

DIRECTIONAL COUPLERS USED FOR VSWR AND POWER MEASUREMENT

by Dick Knadle, K2RIW, 4/25/02.

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 favors 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 an accuracy of 0.01 dB; 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 lose almost all of its 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 favors 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 -10 dB Coupling Coefficient, the measured power should be nearly 10 dB weaker than 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 0.0 dBm signal generator is applied to a 10 dB coupler, and it measured -10 dBm during the Forward Measurement, and -30 dBm during the Reverse measurement, that would indicate a Directivity of 20 dB (the difference in the readings). A DC of "Good" quality will show a directivity of 20 dB; that is, the apparent reflection from the termination will appear to be -20 dB (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 30 dB (an apparent VSWR of 1.065:1), and there are Instrumentation-type DC's that can display a Directivity of over 50 dB (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 20 dB will not be able to easily resolve the Reflection Coefficient from an unknown load of better than about -20 dB, and there are ways to get around this. Depending on how well your DC is internally balanced, the finite Directivity (-20 dB 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 -0.0 dB. 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 10 GHz (and below), an "Open Circuit" will have Reflection Coefficient of nearly -0.0 dB, 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 -12.9 dB). 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 10 dB (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 6 dB 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 -20 dB), 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.

$$(1) \text{ Rho} = \text{ALOG}(-\text{dB}/20)$$

$$(2) \text{ VSWR} = (1 + \text{Rho}) / (1 - \text{Rho}) \text{ Where:}$$

$$\text{ALOG} = \text{Anti-LOG, or } 10^{(-\text{dB}/20)}$$

$$\text{Rho} = |\text{Absolute Value}| \text{ of the Reflection Coefficient (as a Voltage).}$$

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 dB's, 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 2 GHz, you would find that it has useful operation all the way down to 10 MHz (and probably below). The only thing that changes is it's 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 it's 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 2 GHz, 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 1.5 GHz, a second zero near 3 GHz, a second broad peak near 4.5 GHz, 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 432 MHz", Ham Radio, February, 1970, I needed to test the power output, and harmonic content, of the 144 MHz section and the 432 MHz 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 -30 dB 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 -30 dB DC at that frequency range, and non of their DC's could tolerate 300 watts.

I studied what they had and found a solution. They had a Narda -10 dB type-N Directional Coupler rated for 8 to 12 GHz and 1 watt maximum. I reasoned that the coupling section was 1/4 wave long (90 degrees in phase length) at 10 GHz, the center of it's frequency range. I then divided 144 MHz by 10 GHz, multiplied by 90 degrees, and reasoned that the coupling section was only 1.296 degrees long at 144 MHz. The SIN of 1.296 degrees is 0.02262. Since this is a voltage response I took $20 \cdot \text{LOG}(0.02262) = -32.9 \text{ dB}$. That means that the coupled response at 144 MHz would be -32.9 dB (weaker) than at 10 GHz, where it was a -10 dB coupler. Therefore it is a -42.9 dB coupler at 144 MHz. I calibrated it at 144 MHz 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 -43.1 dB, that means that the internal 50 ohm termination would never see more than 0.015 watts when I applied 300 watts of 144 MHz 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.

(2) 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 -6 dB per octave (-20 dB per decade) as you go down in frequency. Therefore the "-43.1 dB coupler" I used at 144 MHz would be a -63.1 dB coupler at 14.4 MHz. 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 6 dB 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 favorite 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 slugs approximate 20 dB of Directivity could show an apparent antenna reflection of -20 dB (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) But, 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 skeptical 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 center, 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 -- it's 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 favorite 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 five paragraph 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, then 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, Hi. 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 relative Leakage Magnitude by using the following formulae:

- (3) Leakage Voltage = $(a - 1) / (a + 1)$.
 (4) Leakage Voltage(dB) = $20 * \text{LOG}[(a - 1) / (a + 1)]$.
 (5) $a = \text{ALOG}[\text{Ripple} / 20]$.

Where:

Ripple is expressed in Peak-to-Peak dB's, a positive number.
 LOG is calculated in base 10.
 ALOG is the Anti-Log, or $10^{(\text{Ripple} / 20)}$.
 "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 Coefficient is around -19.5 dB. As I operate the Trombone after the Coupler, I see a Peak reading of -19 dB, and a valley reading of -21 dB. That's a Peak-to-Peak reading of 2 dB. Formulae (3) and (4) tells me that my Leakage Signal is 0.1146 volts, or -18.81 dB (weaker) than the Peak and Valley measurements I have made. That relative Leakage voltage was in-phase at the -19 dB reading, and out-of-phase at the -21 dB reading. I can choose to subtract the voltage from the -19 dB, or add it to the -21 dB reading. This relative voltage will thus be 1.1146, or 0.9954 (as a voltage), and I can take $20 * \text{LOG}$ of these voltages. Thus, I can either add 0.94 dB (in absolute terms) to the -19 reading, or subtract 1.06 dB (in absolute terms) from the -21 dB reading. In either case the corrected reading will be an antenna Reflection Coefficient of -19.94 dB.

I used this approach to demonstrate what is happening. In reality, Mother Nature almost always considers RF energy (linearly) in voltage terms. Therefore, I could have converted the -19 dB and the -21 dB readings into voltages -- for example, $\text{ALOG}[(-19 \text{ dB})/20] = 0.1122$. Then I could average these voltages and converted them back into voltage dB's by using $20 * \text{LOG}[\text{average}]$. The corrected Reflection Coefficient (again) will be -19.94 dB, and this is an easier approach -- you don't have to remember which number to add or subtract.

There have been technologists who have noticed the ripple in Reflection Coefficient that occurs when they operate a line stretcher device (such as a Trombone Line) between their Directional Power Meter (Bird-type) or Directional Coupler. They often (simplistically) average the Peak and Valley readings (in dB's). In the example case of -19 dB, and -21 dB readings, the average of -20 dB is not a bad estimate -- the corrected reading was -19.94 dB. As long as the ripple amplitude is low (2 dB), and the Reflection Coefficient is good (approximately -20 dB), then the dB averaging technique has a reasonable accuracy. Notice that the true Reflection is always slightly worse than the dB average. A purist will notice that averaging dB's is almost never mathematically correct.

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

73 es Good VHF/UHF/SHF DX,
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