Chapter 12

Measurement

Testing Times

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Introduction

This is article covers a range of test equipment from simple diode detectors through to spectrum and network analysers, how to build them – diode detectors not network analysers! Where to buy, how much, etc. Most importantly I aim to cover their usage in a typical home workshop – not in some esoteric research lab.

Your first test lab

Let's admit it, part of the fun in microwaves is spending the time on the bench with a piece of equipment, trying to get that last extra bit of performance from it. I hate to think how many hours are spent getting half a dB more from amplifiers but to be able to do this you need a certain amount of test equipment. Building an LO chain for your 10G transverter needs a different set. Let's look at some of the things you'll find reallyuseful in say, building a 10G system. You probably have many of them already so you're half way there.

Tools

It may seem very basic but you will need some good quality hand tools. Don't buy junk which wears out or won't close properly. Personally I like Lindstrom but CK aren't too bad. Next you'll need a good soldering iron, preferably two. Try and get a temperature controlled one like the Weller TCP series. The second one can be a bigger one for soldering tinplate, etc. Get some 22swg solder and some SMD solder paste (RS/Electromail). A good 6" stainless steel rule comes in handy as does a magnifier. A good hand drill and a variety of twist drills are needed, from 0.4mm through to 10mm.

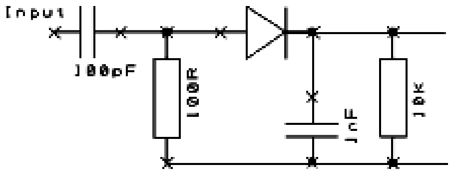
Meters

Seen those £9.99 DVMs you can get? Keep walking! Most of these aren't designed to give much in the way of accuracy and you really have to spend a little more to get a decent one (Having said that, a $4.99 one obtained in the States is to 0.1% - just luck). You don't need all the bells and whistles, just decent accuracy. Next you need an analogue meter, you just can't see the changes fast enough on a DVM to be able to align things. Old AVOs and other good meters go for £4 up at rallies.

RF

You may be thinking that you need stacks of expensive HP test gear to build your first 1.3/2.3GHz transverter or ATV transmitter? It can be done with two things – a homebrew RF detector and a homebrew wavemeter to 2.6GHz. I'll describe how to make them in a second. A few more can make things easier and I'd suggest a signal source, a surplus detector and some co-axial attenuators. I'm actually going to cheat and tell you how to make two detectors since you really can't describe the first one as requiring any effort.

To make a great RF probe, good enough to align your LO sources first off, you'll need a glass Schottky diode (HP HSCH2800 etc), two capacitors, one about 1-100pF (lower is better for microwave work) and the other 1nF, one 10K resistor, one 100R resistor and two bits of wires. The circuit below shows how it works but the photo tells the real story. Just twist all the bits together and cut off the leads, if you want you can use some solder! Costs about £2. If you are worried about



cosmetics you can package it in a pen, cigar tube, whatever! The second detector is more accurate and can be used up to several GHz. You'll need to make the PCB. This is basically the same circuit but using surface mount devices (SMD) – it'll be good practice since you'll be mounting lots of SMDs over time. Without all the stray reactance's from those leads it will have a fairly uniform response and the published graphs show a plot of power vs. output volts for different diode types.

The second item is a cavity wavemeter, very accurate and useful for checking the LO strip, typically a DDK004, is on the right frequency (typically within a few kHz). To build it you'll need to do some metalwork with either brass sheet (preferred) or tinplate. The device consists of a 3 sided long box with a 4 or 5mm brass/copper tube/rod in the middle. You can either mount it up on a piece of wood and calibrate it using a ruler or measure the depth the rod is in the cavity each time. Full constructional details of one based on a tube are in the RSGB Microwave Manual, Volume 2.

Of course, surplus commercial units are better and can be had for as little as £20.

The other optional items you can't make. That's the bad news, the good news is that commercial detectors and attenuators are about at rallies and round tables.

Commercial detectors typically come in SMA or N type connectors and cover a range up to 12.4 or 18GHz. Get attenuator(s) that match your detector, either N or SMA, and one or more adapters from N to SMA. If you can, get 3dB, 6dB and 10dB ones. Look for names like Weinschel, Narda, MidWest Microwave or, if you are lucky, Hewlett Packard (HP). A very useful one would be a 12.4GHz 10dB 2W. A good detector is from £5-15 and attenuators from £1-5 although the 10dB 2W one could be up to £25 – unless you are extremely careless it'll last a lifetime. Well, what haven't I mentioned? There are lots of things you can add to your 'lab' and I'll cover them later.

Scalar Network Analysers

Impressive sounding name! Many of you will have used something similar without really thinking about it. At its simplest it is an RF source which can be varied over a range of frequencies ('swept'), a detector with a logarithmic amplifier and an oscilloscope. Add a second detector and a directional coupler and you have a versatile tool.

Before you start thinking about how to build one, let me tell you that these units, without the RF source, come on to the surplus market for £25-60 without the detector head. In fact because they have no detector heads! Detectors, when available, tend to be about £75-300 each. Of course you may ask what use one is without the detectors? Well, mostly they can be used with homebrew detectors or with commercial N/SMA detectors and a few resistors or an op-amp. Except the HP network analysers which, in order to get a better dynamic range, use an AC coupled amplifier and AM modulate the RF source at 27.8KHz. Look for the Wiltron

560/560A and the Marconi 6500, unless you can get one with detectors in which case the HP8755 with an 182T is a nice unit. Later units, like the 8756/7, are probably outside most amateurs budgets at £800 up.

Typically the units require two interconnections between the sweep oscillator and the network analyser. One will be the sweep control voltage, a sawtooth/ramp waveform, from the oscillator to the analyser and this varies from 0 to –10V, 0 to –8V and +/-5V depending on model. Another is the blanking output which blanks the CRT display when the sweep ramp is decaying (retrace). On the HP units there will be the AM modulation input as well and some Wiltrons have a marker output. The source can be from a simple one transistor VCO up to a full blown HP sweep oscillator. HP and other sweepers are regularly available surplus and I'll cover sweepers later. Don't forget your old Gunn oscillator can be readily made into a sweep oscillator with the addition of an op-amp sawtooth generator and an op-amp level shifter. You can get by without blanking to start with, it looks messy but does the job. Having got one, what can you do with it? Well, all those filter alignments become easy with one of these – you can *see* the filter response. Think your 10G antenna isn't behaving? Sweep it with a Gunn and either a circulator or a directional coupler and see whether the reflected power is better higher or lower than 10368. Building a 23cm amplifier? Sweep it with a one transistor VCO and see how flat it is and whether it covers just 1296 or 1268 (satellite) as well.

Sweepers

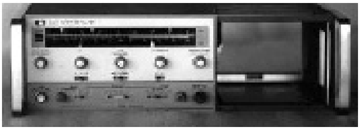
Some people may think this is my favourite topic! But if I had to keep one piece of professional RF equipment then this would be a sweeper. What's a sweeper? A signal generator where the frequency can be linearly varied over time by a ramp voltage. A super VCO. There's more to it than that, you can specify the start and end frequencies and the time taken for the sweep and some have markers so you can 'spot' a particular frequency, like the centre of a filter bandpass. As an aside, one of the professional magazines described the idealised filter response as the 'Barthead'! Think about it…

As I mentioned last time, sweepers are available if you keep your eyes open at rallies, from some of the dealers or on the Internet from the USA or Germany. In the UK probably the most common is the HP 8620 which is both quite small and very versatile since it accepts a range of HP oscillator plug-ins covering 10MHz to 22GHz. A basic 8620A without a plug in you'd pay between £30 and £60 for. A late model 'C with the options, such as HPIB, goes for up to £300. The bad news is that without one of the plug in oscillator modules it makes a reasonable door stop and not much else. The second piece of bad news is that there are quite a few non working units too! So choose carefully at rallies, that bargain may be useless or difficult to fix. The range of plug ins is listed on the website www.microwavers.org/sweepers for reference. There may be others and some options increased the range of the 18/22GHz units (usually options beginning H).

Another sweeper which you may find is the HP 8690. This is a larger unit than the 8620 and has a wider range of modules – even some 3rd party to 140GHz.

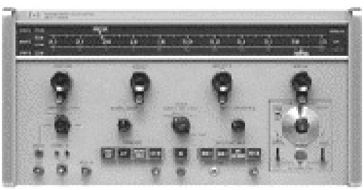
Many of the plug ins use Backward Wave Oscillators (BWOs) which have a finite life. So, even one working now may not have much left to go –see if it has an hours indicator on the chassis. The 8690 doesn't seem to appear as much as the 8620 in the UK but is more popular in the USA. However, shipping costs make it prohibitive to import and you could buy 2 8620's for the cost of the FedEx bill….but that's another story.

The 8620 was superseded by the 8350a/b. These are *really* nice digital



units which accept an even larger range of plug ins than the 8620. Even better, with the 11869a adapter you can use your old 8620 oscillators in the new mainframe – just as well as the 835xx series are still fetching 4 figure sums after 15 years and you can buy a decent Skoda for one of the wide range 10MHz to 20GHz units. If you get the 11869a adapter then check if it has the loose BNC plug on the purple coax. This is the FM connection to the 8350 back panel and makes phase locking the unit possible without trailing coax through the back of the 11869a adapter. If it is missing you can get the coax connector for the D-type (Arrow?) and make your own with a length of RG174.

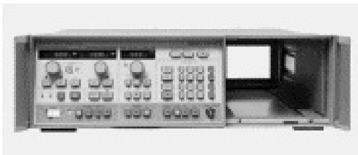
Finally, you may see the Marconi 6600. This is quite large and very heavy and like the HP 8690 has a range of BWO plug-ins up through the mm-wave bands. Getting a bit old now but if the unit is working then still worth buying.



Interconnecting these with your other test equipment can be a bit of a nightmare, especially as you are likely to want to change things around frequently, unlike a professional lab. No, I don't have a clever answer to this but since the connections are mainly BNC it isn't too much of a chore (as I've just rebuilt the shelving for the test gear I can tell you that not having it all against a wall is a big help) and in some cases you can use BNC T pieces to feed two items a once.. Those with time on their hands, having completed the Telegraph crossword, may like to ponder over a nice relay matrix to solve the problem.

If you are starting off then you probably want to use the sweeper with a scope and a detector.

The problem is the output from the sweeper is almost always 0 to +10V and a few scopes want +/- ve on the X



axis. Not a big problem as you can convert it with an op-amp on dual rail supplies. You can also use an op-amp if you need a greater voltage swing. You can use an op-amp to work the other way around as the popular 141 spectrum analyser sweep output has a +/- 5V swing – yes you can use the first LO as a limited range sweeper.

Next up are the scalar network analysers. The two I know of currently in circulation are the Wiltron 560 and the Marconi 6500. These differ in that the Wiltron requires a sweep signal input and the Marconi generates the sweep signal. Connecting the Wiltron is simply a matter of following the information on the back panel but the 6500 won't directly connect to an HP 8620 BNC's, although it will the 8350. Russ, G4PBP, has successfully connected the two by using the sweep input connection on the 50 way accessory programming connector. Pin 28 is the sweep input and Pin 43 is ground. Russ brought these out to a SMC connector on top of the back panel, taking care to ensure that the socket clears the top cover. Connect the SMC to the 0-10V BNC on the 6500 and follow the programming cards in the 6500.

Finally, there is the 8410 vector network analyser. Whilst this is a very specialist instrument it is extremely versatile – tuning multistage filters up is even more of a doddle than using a scalar network analyser and, of course, it is *the* tool for antenna measurements. I'll take some time in another issue to describe the differences between the two types.

The 8410B/C works well with both the 8620C and 8350 sweeper but really needs a programming connector cable to carry some additional control signals – the 8410A doesn't have this capability. Of course, these never come with the units. Fortunately there are only three connections so it is easy to make one up.

Connection	**8410B/C J17**	**8620 J2**	**8350 J13**
Stop Sweep Pulse	Pin 7	Pin 34	18 and 20
Seq. Sweep Trigger	Pin 1	Pin 26	24
External Trigger	Pin 9	Pin 50	n/c
Ground	Pin 11	Pin 43	19

Simple Microwave System Benchmarking

Uffe Lindhardt PA5DD

This article describes a simple way to test the receive performance of your microwave system. It requires that you are able to receive a signal from a known source from within 0-25 km (e.g. a beacon or a neighbouring amateur).

The method relies on free space propagation theory, so it is important to have an unobstructed path to the source. The method does not include any compensations for refraction, reflection, atmospheric losses or ground gain, hence results should be used with caution. Neither does it take account of antenna illumination efficiency and receiver performance. The idea is to keep the calculations as simple and clean as possible. Afterwards the figures can be seen in the light of the omissions.

To further increase transparency and simplicity the units for antenna gain has been adapted to the free space propagation formula, so that the frequency independence of the spreading of energy over the path becomes apparent. Therefore the effect of the transmitter antenna is characterised in dBi and the receive antenna in aperture. This approach and the use of dB as unit makes the calculations a matter of adding together some figures. Note that anything but the TX EIRP are frequency independent, which is convenient when comparing different bands, where the same multi band parabolic dish is used. The antenna aperture is approximated to be equal to the area of the parabolic dish used.

To perform the benchmarking you need to be able to determine the signal-to-noise (S/N) ratio of the incoming signal. This is most easily done using a adjustable attenuator in the IF line (e.g. 144 or 432 MHz) of the microwave transverter. You should preferably have so much IF gain that the noise without attenuation produces a S-meter reading. After having determined that S-meter reading (with fast AGC), you tune to the signal for a maximum reading, afterwards you add attenuation until a reading equal to the noise reading is achieved. The S/N should be at least 20dB for this method to work.

Now you are ready to fill in a table like the one overleaf . You need to know the EIRP of the source signal, the distance to the source, the radius of the parabolic dish used and the bandwidth used for the measurements (normally 3kHz). Start at the top, and calculate your way to the bottom. When comparing the calculated and measured figures, be aware that at least the first 7 - 10dB of difference is accounted for by the omissions in the calculations. The antenna illumination efficiency accounts for 5 - 6 dB, receiver noise figure and feeder loss for another 2 -3 dB. The rest can be attributed to propagation factors, faults in the system or inaccuracy of the data used (e.g. the true EIRP of the source).

Conversion between dBi and antenna aperture can be made using the following formulas:

Antenna gain [dBi] = [Aperture in dB/m²] + 10 * Log ((4 * ?) / [wavelength in meters] ²)

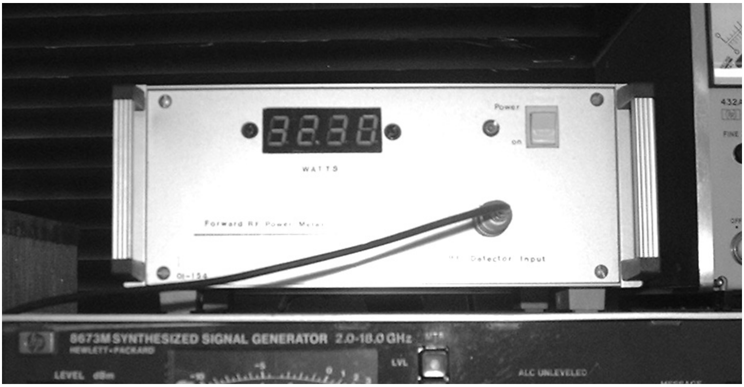
Calculations		**Unit**
TX EIRP	10 * Log [power in mW] + TX antenna gain (dBi)	dBm
Path gain	10 * Log (4 * ? * [distance in meters]²)	dB
=		
Power density at RX antenna		dBm/m²
RX antenna aperture (ideal)	10 * Log (? * [parabola radius in meters]²)	dB/m²
=		
Power at RX input		dBm
Noise floor @290K, 0dB NF	10 * Log [bandwidth in Hz] - 174 dBm/Hz	dBm
<>		
Ideal free space S/N		dB
Measured S/N		dB
<>		
Difference ideal to measured		dB

Shown on the next page, is my own benchmarking using PI7EHG at Schiphol airport. The distance is 25km, and is very close to line-of-sight because the beacons are placed 90 meters higher than the receive antennas. I use the benchmarking to get a picture of absolute performance, but more importantly to track any changes in system performance over time.

PA5DD JO22IC22	**3400 MHz**	**5760 MHz**	**10368 MHz**	**24192 MHz**
PI7EHG (JO22JH14) EIRP	+ 39dBm	+ 41.5dBm	+ 32dBm	+ 26dBm
Path gain (25km)	- 99dB	-99 dB	- 99dB	- 99dB
=				
Power density at RX antenna	- 60dBm/m^2	-57.5dBm/m^2	- 67dBm/m^2	- 73dBm/m^2
RX antenna aperture (ideal)	- 4dB/m^2	- 4dB/m^2	- 4dB/m^2	- 7.5dB/m^2
=				
Power at RX input	- 64dBm	-61.5dBm	- 71dBm	- 80.5dBm
Noise floor @3kHz,290K,0dB NF	- 139dBm	- 139dBm	- 139dBm	- 139dBm
<>				
Ideal free space S/N @3kHz	75dB	77.5dB	68dB	58.5dB
Measured S/N @3kHz	57dB	52dB	56dB	36dB
<>				
Difference ideal to measured	18dB	25.5dB	12dB	22.5dB

Digital Display for a Microwave Diode Detector

John Share, G3OKA



A common technique used to determine voltages at Radio Frequencies is to employ a diode detector circuit designed specifically for the frequencies and power levels of particular interest. The resulting dc voltage is proportional to the RF voltage, however this relationship is not linear due to diodes having a "Square Law Characteristic". Custom scales can be made for Analogue Panel meters but some form of linear conversion is necessary for a digital display.

Analogue Conversion

The square root of a value is the Antilog of half its Logarithm. Obtaining a square root using analogue circuitry requires converting the input to its logarithm, dividing by two, and then converting to the antilog to obtain the result.

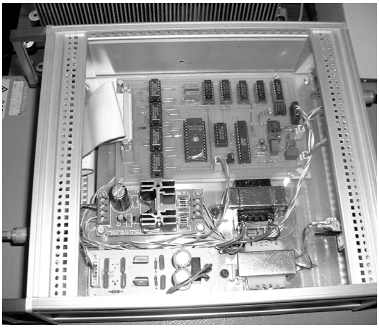
E(out)= Antilog(0.5 * Log(E(in))

Integrated circuit manufacturers have devices that perform Log and Antilog functions, they are expensive and are not too readily available. The building blocks to create these functions are well known (e.g. Clayton, Operational Amplifiers) and it was initially envisaged that a circuit could be constructed and the linear output displayed on a Digital Panel Meter module.

The design and construction of Log or Antilog Amplifiers should not be undertaken without considerable caution. Typically transistor base / emitter junctions are employed to mimic the Log function, these junctions are very unstable due to thermal drift. A prototype built to the Clayton design proved to be virtually impossible to calibrate due to thermal instability. It was quickly rejected as unusable and merely served to underline the justification of the cost of commercial devices.

Digital Conversion

An alternative is to use digital techniques by converting the input signal to a binary number, processing this value in software and displaying the result. Such a task can be readily undertaken by a PC however this is



excessive and a minimal system can be designed. All the input values can be predicted and a look up table can provide a direct output without the need for software processing.

It is necessary to decide on resolution in order to determine how many bits of data are required in the system. Conveniently 7 segment display drivers require four data lines of input, EPROM chips have 8 lines of data output hence they can function two decades of display per byte, two bytes will function four decades of display.

The specific requirement was to display power levels to a maximum of 40 Watts with a resolution of better than 0.1 W, i.e. four decades of display. Digitising the input signal (2.7 volts = 40 Watts) to a comparable resolution required particular consideration of the input at small values where the differential is least pronounced. For correct resolution across the full range it is necessary to use a minimum of ten bits of Analogue to Digital Conversion.

The input signal is digitised using an ADS7806 Analogue to Digital Converter, the output values are connected to the address inputs of the 27c64 EPROM that has been loaded with the 4 digit output value for every input value. The data outputs drive four 7 segment display latch / encoders (CD4511) that in turn power the digital display.

The ADS7806 is configured for parallel data output and places a digitised value on its output pins in two bytes as selected by pin 21. The lower byte consists of only the four least significant bits and these are latched into the 73LS173, the upper byte remains present whilst the upper byte is selected. In this manner the 12 bits of the EPROM address are obtained from the two bytes of data.

It is possible to configure the ADC for a multiplicity of input ranges but for compatibility with other equipment it was desirable to have a 0 to +10 volt input range. (The 0-10v Output shown on the block diagram is taken to a PC where it is digitised for system control.) Selecting the Complementary Offset Binary (COB) data format had the advantage of the most significant bit being asserted when the input went negative. The EPROM was loaded so that all addresses with A11 high were decoded as "0000" to the display. Data in the EPROM was generated by a program written in QB45, this calculated all the data points and saved them on a floppy disc as a text file (Data.txt) that could be viewed in Microsoft Word. A Softy EPROM Programmer was used during development and a compatible file created from this QB45 program was transferred by serial connection at 9k6 baud.

The EPROM address line A12 selects the upper and lower pairs of displays thus with A12 low the display data for the two upper digits are selected and with A12 high the lower two digits are selected.

Timing strobes are generated using a binary counter (73LS93) and an 8 line decoder (74LS138). On the leading edge of t0 a 4 us convert pulse is sent to the ADC which will complete within 16 us. The timing oscillator is considerably slower and t1 occurs much later generating the strobe pulse to the 74LS173. Binary counter output "B" and “C” are “NORed” to select the upper byte and output “C” switches the EPROM between the upper and lower digits. The display latches are loaded at t3 and t6.

Calibration and Setup

Zero offset and gain adjustment trimmers are provided for the input amplifier. The OP07CN has excellent thermal characteristics and does not compromise the system. The specific unit was required to display 40.00 Watts for an input signal of 2.700 Volts. This was derived from a bench power supply and the only adjustment was to set the gain of the input amplifier for an output of 10.00 volts.

There are a number of external adjustments that can be made to the ADS7806 however these proved unnecessary apart from trimming the zero offset. It is essential to take into account the input amplifier when checking the display for given inputs.

Display = 40 (SQR (ADC(in)/10)).
As a guide 1.35 volts applied to the input connector equals 5.00 volts input to the ADC and displays 28.28 Watts.

In Operation

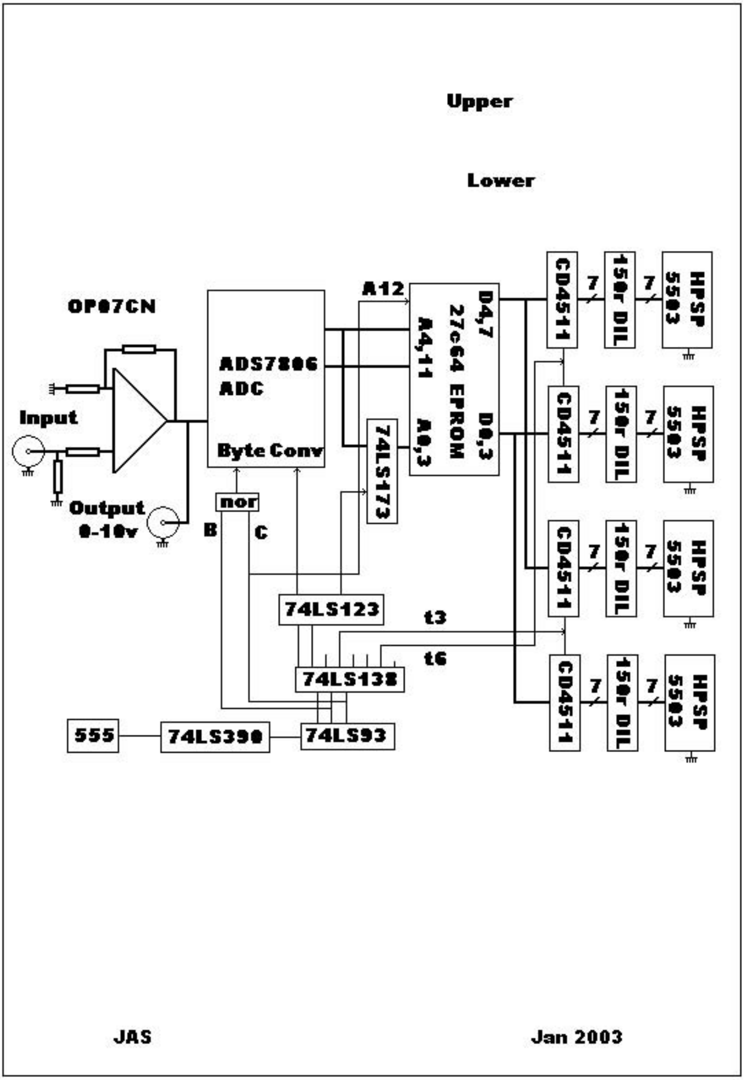
The most remarkable feature of this unit is its display stability, when driven by a test signal the output remained locked for hours on end. Digitising invariably results in LSB dither however the choice of ADC resolution appears to have circumvented this problem and the display LSB is stable, resolution exceeds the original requirement.

Acknowledgements

This unit was designed and built as part of an 18 GHz Microwave system to investigate magnetisation in rock samples at the Geomagnetism Laboratory, University of Liverpool.

EPROM PROGRAM FOR THE UNIT

```
Start:
OPEN "A:DATA.TXT" FOR OUTPUT AS #1
FOR adcout = 0 TO 2047
Vin = adcout / 2048
a = INT(SQR(Vin) * 1024)
Watts = 40 * a / 1024
hexadc$ = HEX$(adcout)
hexstr$ = HEX$(a)
hexadcupper$ = HEX$(adcout + 8192)
MSB = INT(Watts)
LSB = INT(100 * (Watts - MSB))
PRINT #1, hexadc$; " "; MSB; " ";
hexadcupper$; " "; LSB; " ",
NEXT adcout
CLOSE #
```


Upper
Lower
OP07CN
ADS7806
ADC
Byte Conv
Input
Output
0-10v
nor
B
C
A12
D4,7
27c64 EPROM
A4,11
A0,3
D0,3
74LS173
74LS123
74LS138
t3
t6
555
74LS390
74LS93
CD4511
7
150r DIL
HPSP
5503
JAS
Jan 2003

Directional Couplers used for VSWR and Power Measurement

Richard T. Knadle, K2RIW

INTRODUCTION
Over the years, I have heard many engineers and some smart amateurs, express opinions that reflect a considerable misunderstanding about the operation of Directional Couplers, and how to properly use them in the measurement of Voltage Standing Wave Ratio (VSWR), and power. This memo is intended to give some basic information that may help. At first, the average electronic technologist is mystified by at least two of the concepts of how RF behaves within transmission line structures:

(1) The concept of a Directional Coupler (DC); the idea that it favours a signal that flows in one direction, yet rejects (at least partially) a signal that flows in another direction seems (to them) to be in violation of some basic laws -- like the Law of Reciprocity.

(2) On top of this, many technologists have great difficulty believing that a normal transmission line, completely keeps separate, the signals that flow in the two directions on that line, even if those two signals originally came from the same source.

I believe that both of these principles must be absorbed (and understood), if meaningful DC measurements are to be properly executed and believed. Here are my recommended procedures, with some partial explanations of what is taking place at each step.

A DIRECTIONAL COUPLER USED IN A VSWR OR POWER MEASUREMENT PROCEDURE

(I) DIRECTIONAL COUPLER CALIBRATION -- The first step in this procedure is to establish the quality of the Directional Coupler (DC) that you are about to use. I don't care if the label on the DC says it is a "Cadillac" or "Rolls Royce" brand, and the calibration sticker says it is traceable to "The Bureau of Standards" with and accuracy of 0.01dB; you still have to confirm that it is good working order right NOW. It is possible that the DC was thrown onto a concrete floor yesterday, and the internal termination may have been shattered. If that had happened, it could loose almost all of it's directional characteristics -- it's "Directivity."

The confirmation requirement is similar to the proper use of an Ohm Meter. Notice that a good technologist will always short the two leads together; and the Ohm meter had better read a small fraction of an ohm, before the technologist will proceed with the next measurement.

Similarly, a prudent technologist will measure the Directivity of the DC he is about to use. It is also useful to know that sometimes the DC can be used far outside the frequency range it was designed for, as long as the principle of operation is somewhat understood, and a calibration at the present frequency is performed. Here is the Directivity Confirmation procedure.

DIRECTIVITY CONFIRMATION -- Unfortunately, the Directivity Confirmation procedure requires a known good termination (dummy load), and the procedure will have an accuracy that rarely is much better than the quality of that termination being used. First apply an RF signal to the DC "input" port, with a known good termination connected to the "output" port. Position the DC so that it favours the Forward flowing signal. Place a power-measuring device at the directional port. This can be a Power Meter, Spectrum Analyzer, calibrated Crystal Detector, Scalar Network Analyzer, etc. Measure (and record) the DC's response to the forward-flowing signal (in dBm units). If, for instance, you are using a known Directional Coupler (DC) with a -10dB Coupling Coefficient, the measured power should be nearly 10 dB weaker that the power that's being applied from the signal generator. By the way, "dBm" means Decibels of signal strength with reference to a 1 milliwatt signal.

Next, reverse the DC "input" and "output" ports, and repeat (and record) the previous measurement. The difference in the two readings indicates the Directivity. For instance; if a 0.0dBm signal generator is applied to a 10dB coupler, and it measured -10dBm during the Forward Measurement, and -30dBm during the Reverse measurement, that would indicate a Directivity of 20dB (the difference in the readings). A DC of "Good" quality will show a directivity of 2 dB; that is,
the apparent reflection from the termination will appear to be -20dB (an apparent VSWR of 1.22:1), even if the termination is a perfect 50 ohm resistance at the present frequency. An "Excellent" DC will show a Directivity of 30dB (an apparent VSWR of 1.065:1), and there are Instrumentation-type DCs that can display a Directivity of over 50dB (an apparent VSWR of 1.006:1).

More on this later; there are ways of improving your DC's Directivity. Simplistically, you could say that a DC that displays a Directivity of 20dB will not be able to easily resolve the Reflection Coefficient from an unknown load of better than about -20dB and there are ways to get around this. Depending on how well your DC is internally balanced, the finite Directivity (-20dB for instance) represents the degree of response it has to a signal that is flowing in the wrong direction -- this is really it's degree of imbalance. A modern Network Analyzer uses a complicated "12 point" calibration procedure to drastically improve the accuracy of a Reflection measurement it makes with it's "only Good quality" Directional Couplers.

ALTERNATE CALIBRATION PROCEDURE -- There is an alternate Calibration Procedure that does not require the inconvenience of reversing the DC to measure it's Directivity. This is to recognize that a good Short (or Open) circuit has a Reflection Coefficient of nearly -0.0dB. In this method, first measure (and record) the apparent reflected power from a Short (or Open) termination, then place the Known Good Termination on the "output" port of the DC and repeat the measurement. The difference (in dB) between the two measurements represents the DC's Directivity. When using SMA or type N connectors at 10GHz (and below), an "Open Circuit" will have Reflection Coefficient of nearly -0.0dB, and is a good calibration "short/open termination." However, if you're using a Wave Guide (WG) type DC, an open circuited WG flange makes a pretty good transmitting antenna, with a VSWR of about 1.5:1 (reflection coefficient of about -12.9dB). Therefore, don't use this as a high reflection termination. Instead, place a sheet of metal (tightly) across the WG flange as the high reflection termination.

SIGNAL GENERATOR VSWR -- There is an additional danger to the alternate calibration procedure. It is vulnerable to the VSWR of the signal generator. I would only use this procedure if there was a 10dB (or greater) pad between the signal generator and the DC. Without that pad, the reflected signal could re-reflect from the signal generator and cause a confusing reading. The signal generator reflected voltage can add to the incident voltage and create an apparent signal source that would appear as much as 6dB greater (or more) in magnitude -- but only during the short/open portion of the test. Also, if the DUT happens to have a rather high VSWR (reflection of greater than say 20dB), I again would recommend the use of a 10 dB pad at the signal generator.

(II) THE UNKNOWN MEASUREMENT -- Once you have confirmed that your DC is performing properly, it is time to place the Unknown Circuit (the Device Under Test [DUT]) on your DC to measure, and tune, it's Reflection Coefficient. The DUT-reflected signal can then be translated into VSWR by using a look-up table or by performing a two step calculation.

Step (1): Convert the reflection coefficient (in dB) into a reflection Voltage, which is usually represented by the Greek letter Rho.

Step (2): Convert the Rho magnitude into VSWR.

(1) Rho = ALOG(-dB/20)

(2) VSWR = (1 + Rho) / (1 - Rho)

Where:

ALOG = Anti-LOG, or 10^(-dB/20)

Rho = |Absolute Value| of the Reflection Coefficient (as a Voltage).

The final dB of Reflection Coefficient in the numerator must be a negative number that's then divided by 20 and raised to the power of ten in formula (1). At first, some technologists will understand that the dB value is negative dBs, they place it into the formula that has another negative sign in it, that converts it to a positive value (+) and they come up with answers that are crazy.

CHEAP AND BROAD -- The beauty of using a Directional Coupler (DC) in VSWR measurement is that, generally, they are rather inexpensive, and they are rather broadband, therefore a swept frequency measurement is possible if your power detector is a fast acting one, such as a calibrated Crystal Detector (and oscilloscope), a Spectrum Analyzer, or a Scalar Network Analyzer (SNA). As you tune your DUT, it is nice to know that you are tuning for a broadband match, as opposed to an impedance match that is only effective across a narrow frequency range.

(**III) DC ALTERNATES --** There are a large number of devices that can serve as the Directional Coupler (DC). They have such names as Quadrature Hybrid, 90 Degree Hybrid, Branch Hybrid, Branch Coupler, Magic T, Ring Hybrid, Zero-180 Degree Hybrid, Wave Guide Broad Wall Coupler, Wave Guide Narrow Wall Coupler, Wave Guide Beth Hole Coupler, etc. The one kind of hybrid that can't be used this way is a Wilkinson Half Hybrid, or Zero Degree Hybrid.

(IV) DC EXTENDED FREQUENCY RANGE -- Few technologists know that a well constructed Directional Coupler (DC) has an operational frequency range that extends many octaves in the lower frequency direction. For instance, if you plotted the Forward Response of a DC that's rated for operation from 1 to 2GHz, you would find that it has useful operation all the way down to 10MHz (and probably below). The only thing that changes is its frequency flatness, and the Coupling Coefficient decreases -- but that can be a considerable advantage. Here is what's happening:

(A) A TEM-type (non Wave Guide type) Directional Coupler has its greatest coupling at the frequency where the internal coupling section is 1/4 wave long. Above (and below) that frequency the response falls off in a very predictable manner -- it's a SINE wave of amplitude. In other words, if I was sweeping that DC that's rated for 1 to 2GHz, and I plotted the Foreword absolute Voltage response versus frequency at the Coupled Port, the resultant plot would look like a rectified SINE wave, with the horizontal axis being frequency (instead of time). There would be a zero response a zero MHz, a broad peak near 1.5GHz, a second zero near 3GHz, a second broad peak near 4.5GHz, etc. Unfortunately, a DC only has Directivity at the 1/4 wavelength frequency region and at lower frequencies -- but that still leaves many octaves of useful operation.

(B) That predictable response outside of the rated frequency range has turned into an advantage for me on many occasions, here are some examples:

(1) For my first published article, "A Stripline Amplifier/Tripler for 144 and 432MHz", Ham Radio, February, 1970,

I needed to test the power output, and harmonic content, of the 144MHz section and the 432MHz tripler section of that 4CX250B amplifier. I needed a 300 watt frequency-indicating power meter, that I didn't have. A Spectrum Analyzer (SA) can do the job, but it can't tolerate the 300 watts. If I had a -30dB DC, the coupled power would be 0.3 watts and the SA could easily make the measurements. But, my company's Instrumentation Department said they didn't have a -30dB DC at that frequency range, and non of their DCs could tolerate 300 watts. I studied what they had and found a solution. They had a Narda -10dB type N Directional Coupler rated for 8 to 12GHz and 1 watt maximum. I reasoned that the coupling section was 1/4 wave long (90 degrees in phase length) at 10GHz, the centre of it's frequency range. I then divided 144MHz by 10GHz, multiplied by 90 degrees, and reasoned that the coupling section was only 1.296 degrees long at 144MHz. The SIN of 1.296 degrees is 0.02262. Since this is a voltage response I took 20*LOG(0.02262) = -32.9dB.

That means that the coupled response at 144 MHz would be -32.9 dB (weaker) than at 10GHz, where it was a -1 dB coupler. Therefore it is a -42.9 dB coupler at 144MHz. I calibrated it at 144MHz and found it to be a -43.1 dB coupler -- close enough. And, since the internal coupled line is isolated from the main line by -43.1dB, that means that the internal 50 ohm termination would never see more than 0.015 watts when I applied 300 watts of 144MHz signal to the coupler. I similarly calibrated it at the harmonic frequencies, applied the 300 watts to it, it worked like a charm, I made all the measurements this way and they appeared in the article.

In the low frequency area of a coupler's response (near 0 degrees of a SIN function) the response is almost a straight-line response that falls off at -6dB per octave (-20dB per decade) as you go down in frequency. Therefore the "-43.1dB coupler" I used at 144MHz would be a -63.1dB coupler at 14.4MHz. As you are about to see, Directional Power Meters use this principle.

(V) BIRD-TYPE POWER METERS -- It is interesting to note that the slug of a Bird Power Meter is also a less than 1/4 wave section of a Directional Coupler. The Bird slug achieves frequency flatness across it's rated frequency range by using a rectifier circuit that has a low-pass filter action that rises at 6dB per octave as you go down in frequency.

Each slug also has a finite Directivity, depending on how well it was balanced and calibrated at your favourite frequency. Therefore, be careful about falling into the trap of using a high power slug to measure the forward power of your 1 kW XMTR, and then switching to a low power slug to measure a very low VSWR. Your antenna may be perfect, and have no reflected power (voltage), but the slug's approximate 20dB of Directivity could show an apparent antenna reflection of -20dB (10 watts). That could lead you into believing that the antenna VSWR was 1.22:1.

(VI) COUPLER IMPROVEMENT TECHNIQUES --
As the above material shows, a DC that has less than ideal Directivity is really displaying a slight imbalance that causes it to slightly respond to the signal that is flowing in the wrong direction on the main line of the coupler. There are many ways of improving the DC's balance.
(1) Internally, you could re-adjust the accuracy of it's termination, or you could add a small gimmick capacitor in the correct location to improve the Directivity balance.
(2) An even better way is to use a Double Slug Tuner, a Double Stub Tuner, or a Wave Guide E - H Tuner. If you have a known good termination, you can assume that it has perfect absorption and essentially no reflection. You then place the tuner between the DC and the good termination, and adjust it until the DC shows no reflected power from the termination. You then leave the tuner connected to the same port of the DC, while you proceed with the VSWR or power measurements.

When you were adjusting the tuner for a null in the DC's Reflection response, you were really creating a second small reflected signal that was equal in amplitude and 180 degrees out of phase at the DC coupled port. That created the improved balance and made the DC nearly ideal, at that frequency. The bandwidth of this DC correction technique is dependent on the amount of correction that was required. When in doubt, recheck the balance at the next frequency.

(VII) TRANSMISSION LINE DIRECTIONALITY --
When I tell a technologist that a transmission line will keep the two signals completely separate, that flow in opposite directions on a transmission line, they often don't believe it -- particularly if the two signals came from the same source. There are many RF tests that could be performed to prove this, but I have discovered that a well informed sceptical person can always come up with an alternate explanation that supports their point of view.

I have found that the best way is to use visual experiments.
(1) A pool of water is really a radial transmission medium. If I drop a pebble at the North end of the pool, waves will travel to the South. Similarly, a pebble dropped into the South end will create waves that travel to the North. If I drop pebbles at both ends of the pool, the waves will meet at the middle, and pass right through each other with no interference, as long as the waves are kept small enough (use the linear region of wave amplitude -- no white caps).
(2) I can tap the 1/4 inch guy wire on my 200 foot Rohn-55 tower and watch the wave travel up the guy wire, strike the tower, reverse in polarity, and propagate back down to me (it hit a "short circuit"). I can wait until the wave has struck the tower, and started

back to me, then I can strike the wire again (with any polarity) to start a second wave going up the guy wire. As the two waves meet in the centre, they pass right through each other with no interference, as long as the waves are small enough that I don't get into non-linear stretch (deflection) of the steel. (3) I say that most linear transmission mediums obey this property -- even RF in free space. Those waves that meet in free space pass through each other with no real interference. When you move your Handy Talky Radio around a room that is reflective, you will find what you think are signal nulls. This is because you are using an antenna that has no Directivity and it is responding to (adding together, voltage-wise) at least two waves that are out of phase. Similarly, the probe that is used on a Slotted Line VSWR setup has no directivity, and it displays the Standing Wave Ratio that is caused by the signals it picks up that flow in both directions through the Slotted Line. Those two signals were completely independent up until the time they were combined on that non-directive probe wire and then, for the first time, they interfered with each other to generate the effect we call "a standing wave." This measurement technique has become the classic way of specifying the Reflection Coefficient of an RF device -- its VSWR.

(VIII) LETS DO AWAY WITH VSWR -- If you took the directional probe from the slug of a Bird Power Meter and operated it on that Slotted Line, you would discover that the Standing Wave has disappeared, and you could now independently measure the amount of power (or voltage) that is flowing in each direction (by reversing the slug) -- that's really what you wanted to know in the first place.

In the past, that Slotted Line measurement was the only way you could conveniently measure the reflected voltage -- by using an interferometry technique to indirectly measure it as VSWR. It really is time that we abandon "VSWR measurements" because we don't do it that way any more. We should only discuss the Reflection Coefficient -- in watts ratio, volts ratio or dB ratio (choose your favourite units), because we now directly measure the reflected signal. We RF mavens seem to spend half our lives converting back and forth between VSWR, Voltage Reflection Coefficient (S11, S22) or Power Reflection Coefficient, just so that we can communicate with a technologist (or the data sheet) that uses the other system of units.

"VSWR" is now a "coded message". It's really time that we "Break the Code" or stop using that code when we're buying components or training the new RF recruits. I'll admit that we will have to keep mentioning it to students, for historic reasons.

(IX) TROMBONE IMPROVEMENT

I'll warn you that these last three paragraphs will only be appreciated by a person with a rather exacting-type of personality!

Once you accept the fact that RF power can independently flow in two directions on a transmission line, you then realize that changing the length of a lossless transmission line (of the same impedance) does not change the Reflection Coefficient; thus it doesn't change the true VSWR of your antenna. However, if the Directional Coupler (DC) device you're using (coupler or a Bird) has less than ideal Directivity, than the Reflection Coefficient, and VSWR, will appear to change. This is because there is a small amount of Forward-flowing signal (I'll call it the Leakage Signal) that's mistakenly Being picked up by your coupling device, that beats against the real Reflected Signal that your coupler is now measuring (from your antenna, for instance). As you change the length of the transmission line (with a Trombone Line), the two signals go in and out of phase with each other. This will show up as a cyclicity of the apparent Reflected Signal Power, as the Trombone is operated. This assumes that your trombone can move more than one half wavelength at your frequency – you're not going to do this at 80 meters! Although on 80 meters you could insert fixed lengths of low loss cable (of the same impedance) to get the same effect.

Knowing the operation of the system, and its shortcomings, can allow you to gain higher accuracy in the Reflection Coefficient measurement. A perfect DC or Bird would show no change in reading as the Trombone (on the antenna side) is operated. The magnitude of the "ripple" is an interferometry effect that is telling you exactly how strong is the Leakage Signal into your coupling device. Once you know the strength of the Leakage, you can subtract it out of your measurement. This is exactly the accuracy improvement procedure that is done in the microprocessor of a modern Network Analyzer.

You can convert the Ripple into a Leakage Magnitude by using the following formulae:

Leakage Voltage = (a - 1) / (a + 1).
Leakage Voltage (dB) = 20*LOG[(a - 1) / (a + 1)].
a = ALOG[Ripple / 20].

Where:

Ripple is expressed in Peak-to-Peak dBs, a positive number.
LOG is calculated in base 10.
ALOG is the Anti-Log, or 10^(Ripple / 20).

"a" must be a positive number, greater than 1.

Here is a measurement example. Assume I'm measuring the Reflection Coefficient of my UHF antenna system and my DC says that the Reflection is around -19.5dB. As I operate the Trombone after the Coupler, I see a Peak reading of -19dB, and a valley reading of -21dB. That's a Peak-to-Peak reading of 2dB. The formula tells me that my Leakage Signal is 0.1146, or -18.81dB (weaker) than the Peak and Valley measurements I have made.

That relative Leakage voltage was in-phase at the -19dB reading, and out-of-phase at the -21dB reading. I can choose to subtract the voltage from the -19dB, or add it to the -21dB reading. This relative voltage will thus be 1.1146, or 0.9954 (as a voltage), and I can take 20*LOG of these voltages. Thus, I can either add 0.94dB (in absolute terms) to the -19 reading, or subtract 1.06dB (in absolute terms) from the -21 dB reading. In either case the corrected reading will be an antenna Reflection Coefficient of -19.94dB.

I hope this information is useful to those who could read this far. Feel free to correct the mistakes!