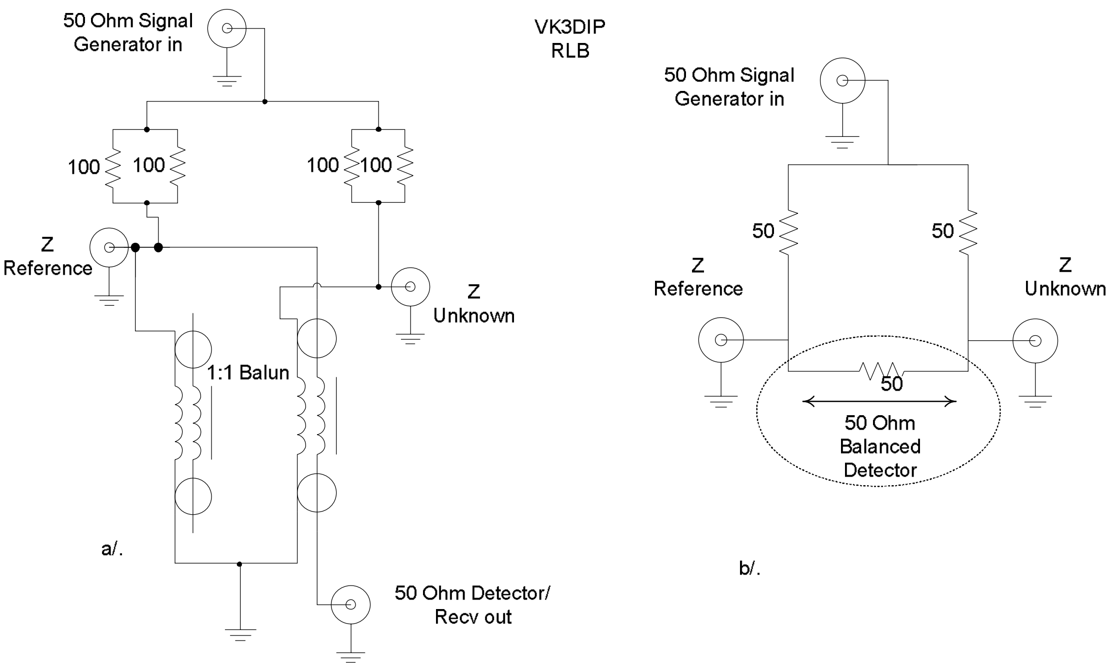
Further Reflections on a Wideband Return Loss Bridge

By Paul McMahon VK3DIP

Since my article on a Return Loss Bridge appeared in AR I have had a number of people contact me with questions, comments, and the results of tests on their versions of the RLB. This article is effectively a summary of these plus some additional work I have done on subsequent versions of the RLB. Also included are the results of some tests done on my prototypes using somewhat better quality test equipment than previously used.

The Balun

The vast majority of the questions I have been asked boil down to a request for more details of the Balun; how does it work, why four cores, should I (or can I) use more, less, why does it even need a Balun etc. The following is my description of the balun and how it works, I am sure this is not the only way this could be explained but hopefully this will give a better idea of why I built it the way I did.



<Fig 1 a/. The Mark 1 RLB circuit. b/. The simplified circuit.>

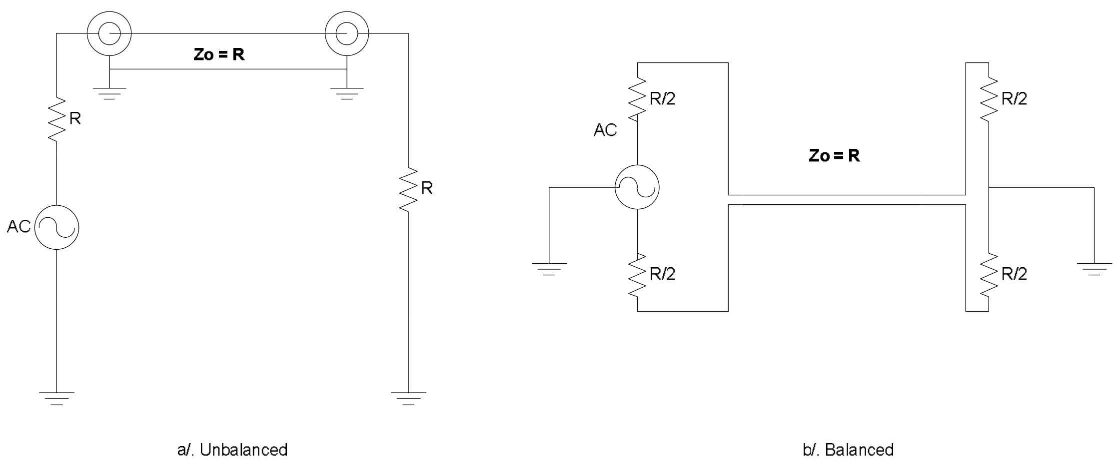
Figure 1 above reproduces the circuit from the original article (a/.), along with a simplified version of the circuit (b/.) that is the effective result if the Balun is ideal. As an aside you may note that the circuit at b/. is effectively that of a 50 Ohm resistive 6db splitter, and shares many of the characteristics of such a device.

The function of the Balun then is to transform the 50 Ohm unbalanced input impedance of the detector (ie. one side of the real detector input is earthed), to a balanced, effectively floating (ie. neither side of the transformed detector input is earthed), 50 Ohm impedance between the two Z connectors.

In the ideal Balun case the impedance presented will be exactly 50 Ohms and the detector will be exactly balanced. Minor divergence from this effective 50 Ohm presented will only result in corresponding minor mismatches and losses. However even minor amounts of residual unbalance will result in the detected signal not correctly representing differences between the Z Unknown and Z Reference ports. For example if the effective resistance presented was 40 Ohms instead of 50 then, apart from a 20dB return loss, so long as things are balanced, a null on the detector would still indicate that the Unknown and Reference were equal, and a peak would indicate maximal difference between the two. A problem in balance will however show up as the detector indicating a null when the Reference does not equal the Unknown.

So what do balanced and unbalanced mean? In simple terms for a two terminal source or load, unbalanced means that one terminal is connected to earth, or at earth potential (a virtual earth) , in the balanced case both terminals are not earthed but have symmetrical mirror images of each other about earth (or virtual earth). With AC or RF in the unbalanced case the earthed terminal is always at zero volts while the other varies from zero to some positive value with respect to earth. In the balanced case the terminals will have potentials of equal magnitude but opposite sign. A physical analogy could be something like a lever with the pivot at one end is unbalanced, while a see-saw with the pivot in the middle is balanced.

We can see this in Figure 2. (Note that while for simplicity I have shown a hard earth the same is true with a virtual earth which has no actual connection to physical earth.)

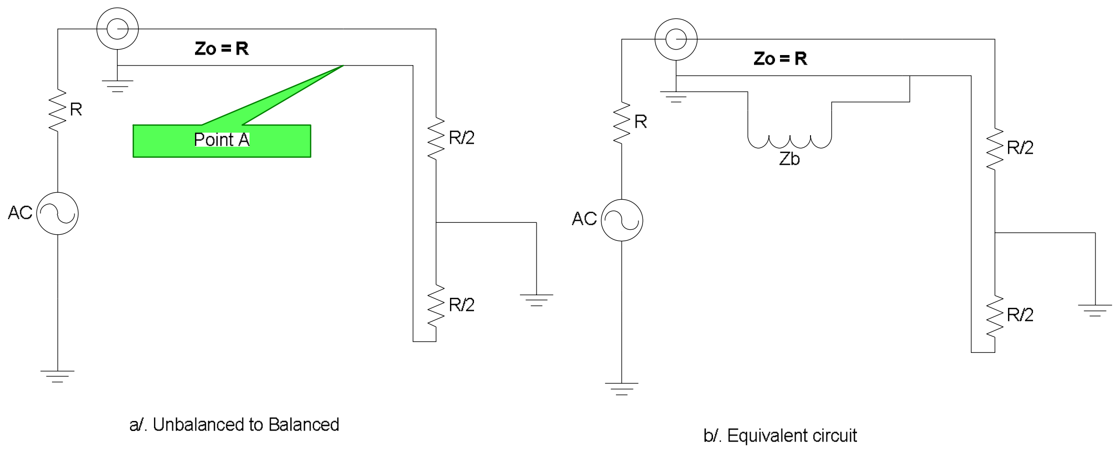


<Figure 2. The Unbalanced and Balanced cases.>

Here, in both cases, a source of output impedance R feeds a load of impedance R via a transmission line of impedance Zo = R. Having the values of R the same is for matching and power transfer not balancing purposes. In the balanced case the value of R is effectively split in two either side of earth and that the equality of these values is what effects the balance. Put another way the closer the earth (or virtual earth) is to the middle the better is the balance.

To understand the operation of this Balun we also need to look at coaxial transmission lines. In the normal, and desired, mode of operation RF energy flows only in the inside of the coax, ie. in the area between the outside of the inner conductor and the inside of the outer conductor / braid. In this case the outside of the outer braid is actually at earth potential. This normal circumstance is enforced usually by the outer braid being physically connected to earth at both ends of the cable and sometimes along its length. In normal use one connects a 50 Ohm unbalanced source (a transceiver say) to a nominally 50 Ohm unbalanced load (a properly tuned Yagi with a gamma match say) via 50 Ohm Coax.

Figure 3 shows what happens when we just connect up to a balanced load using intrinsically unbalanced coax.



<Figure 3. Connecting an Unbalanced source to a Balanced load with some Coax.>

We can see from figure 3a/. that everything looks OK except for the fact that at point A the outer braid of the coax is effectively shorting out the lower of the two R/2 resistors in the load. Understanding what is happening here can be a bit difficult at first and perhaps it helps to think of this as being a bit like a garden hose with the water flowing down the inside which is good, but something is not quite right at the nozzle end and water is running back down the outside of the hose. A similar thing is happening with the coax here, the RF power is flowing down the inside of the coax and because of the imbalance some is flowing back down the low impedance path formed by the outer of the coax which is connected to earth at the source end.

Note this current flowing on the outside of the coax is not a reflection or a standing wave all that happens inside the coax.

The effect is perhaps simpler to understand in figure 3b/. where the impedance of the outer of the coax is shown explicitly (as Zb) separately to the transmission line. Normally then, unless we have done something special to make the impedance of the outside of the braid (ie Zb) high, just connecting up an unbalanced bit of coax to a balanced load is not a good thing. Of course lots of people do just this with wire dipoles and other antennas, but in this case there is usually a long bit of coax involved which in itself increases the inductance of the outer braid. In addition the current on the outside of the coax will radiate (or receive) also, so the main effect will be on radiation patterns. As an aside in the antenna case with for example a dipole where there is no hard earth centre connection and there is only a virtual earth the net effect, apart from sharing the current between the antenna and outside of the coax, is to effectively move the virtual earth point along the dipole away from the centre of the antenna. Both the current on the outer of the coax and the movement of the virtual centre point will distort the antenna pattern.

One way to make this piece of coax into a balun is to increase Zb without otherwise interfering with the flow of power. This sort of Balun is called a choke or current mode Balun because we are dealing with the flow of currents and effectively turning the outer of the coax into an RF choke.

We can do this several ways:

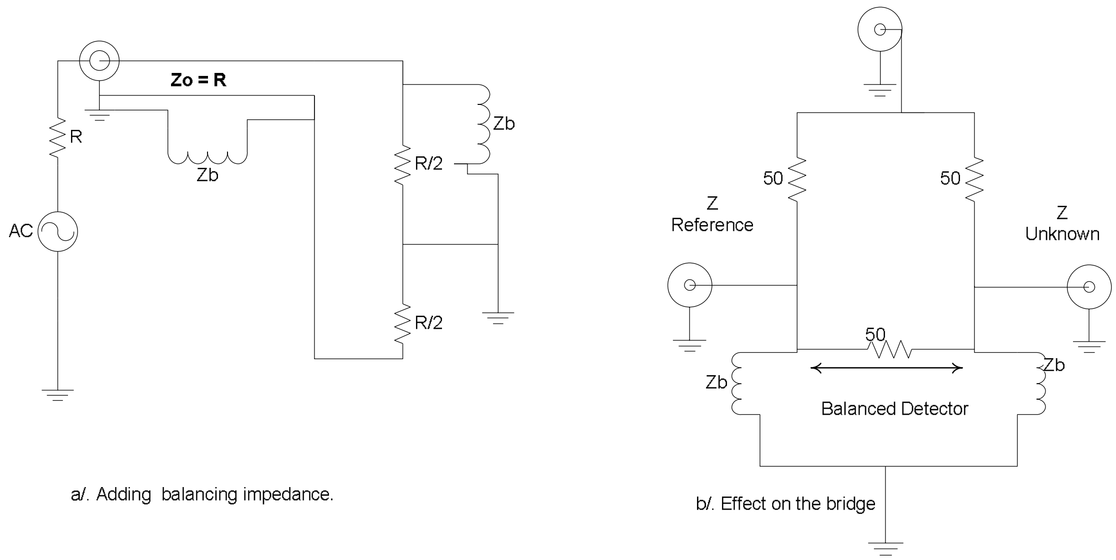
1. We can wind the coax into a simple coil and thus increase the effective inductance of the outer without affecting the other properties of the coax. This works best at higher frequencies as the impedance of a set value of inductance increases with frequency.
2. We can increase the inductance of this coil by winding it on, or surrounding it with, some sort of ferromagnetic material.
3. We can use an appropriate ferrite material that will add a resistive component as well as increasing the inductance. This is fine here, where we are not using too much power, but be careful in a transmitting case where this resistance may dissipate some power and get hot. If a ferrite gets too hot it looses its ferrite properties.
4. Some form of quarter wave shorted stub or sleeve can be added over the coax, though this is obviously more for a single frequency.

Note, there are other ways of making baluns, such as using transformers, that are not covered here.

What we can’t do is just add a resistor in series as that would end up being in both the inner and outer paths.

The approach taken with the RLB here then is option 3 above, the only hard thing is finding an appropriate ferrite that will work over the frequency range of interest. In my case the simplest way to get this ferrite was in the form of the two-hole balun formers intended for TV frequencies which cover most of the range we are interested in. The nature of this ferrite is that the inductance of the windings has the main effect at lower frequencies, while at higher frequencies the effective resistance will predominate. The problem with this at the extremes is that at the lower frequencies we need very high inductances to get high impedances, while at the higher frequencies the resistive component tails off unless we have some very exotic ferrite.

So even if we manage to get a reasonable high value of impedance within a band of frequencies, at the edges things get less than perfect ie. the shunt impedance across one half of the load (Zb) will drop which will in turn effectively lower the value of this half of the load. This is where the idea that balance is more important than matching comes in. The simplest way to maintain this balance at the extremes is to also shunt the other side of the load with the exact same value (ie equal to Zb). This is illustrated in figure 4/.



<Figure 4. The effect of a balancing impedance.>

In Figure 4a/. the second Zb is seen added across the other half of the load. To make sure these two Zb’s are as close to the same value as possible, no matter at what frequency, we make the second Zb by duplicating as close as possible the winding that we have for the main coax line using the same sort of wire (ie coax) even though in this case only the outer matters which is why we don’t have any connection to the second coax inner. The net effect of this is to get us to Figure 4b/. where we see that even if Zb starts to shunt one side of the detector, the other side will be equally shunted maintaining the balance thus only the match (and of course losses) will suffer not the balance, so we will still correctly show when Z Reference equals Z Unknown etc..

There are a couple of other factors that need to be considered in order to maximise the effectiveness of the balun operation.

Firstly we need to maximise the inductance to get the balun to work well at low frequencies which means winding lots of turns, or using large bits of ferrite. The problem with large numbers of turns is that this tends to increase leakage capacitance between those turns, which directly counteracts the effect of the extra inductance. This particularly affects working at higher frequencies. ie. we can make the balun work better down low by compromising at the high end, and the opposite is also true.

Secondly it can be very difficult to wind exactly the same coil twice and end up with exactly the same values of inductance etc., for example two supposedly identical ferrite cores can have slightly different attributes.

To try and address these two items in my RLB Balun I used the configuration I did, ie. just one turn (or a half depending how you count it) to minimize capacitance and lots of ferrite with each individual ferrite core used half and half for the main and the balancing line. You can refer to the original article for further details of this. The down side of this approach is that just the single turn even with four cores doesn’t give much inductance and thus limits the impedance at the low end. In the case of the original prototype I stuck with the four cores that fitted easily in the box I had.

Possible Improvements not just to the Balun.

Several people who have made versions of this RLB have suggested improvements and I also have been lucky to have some tests done on a couple of prototypes with some very expensive and thus theoretically very good test equipment.

1/. Add more cores. A general rule of thumb seems to be the more ferrite the better, I have now build versions with up to 9 cores with improvements being seen particularly at lower frequencies.

2/. Use N connectors instead of BNC's. This can be an almost religious thing with some people but from my tests with this RLB N's seem to be better especially at the high end.

3/. Use as good a quality coax as you can find for the balun.

4/. Try and get the transitions from connector to coax or resistor as smooth and constant impedance as possible. This means things like using special panel N or BNC connectors that are more like line connectors, and or PCB microstrip line.

5/. Get (or effectively make) some better ferrite. It is very difficult to find one ferrite material that has both high permittivity for high inductance down low, coupled with high effective resistance up into the GHz. An alternative to this is to use a mixture of different ferrite cores that span the range of interest, ie. it is quite possible to find some cores that have a higher permittivity that will work better down low, and some other cores that have higher effective resistance for up high and just use both types together. If you do, be sure to put the lower frequency cores at the connector end working up to the higher frequency ones at the end going to the resistors in the bridge. Doing this optimises the high frequency response.

6/. Use the best 50 ohm terminations you can. I have found that three 150 Ohm surface mount resistors in parallel (or alternately six by 75 Ohm in series parallel) spaced at roughly 120 degrees around the end of an N panel plug works well. See later for details.

7/. Unless you happen to know that the resistors you are using are specially made for microwave work use as physically small a surface mount resistor/s as you can find. Preferably a single 50 Ohms (49.9 Ohm is the closest standard value) mounted face down for each arm of the bridge. Face down supposedly gives you a shorter lead length. Also with respect to the size there is a school of thought that says it is better to have the width of the resistor equal to the width of the conductor or track it is connecting too. This nominally makes the stray capacitance and inductance of the resistor the same as the conductor or track.

An Improved Version of the RLB.

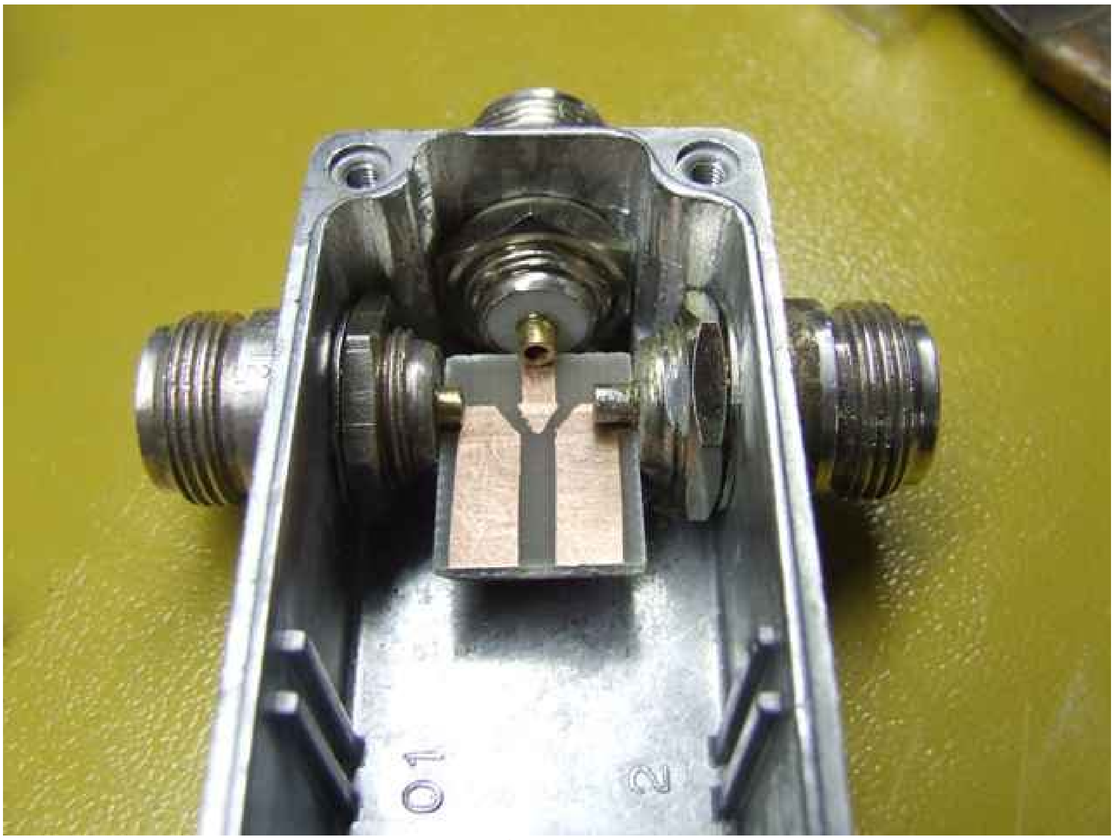
Taking a number of the ideas from the above I have made a number of improved versions of the RLB in the same sized box, and bigger. The one described here performs quite a bit better than the initial one, while the bits to make it are still reasonably readily available. The major changes are; N connectors instead of BNC, nine cores instead of four, and a microstripline version of the small bit of PCB connecting it all. The circuit for this improved version of the bridge is basically identical to before and the best way to see how some of these things went in is to look at the following photos .

In Photo 1 and 2 you can see the small bit of PCB I used which was about one cm square sized to fit exactly between the connectors in the box.   It was made from normal double sided fibreglass board with three nominally 50 Ohm strip-line arms going to the three N connectors which are the thinner lines you can see and two fatter lines which are nominally 25 Ohms each (two unbalanced 25 Ohms are equivalent to one balanced 50 Ohms) for connection to the balun output. In my case I made the board by covering both sides with tape and cutting away the tape covering on the top side as required before etching. I have not given a definitive board pattern here as this will depend very much on what sort of board is used and the exact physical layout of the bridge. In my case for the board I had, I calculated the line widths from some formulas in an old RSGB VHF/UHF handbook, at about 2.5mm wide for 50 Ohms and 7mm for the 25 Ohms. In my case I had to make the wider lines a bit thinner than 7 mm just to fit in the box, but this doesn’t seem to have made too much difference. It is very important that the ground plane (ie. the un-etched underneath) of the PCB must make good contact with the earth rims of the N connectors thus the need to size the PCB to make a good tight fit between the connectors.

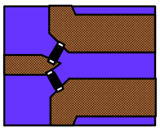
On the PCB the two nominal 50 Ohm resistors (either 2 by 100 Ohms in parallel as in version 1 or a single 49.9 Ohm which I used for this version) are mounted face down at the intersection of the three arms as indicated in Figure 5.

Note also in Photo 1 and 2 how the three N connectors are mounted. I realised afterwards it would have been a lot simpler to tap (ie thread) the holes in the case and then just screw the connectors in, rather than as shown in the photos where I had quite a bit of trouble trying to make room to fit the nuts on the connectors. You will also see I shortened the solder leads on the connectors slightly to fit the PCB better. If you want to use the same case as I used here and in the original version, they are available from Electus Distribution, the parent/wholesale arm of Jaycar, as part number HB-5026. A number of people who have made versions of this bridge have made their own case either out of PCB or in one case milled brass, this gives a lot more flexibility with respect to fitting things in, with the size and arms on the PCB just extended as required.

<Photo 1. The box after fitting the N connectors, also the piece of microstrip (ie. PCB).>



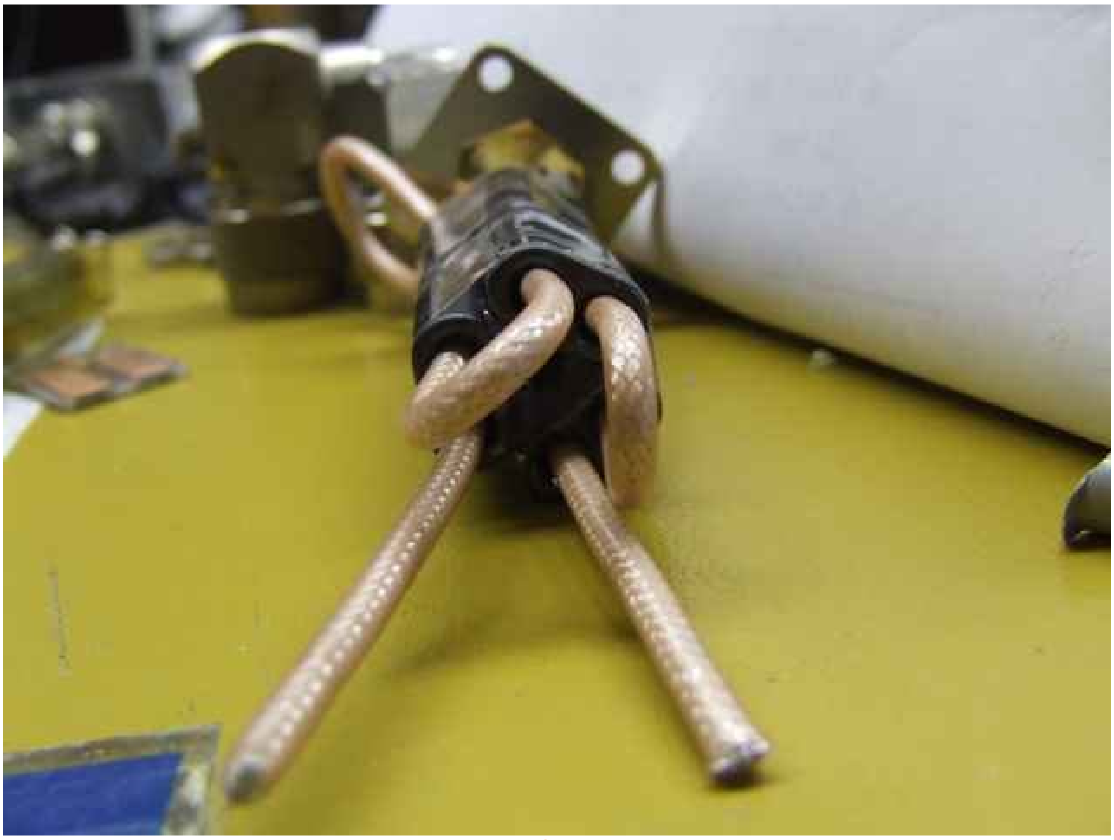
<Photo 2. Close up of the connectors and the PCB.>



<Figure 5. PCB showing resistor placement.>

For this version the Balun configuration I used was as shown in Photo 3 and 4. I taped three balun cores together as a stick and then assembled three sticks together to form effectively a single large six hole core held together with hot melt glue. The coax (again RG316 in this case) is wound through the holes as shown in the photos.

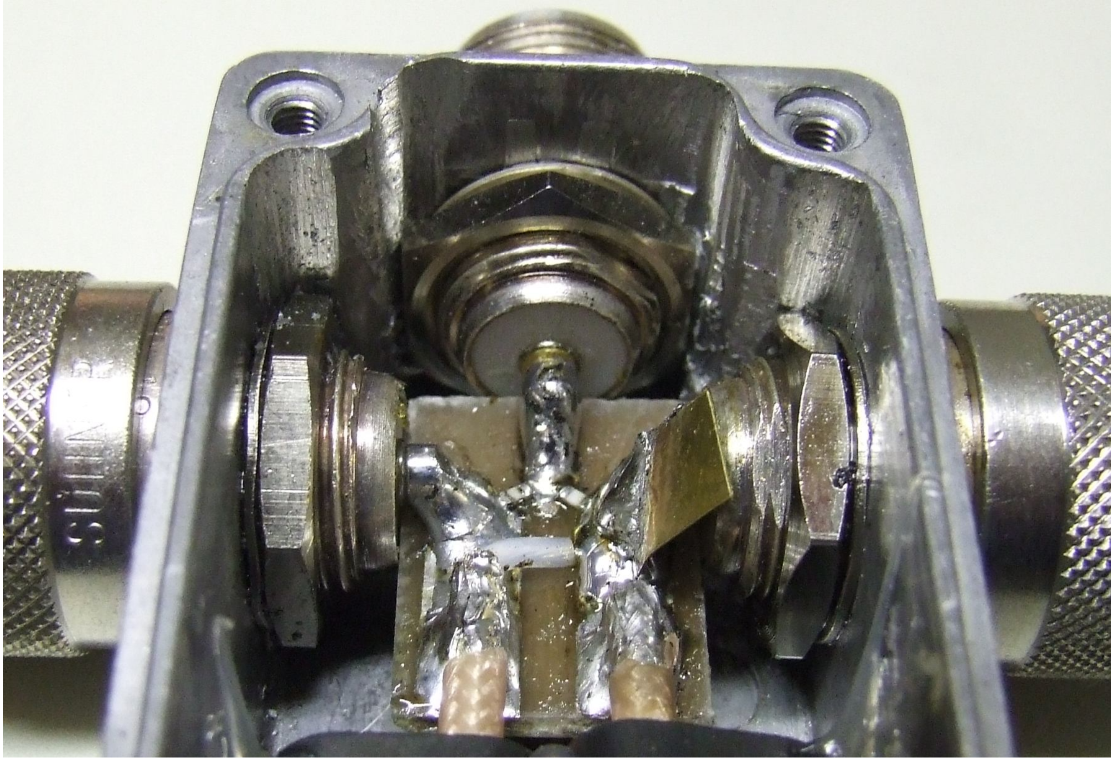
<Photo 3. The nine cores and the coax on the connector.>



<Photo 4. Close up of the coax on the cores.>

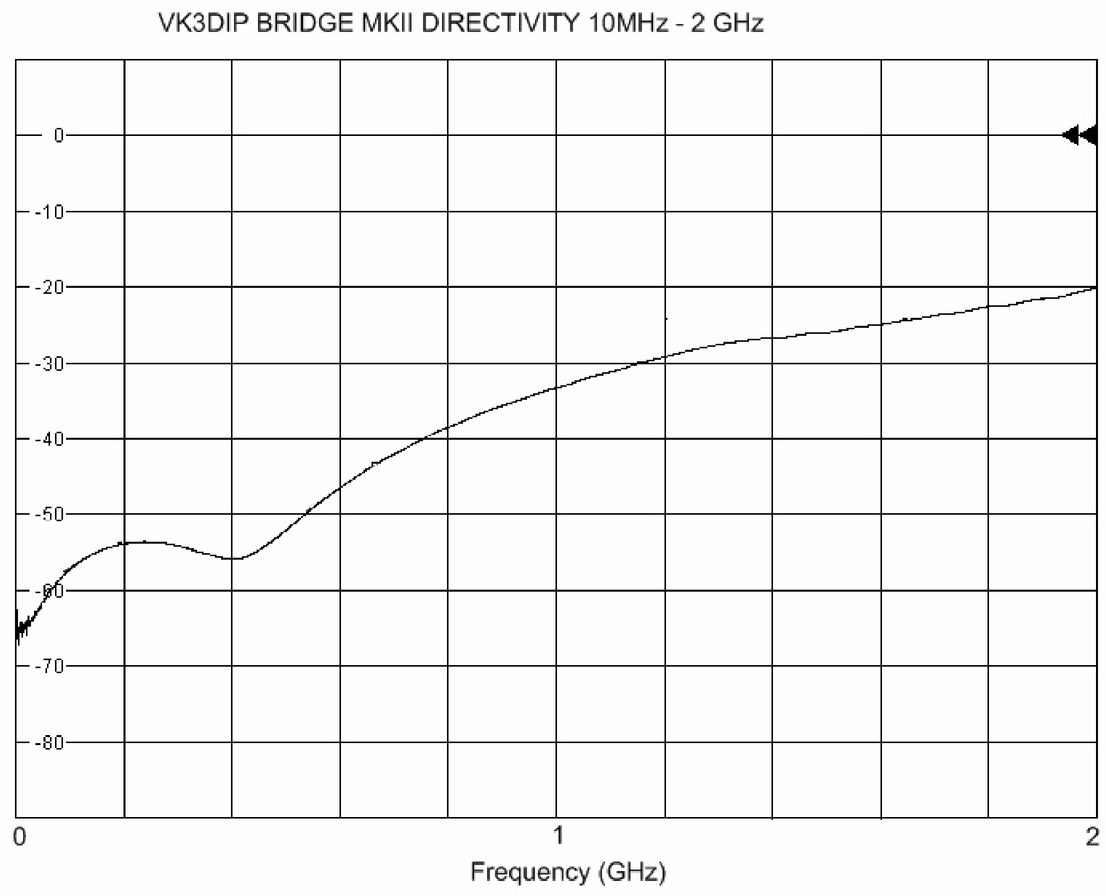
Also in Photo 3 you will see the panel mount N connector I used and how the outer of the extra bit of coax (ie the braid only) is soldered to the side of the connector where the main RG316 line exits. Note, it is important to get the coax as close as possible to the cores with minimum air gaps.

Photo 5. Shows the ends of the coax from the balun soldered on the board. Note the short section of coax inner from the main line on the left connecting to the other side braid and N connector inner. On the right hand side there is a small piece of brass shim soldered on the board which can be bent backwards and forwards to slightly increase the C on one side of the bridge. At least one person who has made a version of the RLB has found that this can be beneficial in balancing out remaining minor differences between the sides especially if the standard (ie 50 Ohm termination) or bridge resistors used are less than perfect. In my case the shim did make a small difference but as it had to be basically adjusted to suit a particular termination and as I wanted to use a number of different terminations I ended up removing it.



<Photo 5. All wired up.>

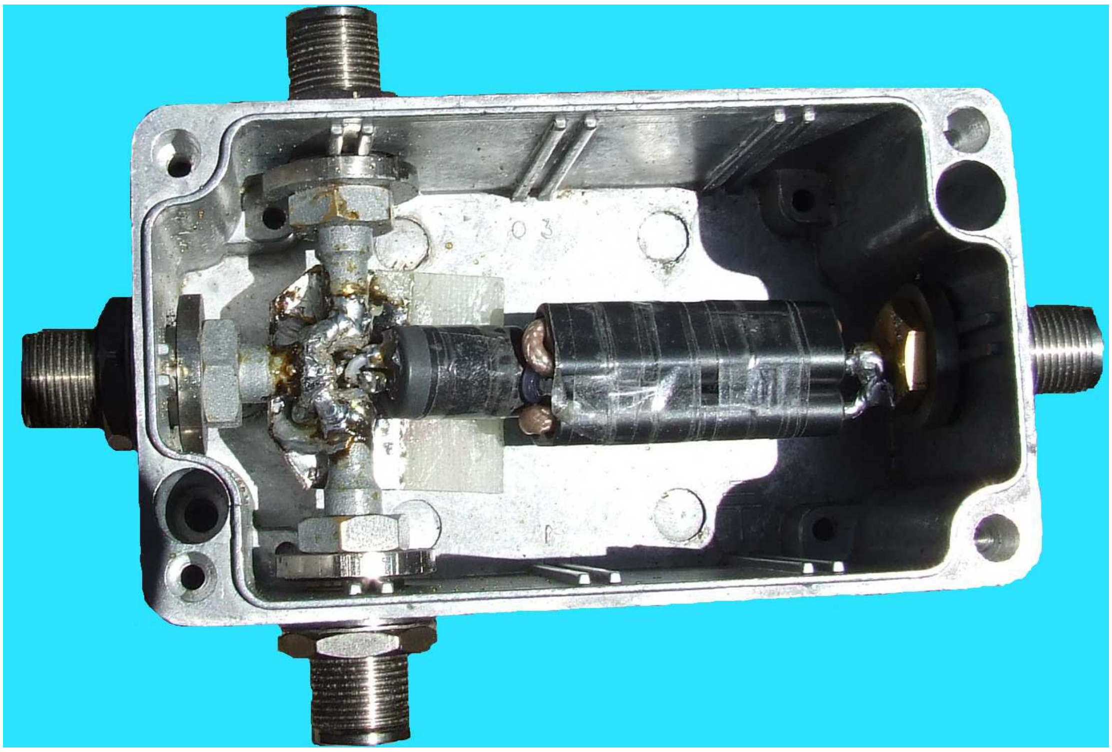
The measured performance of this version of the bridge is shown in Figure 6. These tests were done with commercial equipment and should be pretty reliable. You can see that this version of the bridge is quite good for 70cm and below and is probably still usable quite a bit higher given a suitable 50 Ohm standard or reference termination.



<Figure 6. Directivity of Mark II RLB.>

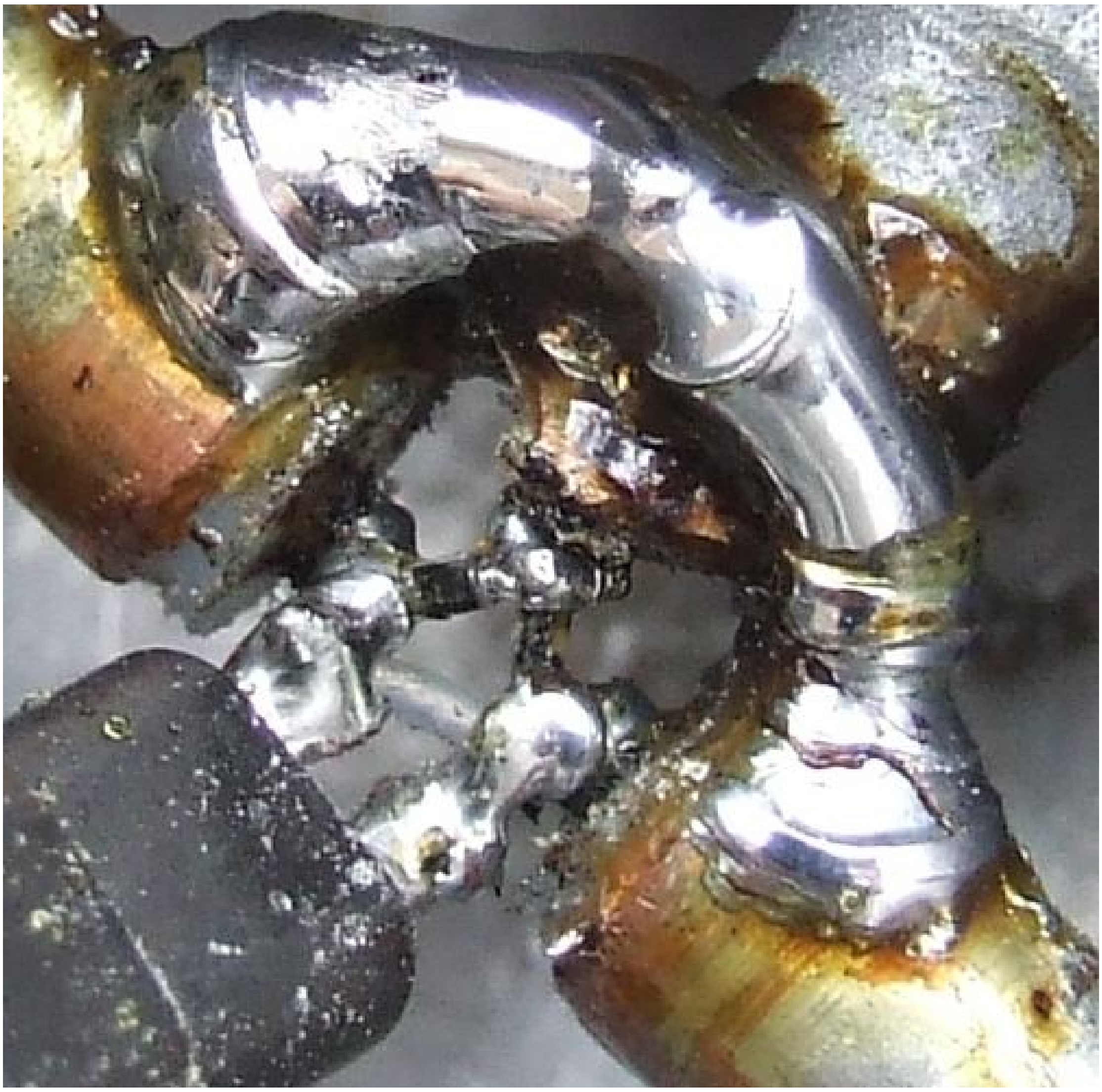
Yet another version of the bridge

While I am more than happy with the Mark II RLB, I happened to pick up at a Hamvention reasonably cheaply a number of female N chassis connectors with short lengths of semi-ridged coax fitted (RG401) , so I thought I would try them out as an alternative. The following photos give some idea of how this worked out.


<Photo 6. The Mark III RLB>


<Photo 7. The Mark III RLB Balun>

In the photos you will see I used basically the mark II balun with the addition of three toroids that are rated to provide good effective resistance at 1 GHz. Because the parts for the Mark III are not readily available I don't expect anyone else to be making one of these so only the minimum detail on construction is provided here.



<Photo 8. Closeup of connections.>

The interesting thing here though is seen in the overall directivity of the Mark III shown in figure 7. Where we can see significant improvement at and above 1 GHZ, yet the area below say 500 MHz is actually not as good. This is in line with my earlier statement that improving things at the high end often makes the low end worse.

<Figure 7. Measured Directivity of the Mark III bridge.>

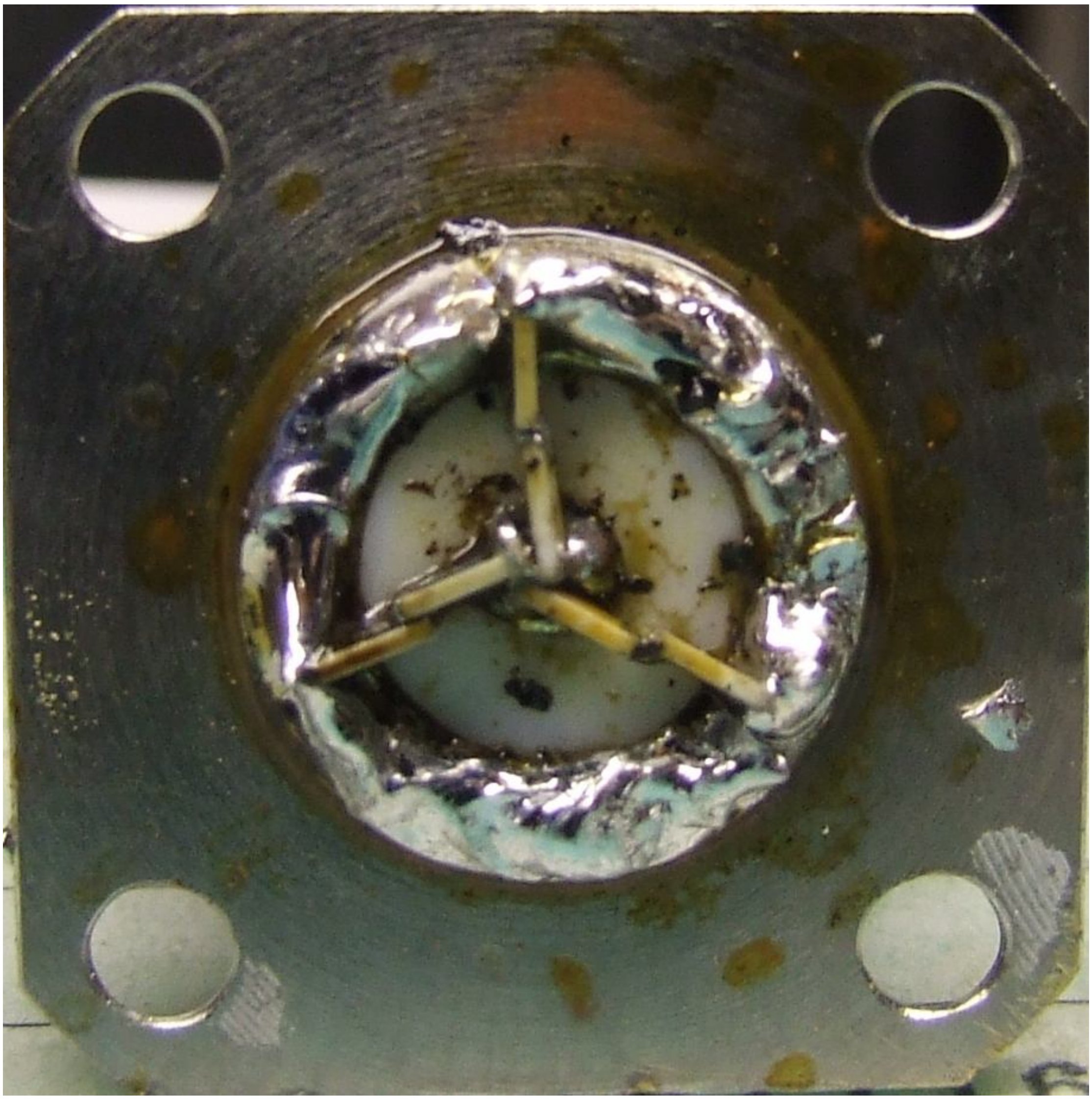
A “Good” Terminator.

The key I have found to getting good performance from these RLB’s is to have as good a reference 50 Ohm terminator as possible. If you don’t have a suitable terminator the best I have managed to make so far is shown in the following photos

<Photo 9. The panel mount connector, before and after modification.>

I start with a good quality N solder tag panel mount connector. If you can't find the panel mount male I used then the female with a male/male adaptor would be nearly as good. As seen in Photo 9, I first modify the connector by sawing off the gold coloured centre solder tag flush with the body, and with a file both smooth this out and remove the surface plating on the ring around the outside of the dielectric to aid soldering.

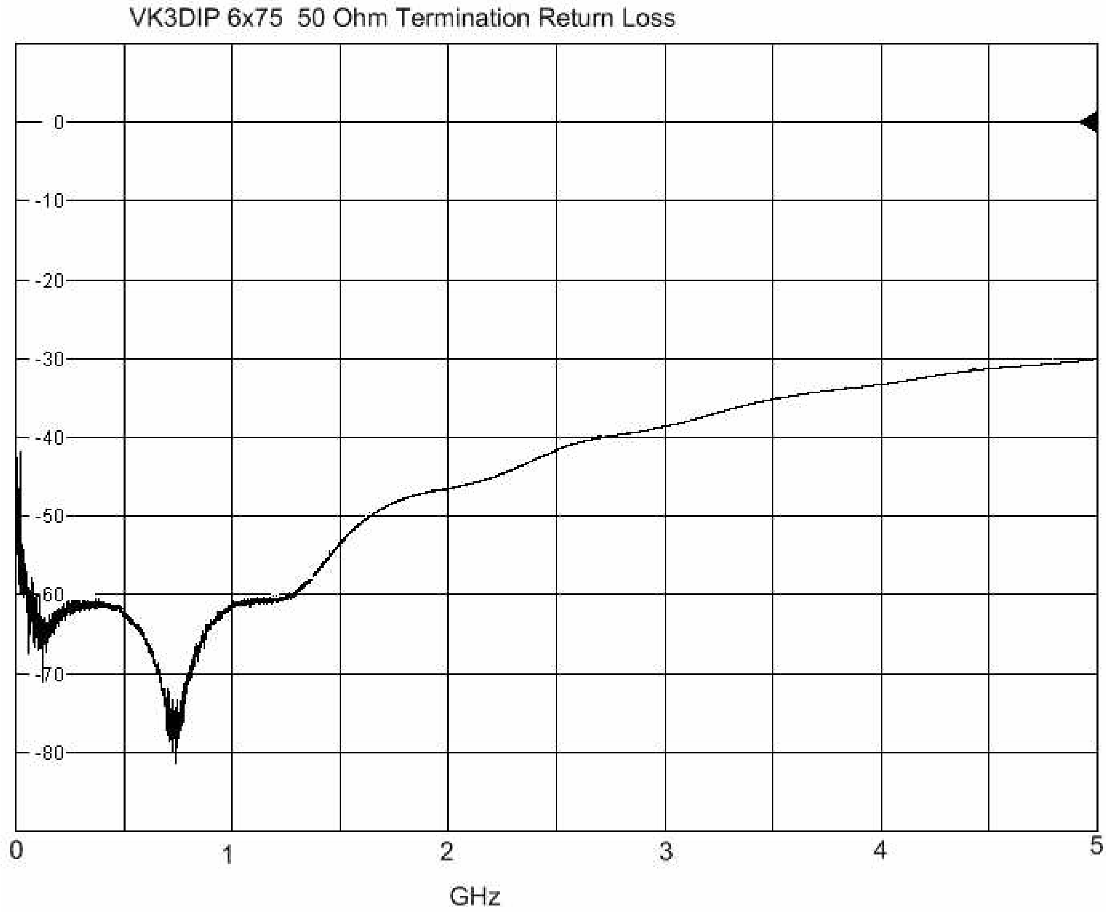
<Photo 10. 3 by 150 Ohm 7225 size>



<Photo 11. 6 by 75 Ohm 1206 size.>

Photo’s 10 and 11 show two versions of the terminator; one using three 150 Ohm larger (7225) surface mount resistors, and the other with six 75 Ohm smaller (1206) resistors. In both cases the resistors are mounted at about 120 degree spacing around the centre pin. Using at least the three resistors seems to work significantly better than just one 49.9 or two 100 Ohm resistors. Note the resistors are mounted on edge to increase cooling efficiency in case of short power overloads. The larger SM 3 by 150 is a nominal 1.8 watt terminator while the 6 by 75 version is a nominal 0.75 W device.

The measured performance of the 6 by 75 Ohm version is shown in figure 8. This is for just the device as shown in Photo 11 with a small homemade metal box screwed on via the panel mounting holes to protect the resistors. The response of the 6 by 75 Ohm version is given here, despite being the more difficult to build, because it should be easier to obtain the 75 Ohm 1206 resistors, and because it actually had the better performance. It is also possible to improve this response if a small amount of variable C, such as a small piece of shim brass, is added from the centre pin to deck and tweaking it a bit. Adjusting this without access to either (calibrated) commercial measurement gear or a known excellent termination is problematic; however the bare version is easily good enough for either the Mark II or Mark III bridge.



<Figure 8 . 6 by 75 Ohm Termination measured return loss.>

73 Paul McMahon
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