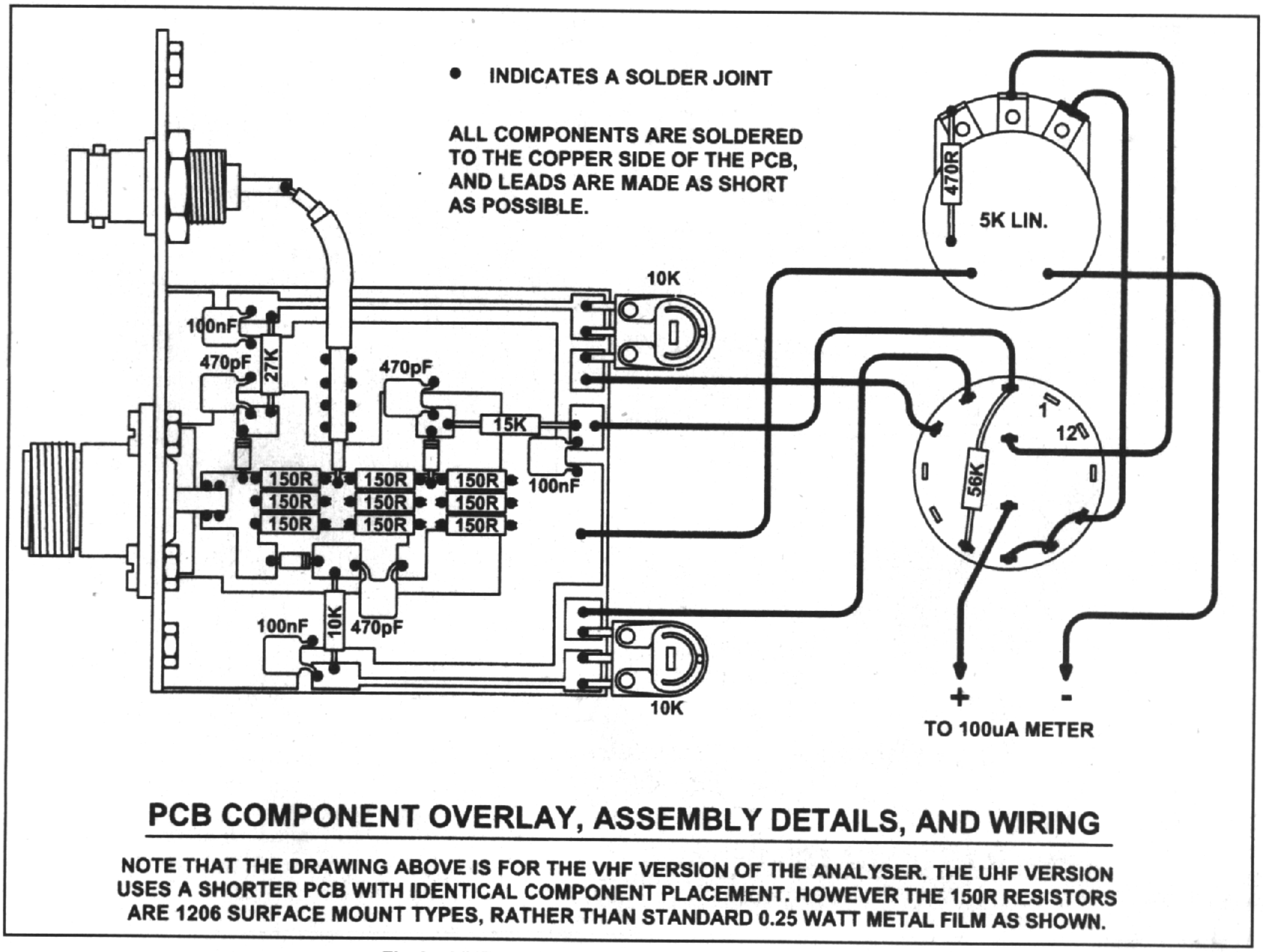

Fig 9 – VHF version component layout and wiring.

Setting up

Switch the Analyser to its "CHECK INPUT" setting. Using a frequency in the 5-30 MHz range, gradually increase input to the analyser bridge to around the 1 W level (middle of the "INPUT OK" scale). Switch to "SET FSD" and, using the front panel potentiometer, carefully adjust for full-scale on the meter. Next, using the appropriate trimpot, adjust for full-scale deflection on both the "SWR" and "R or Z" switch positions. This completes all calibration. (The frequency of between 5 and 30 MHz is recommended simply so that the capacitive effects of the connector are negligible on the resistance scale - on the UHF version you can set up at 146 MHz).

If you have a really good 50 Ω dummy load, use it to check whether the instrument

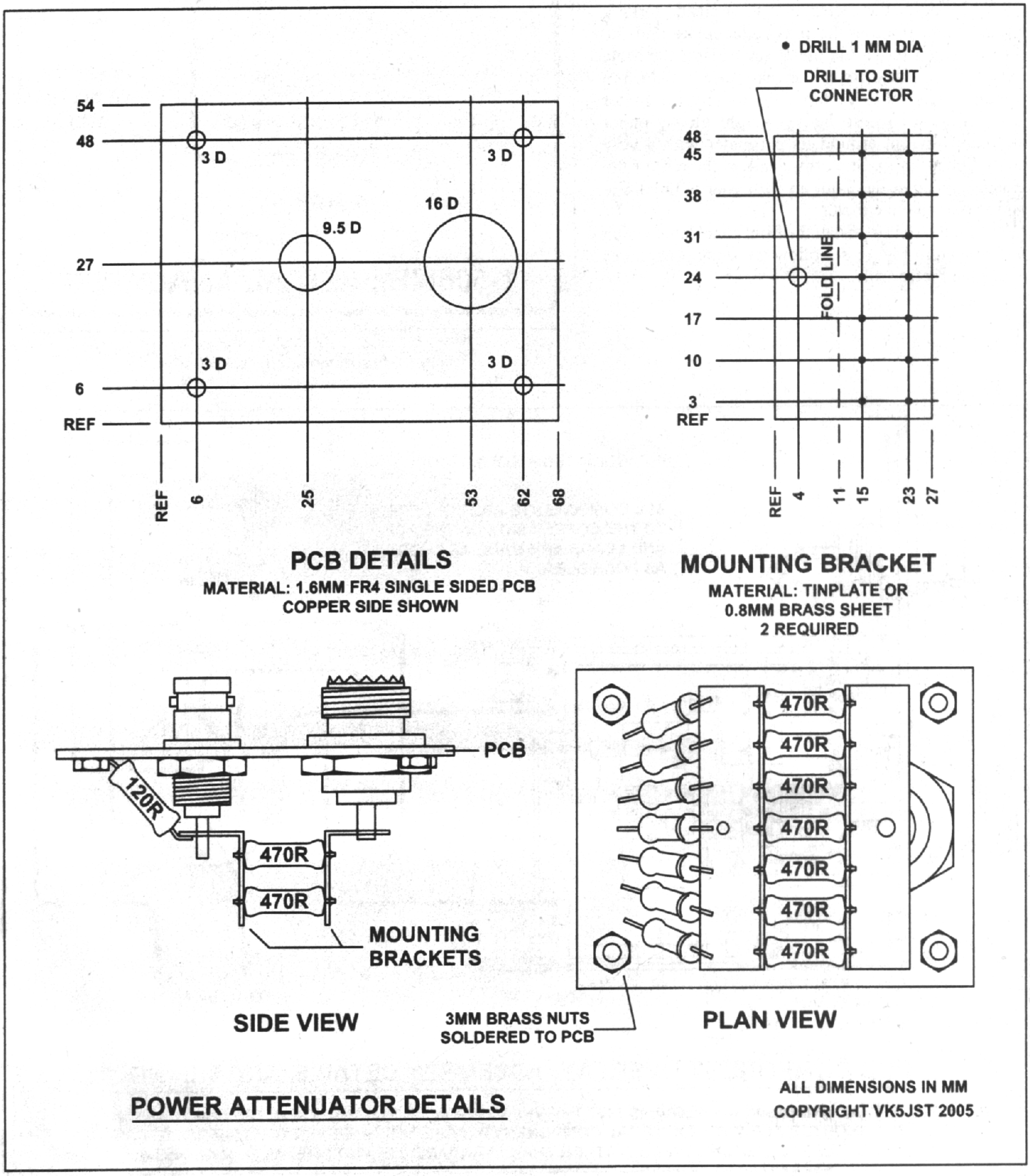

Fig 10 – Power attenuator details.

indicates an SWR of 1 and a resistance of 50 Ω over the frequency range quoted for your load. Unfortunately, many dummy loads fail this test miserably and a good dummy load which operates correctly at VHF or UHF (SWR less than 1.05) is very difficult to make. The Analyser design was carefully tested using a borrowed precision 50 Ω load at both 2 metres and 70 cm (thanks VK5ZBQ). With the surface-mount resistor bridge, an SWR of 1.05 was measured at 470 MHz. Version 1, using standard quarter watt metal film resistors in the bridge, gave an SWR reading of 1.3 at 470 MHz and 1.03 at 146 MHz. It also incorrectly indicated the resistance as 70 Ω at 470 MHz.

Using the analyser

Select a test frequency on your handheld (see Photo 1) and adjust the power output for around 1 W (or use the inbuilt attenuator to produce 0.4 - 2 W into the test circuit from your HF rig). Switch to "SET FSD", adjust for full scale, and then check "SWR". Check the apparent impedance (Z) on the R or Z scale. Now switch your radio to a slightly higher frequency, recalibrate the instrument and note changes to SWR and impedance. If the impedance fell on the second test the aerial is too short and needs extending. If the impedance rose then you are measuring above the aerial's resonant frequency and it needs to be shortened. Note that the frequency change should be kept relatively small (1 - 2%). It is very easy to completely miss the aerial resonance with a big frequency change (say from F2 to F3 in Figure 4) and fool yourself. This is particularly so on multi-element Yagis with small element diameters, as the bandwidth can be very narrow.

Once you know where you are relative to resonance, you can work out whether to lengthen or shorten, add inductance or capacitance, adjust the matching network for a better match, use a different feed line or balun, or take any one of thousands of possible actions including hurling the antenna over the nearest fence. And in the process you will end up really learning something about the mystical subject of aerials.

Enjoy!

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Parts List

9	150 Ω 0.25 watt metal film OR
9	150 Ω 0.25 watt type 1206 SM
7	120 Ω 1 watt metal film
1	470 Ω 0.25 watt metal film
14	470 Ω 1 watt metal film
1	10 kΩ 0.25 watt metal film
1	15 kΩ 0.25 watt metal film
1	27 kΩ 0.25 watt metal film
1	56 kΩ 0.25 watt metal film
2	10 kΩ trimpots Jaycar RT4016
1	5 kΩ linear pot
3	470 pF 50 V NPO monolithic capacitors
3	100 nF 50 V monolithic capacitors
3	1N5711 (HP 5082-2800) Schottky diodes DSE Z3231
2	BNC connectors Altronics P0516
1	SO239 connector Altronics P0510
1	N type connector DSE P2410
3	printed circuit boards- see text
1	2 pole 6 position rotary switch Jaycar SR1212
2	knobs
1	100 μA meter type MU-65 Altronics Q0550
1	Jiffy box 197 x 113 x 63mm Jaycar HB6012
14	3 mm brass nuts
14	3 mm countersunk screws

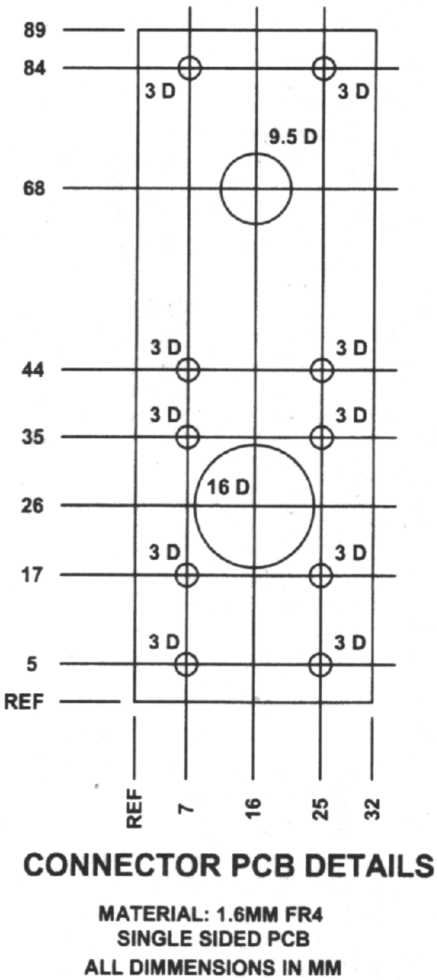

Fig 11 – Connector PCB details.

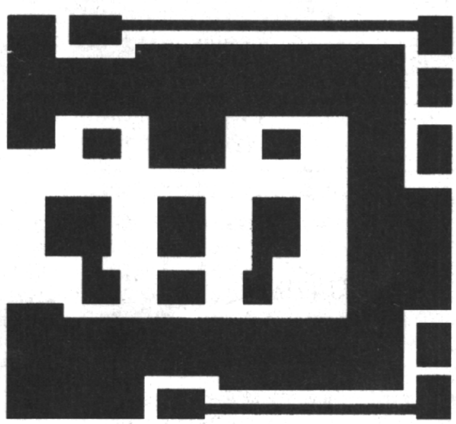

Fig 12 – VHF board template.

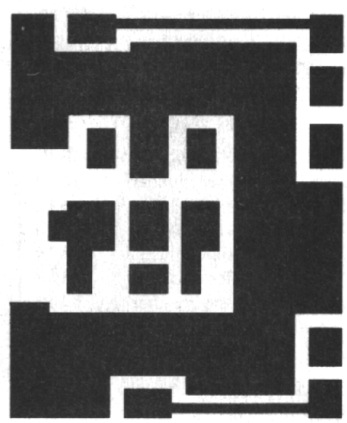

Fig 13 – UHF board template.