SWR Meters Make You Stupid

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SWR Meters Make You Stupid

Or

Ladder Line to Eternity

It may have already occurred to you that it might be desirable to locate your amateur radio antenna at some distance from your transmitter and/or receiver. In fact, unless you intend to operate your station from the top of a tree or a tower, it is *very* likely that you will be employing some form of *transmission line.* The purpose of a transmission line is to convey radio frequency energy from a radio set to an antenna, or vice versa, in as painless a fashion as possible. You can think of a transmission line as an extension cord for R.F. In fact, for the lower regions of the radio frequency spectrum, *actual* extension cord can serve reasonably well, for reasonable distances.

Like so many other facets of Amateur Radio, the transmission line seems to have taken on a life of its own, accumulating a vast, sticky, woolly hairball of misinformation along the way. This is all so unnecessary. A transmission line is a means to an end, *never* an end in itself. And don't let anyone tell you otherwise.

A Bit of History

In the early years of radio, there wasn't much of a line of demarcation between a transmission line and an antenna. In fact, let's look at a very typical amateur radio antenna of days past. It consisted of an array of parallel wires, or "flat-top" arranged much like a clothes line, and a SINGLE WIRE leading from the flat top to the transmitter. This single wire "transmission line" typically radiated as much signal as the flat-top antenna itself, which wasn't necessarily a bad thing. Anything you could hang out there in space that radiated a signal was a help.

Countless hundreds of thousands of long-distance radio contacts were made with such contraptions.

If it Ain't Broke, Fix it Anyway

Despite the unquestioned effectiveness of such an arrangement for much of amateur radio's history, for some mysterious reason, sometime around the end of the First War to End All Wars, it was decided that life shouldn't be so simple. This bizarre concept of "specialization" began to infiltrate life on Planet Earth. The specialization Nazis decided that an antenna should radiate and a transmission line should not. It was discovered that a single wire transmission line could be made to *not radiate* by placing *another* single wire transmission line next to it, and grounding it at the "bottom" end--the end nearest the transmitter. Add twice the copper to disable half the antenna...such a deal! Sounds like a government project, doesn't it?

Well, this is one concept that, alas, couldn't be blamed on the government. It was actual radio amateurs who came up with this "idea." The end product of this was what was called the "Zepp" antenna, because it was used on Zeppelins.

Actually, we shouldn't be too harsh. The whole idea of a non-radiating transmission line was to somewhat remove one source of high voltage R.F. from the immediate vicinity of a gasbag the size of Milwaukee filled with hydrogen. For some peculiar reason, certain white-smocked hand-wringers were a bit nervous about sources of high voltage R.F. being right next to a gasbag the size of Milwaukee filled with hydrogen. Since the onboard radios at the time were *spark gap transmitters*, it probably wasn't too bad an idea to keep this fact under consideration, after all. We *still* ended up with the Hindenburg disaster, but at least it wasn't caused by the radio on board! (At least as far as we know).

After hams resumed their post-war operations, and had better things to do with their skills than preventing dirigibles from bursting into flames, they discovered that the Zepp antenna actually worked fairly well on the ground, as well. (Well, actually a few feet OFF the ground, but you see our point).

Now, in order to keep the two halves of the Zepp transmission line fairly parallel, under which condition they did the least amount of radiating, the two wires were held together (or apart) with uniformly spaced insulators, giving the transmission line a somewhat ladder-like appearance. Oddly enough, it came to be called ladder line. Of course, once again, they couldn't leave well enough alone. Some genius somewhere imagined that the TOP end of the second wire of the ladder line should actually *go* somewhere. In the conventional Zepp configuration, it didn't. It just ended. This bothered some people. The fact that it actually *worked* was immaterial. Some people just hate things like lopsided antennas and the number Pi, no matter how well they work. So, once again, they decided to try to fix something that wasn't all that broken.

After a lot of pondering about exactly WHAT the free end of the ladder line should go to, one of the aforementioned someones decided that if that went to an antenna wire as well, things might be more symmetrical.

And so was born the `Double Zepp" antenna, actually two Zepp antennas fed end to end with just one transmission line. The symmetry gods were pleased. And to be honest, the antenna actually worked slightly better than the single-sided Zepp...it had a slight amount of actual *gain* over the original incarnation. But, perhaps more significantly, the function of the antenna and the transmission line were now two entirely separate entities. Everything was wonderful.

Actually, not. Our troubles had just begun.

Don't Try This at Home

With a few very rare exceptions, the early impoverished radio amateur usually had little if anything that resembled actual test equipment. In fact, most of the diagnostic equipment that modern hams take for granted was not available *at any price* for much of amateur radio's existence. This was actually a good thing, for a few reasons:

1. Amateur radio station performance was based strictly on...well...*performance.* The only indication that things were working as they should was the fact that one was making a lot of contacts. The lack of test equipment kept the end goal well in sight.
2. Ham radio was cheaper. Why use an expensive plate current meter when you could check your transmitter's tuning by seeing how long an R.F. arc you could draw from the final tube's plate cap to the tip of a lead pencil held in your bare hand? YES! Hams actually DID this...and most lived to tell about it. Cabinet? What cabinet?
3. You were likely to make a useful accidental discovery from time to time. Theory is great...up to a point. It helps explain what you already discovered by accident, but it doesn't often lead to new discoveries, at least on its own. You need to get knocked on your keister a few times and singe a few

eyebrows to really understand radio. (Don't tell OSHA I said this, by the way).

The salient point is that having a lot of "tools" around usually gives you more information than you need to know, and unless you know how to USE that information, it can be worse than ignorance, as we shall shortly see.

Sometime between the two wars to end all wars, radio amateurs discovered that you could make a transmission line radiate almost NOTHING if you kept the currents in each leg of the ladder precisely equal in magnitude, and OUT OF PHASE. This allowed the antenna to behave more like a pure antenna, and the transmission line to behave like a pure transmission line. The original Zepp was a half-step in this direction, but the double Zepp really completed the task. Hams started worrying about transmission line current balance a lot...whether they could afford to or not. If you were really cheap and/or poor, the instrument of choice was a pair of incandescent lamps, one in each leg of the ladder line. If you were really high-falutin' you had an actual R.F. ammeter in each leg. (You can see these instruments in a lot of ancient ham station photos; they were about the size of modern watt-hour meters). If the currents were equal in each leg, it meant your antenna was doing most of the radiating, and the transmission line wasn't, which was generally a good thing. With but one small rub.

The antenna current meters, whether they were just a couple of light bulbs or high-falutin' R.F. ammeters, told you nothing about the relative phase between the two legs. However, it was generally assumed that if your double Zepp antenna was PHYSICALLY symmetrical, and your ladder line was relatively perpendicular to said double Zepp, the current phases WOULD be, indeed, equal and opposite. So, though not really scientifically rigorous, the R.F. ammeter pairs turned out to be quite useful. At the very least, tuning for MAXIMUM R.F. current always resulted in the strongest radiated signal. In the case of light bulbs, you just tuned for maximum brightness, and all was right in the world. For a while, at least.

However, hams being who they were, weren't content unless they had something new to worry about. At this point, we need to take a small departure, and introduce yet another Dead Ham, an obscure German electrical engineer by the name of Ernst Lecher. He lived at the turn of the century...the 20th century, that is. His work had already, for the most part, been learned and forgotten by much of the radio world by mid century. Alas, poor Ernst did much of his great work before anyone had a use for radio. He was well ahead of his time. Unfortunately, if you look up Ernst Lecher on the Internet, you will be inundated with all sorts of really bizarre "information" about things like psychic energy and even *dousing rods,* for Pete's sake!

Let me set the record straight on behalf of poor Ernst, who is undoubtedly spinning in his grave and unable to defend himself against his brainless "disciples" and various other tin-foil-hat groupies. Ernst Lecher had ABSOLUTELY NOTHING to do with metaphysics, dousing rods, psychic energy, or any other kind of New Age wacko pseudo-science. He was a REAL scientist, a REAL engineer, and achieved REAL results in a REAL laboratory. I pronounce a festering POX upon all those who desecrate his name with such unmitigated balderdash and buffalo snot.

Let's look, instead, at his REAL contribution to radio knowledge, the Lecher Line, (also known as the Lecher Wire).

A Lecher line is a fabulously simple and revealing instrument. It allows you to measure wavelength of a radio signal directly...the first instrument in existence to allow one to do so. It consists of nothing more than a pair of parallel wires or copper rods, a couple of wavelengths long or so, at the frequency of interest, with a yardstick or (or meter stick) placed along the line. You also have a moveable voltage detector so you can measure R.F. voltage at any location along the line. (I built a really snazzy Lecher Line for my electronics class that always generates lots of ooohs and ahhs from my rapt students).

You feed a small amount of R.F. into one end of the line, which sets up STANDING WAVES along the line. As you slide the R.F. voltage indicator along the line, the voltage will swing between some maximum voltage and zero each half wavelength. You simply measure the distance between the zero voltage points and voila, you have precisely half a wavelength. Well, *almost* precisely, since there's a small delay time of a wave propagating through a Lecher Line as compared to free space...that is, the VELOCITY FACTOR through a transmission line is slightly less than that of free space. Just a couple of percent additional delay for a typical set of lines with about 3" spacing between rods. (You can also measure the distance between MAXIMUM voltage points, but these are much less defined, whereas a ZERO or NULL is extremely sharp).

At any rate, it's a very sensitive and accurate instrument...in fact, until the 1950s the Lecher Wire was the most accurate means of measuring UHF signals known. Frequency counters didn't exist.

The Lecher Line also serves as an extremely high Q (selective) circuit in UHF amplifiers and filters. Variations of the Lecher Line (loaded Lecher Lines) have also been used that are a bit smaller than the full sized version. Most high power FM broadcast transmitters still use some variation of the loaded Lecher Line in the plate tuning circuit.

In addition, devices such as the shorted stub tuner, nearly universal in the microwave industry, are based on the Lecher Line. In fact, as any microwave engineer can tell you, ANY impedance can be matched to ANY OTHER impedance using just two stub tuners. All because of Ernst Lecher and his fabulous trained STANDING WAVES.

So simple, so educational, so elegant, and so incredibly useful. And yet, sadly, one more source of posthumous Ernst angst.

For, in recent years, STANDING WAVES have come to be viewed as something to be avoided like the Ebola virus. This, more than any other misconception, has resulted in the single greatest source of Amateur Radio Stupidity Exchange (ARSE). For some inexplicable reason that will probably never be known, presumably sentient, rational beings become the village idiots of the Petri dish when the term STANDING WAVE is uttered, wringing their collective hands, palpitating in unison and hyperventilating in horror.

The fact of the matter is that about 95% of what makes radio work at all is the application of STANDING WAVES of some sort. Standing Waves are like water. Just because some Cro-Magnon manages to drown himself in a bathtub is no reason the rest of us need to live on a diet of dry sand. Amateur Radio NEEDS standings waves to survive!

Now, there may be a few readers who have never encountered the term standing wave ratio, or SWR. If you happen to be one of these individuals, consider yourself most blessed, indeed. You will not have to "unlearn" anything. You are a blank slate, unencumbered by countless man-centuries of accumulated collective ignorance pertinent to the subject.

Are you ready?

Great! Let's get started.

One of the best habits you can get into as a new radio amateur is the habit of MEASURING everything. You NEVER want to take anyone's word for anything when it comes to amateur radio electronics, (or any other subject, for that matter), even from an infallible reliable source (or even me!) This one habit alone, if followed religiously, would eliminate 99% of *ARSE*, as defined above. The fact of the matter is that actually doing experiments takes a bit of work...repeating ignorance takes none whatsoever. Well, maybe flapping your gums uses a calorie or two, but that's about it.

Here's another great principle, right from the physics lab: If you want to know what's happening, follow the heat.

What's this mean? Quite simple, actually, but it does have some subtle implications. When you generate a certain amount of radio frequency energy, it can only go to two places. It can be radiated into space. Or it can make something hot. There are no other options.

We'll see why this is crucially important as we move along.

No End in Sight

Let's take a look at a transmission line that's infinitely long...our Ladder Line to Eternity. At the far end of the ladder line, let's put a 100 watt light bulb. (Granted, it may take you a while to stroll out there and attach the light bulb, and then stroll back to complete the experiment, but bear with us for a moment).

Now, let's connect a 100 watt radio transmitter to the input end of our infinite transmission line. Let's turn on the radio transmitter for precisely one second, and then turn it off. Now, let's go make some coffee, and while it's perking away, or dripping away, or reheating in the microwave, we'll rummage around in our closet and find an old pair of binoculars. We grab our coffee and sit down on the lawn and train our binoculars toward the end or our infinite length transmission line. (It might be advantageous to do this experiment at night, as you can imagine). Actually, it will take an infinite amount of time for the one-second R.F. burst to get to the light bulb, and ANOTHER infinite period of time to see the results of the light bulb.

Most likely, this experiment will fail, unless you live to a REALLY REALLY REALLY ripe old age. But that's okay; even failed experiments are educational.

Let's modify our experiment a little, so as to be a bit more likely to succeed. Let's use a transmission line that's only one light minute long. That will be a mere 11.16 million miles long, plus some spare change, a MUCH more manageable figure.

Again, let's turn our transmitter on for one second, and then turn it off. We'll now train our binoculars on the light bulb a mere 11.16 million miles away. After TWO minutes, we'll see the light bulb turn on, for exactly one second. (Again, keeping in mind it takes a minute for the light from the bulb to get back to your eyeball).

Now, isn't that amazing?

At the risk of unduly complicating matters, we'll add a few minor details. One should know that a conventional incandescent light bulb is horribly inefficient. If you're lucky, about 2-1/2% of the energy is actually converted into light; the remaining 97.5% is, you guessed it, HEAT. It also has a resistance that changes dramatically with the power applied, which becomes more relevant when we use light bulbs for actual R.F. indicators. But we have a long ways to go in our lesson before those factors become significant.

The important point to glean from this is that ALL the energy we sent down the transmission line, (100 watt-seconds in this case, to be precise) is *dissipated*, that is, never to be heard from again. It is LOST energy. Radio energy radiated from an antenna is also LOST energy. Of course, it might be a little philosophically *weird* to call the energy radiated from an antenna "lost" because that is the whole purpose of the thing in the first place. But we can never call that energy back, which is the important point.

Now, if you've been really paying attention, you may have thought to yourself, "What about that 59 second interval before the energy reaches the light bulb? How can we even define

POWER or ENERGY? Don't you need some sort of LOAD? Until the burst gets to the light bulb, there IS no load! Aren't we violating Ohm's Law...or *something*?"

All excellent questions. And they are central to the discussion.

This is where we encounter a mysterious entity known as "Characteristic Impedance." Characteristic impedance can be thought of as an EQUIVALENT RESISTANCE at the input end of an infinitely long transmission line. Its value is independent of the length of the line. It is a function of the spacing between the conductors, and the diameter of the conductors. There's a formula that's not too complicated, but you don't need to memorize it. You just need to know that the characteristic impedance is LOW for closely spaced, fat conductors, and HIGH for widely spaced, thin conductors. For typical commercial-grade ladder line, it's about 450 ohms. In days of yore, homebrew ladder line generally ran at around 600 ohms.

Now, this is where we get to the good stuff.

As far as your transmitter is concerned, characteristic impedance of an infinite line appears as a REAL resistance. You can calculate power generated just as if the input terminals of the transmission line were a REAL flesh-and-blood (or at least, CARBON) resistor.

And furthermore... until the transmitted signal REACHES the far end of the transmission line AND back (we'll talk about reflected waves shortly) the input impedance is also equal to the characteristic impedance of the transmission line. In other words, the impedance a transmitter sees for a BURST is always equal to the Characteristic Impedance, no matter WHAT happens to be dangling at the far end of the line. (We will see that for STEADY STATE radio signals the situation can be very different). We could also say that AT THE INSTANT of launch, we can use the characteristic impedance to calculate power and energy of any transmitted signal, using voltage and current, just as if it were an actual physical resistance.

So now, if we were to REMOVE the light bulb from the far end of the transmission line, and repeat the experiment, it wouldn't make a hill of beans worth of difference as far as our transmitter is concerned...at least for two minutes...after which time it wouldn't matter anyway, since by that time our transmitter has been long shut down! Our transmitter has no way of knowing (or caring) what's at the far end of the transmission line, under instantaneous (short burst) conditions.

I think you'll agree that the description of a burst's behavior in a transmission line is pretty trivial...hardly worth elaborating.

Where things get interesting (and more complicated) though, is when we have FORWARD and REFLECTED waves occurring simultaneously. But take heart...we don't have to deal with that quite yet.

Let's return to our missing light bulb configuration. What DOES happen to that 100 watt-second burst when it encounters a "bridge out" condition?

Interestingly enough, the R.F. energy doesn't just blorp out of the end of the transmission line into space. If it COULD do this, there wouldn't be much point in an antenna in the first place. In fact, if you could invent a transmission line that *could* efficiently blorp R.F. off into space, you'd be a very rich person.

Instead, what happens is that the R.F. burst gets TOTALLY REFLECTED back toward the source. That energy has to go somewhere, and if it's not converted into heat or radiated into space as a radio signal, it has to find someplace where it CAN do either one or the other.

Well, to be perfectly honest, it DOES have one other option. It can keep bouncing around forever. We'll talk about that option a bit later.

But first, let's modify our test setup once more. Let's leave the far end of the transmission line flapping in the breeze. (Hmmm...I guess at 11.16 million miles out in space, there probably isn't much of a breeze). Anyway...we have an UNTERMINATED transmission line out yonder.

At the NEAR end we'll connect a double throw switch, so we can conveniently connect either a transmitter or a light bulb to the transmission line.

Now, we'll throw the switch to the transmitter side and send a one second burst. Next, we'll shut off the transmitter and throw the switch to the light bulb side, and wait a couple of minutes. (Actually one minute and 59 seconds).

Voila! At the appointed time, the light bulb shines for one second. Aren't we amazed? What have we learned?

Well, a couple of things, at least. Number one is that REFLECTED energy is REAL energy. We were able to light our light bulb with the energy that was reflected from the far end of the un-terminated transmission line.

The second thing we learned is that that transmission line is 11.16 million miles long. Well, we already knew then when we strung the thing out there, didn't we? But, in case we *didn't*, we could have determined its length by carefully measuring the round trip time, knowing that electrical currents travel through a transmission line at about 186,000 miles a second, plus some loose change.

In fact, telecommunications people actually use this method in the real world for locating discontinuities in otherwise inaccessible transmission lines. This method is called TDR for "Time Domain Reflectivity" measurement. As you might suspect, in the real world, we don't usually have 11.16 million-mile-long transmission lines. Actual TDR tests use much shorter bursts...generally in the order of nanoseconds...which will allow you to measure transmission lines that are mere hundreds of feet long. As long as your outgoing burst quits before your reflected burst comes back, you can do TDR tests. (You also don't generally use light bulbs for TDR detectors, but rather oscilloscopes).

Now, let's talk a bit about the *discontinuities* mentioned in the previous paragraph. You don't need totally open (or shorted) transmission line to give you a reflected energy burst. It's just that under these two conditions you get TOTAL reflected energy. (You also get total reflected energy if the termination is a pure reactance...either a perfect capacitor or inductor...but we'll address that later).

At any rate, a *discontinuity* is any sudden change in the characteristic impedance of the transmission line, such as a point where the lines are squished closer together or stretched apart. (A sudden right-angle bend will also cause a *small* discontinuity). A burst of R.F. will be partially reflected from any discontinuity in a transmission line. Part of it will be returned to sender; part of it will be passed along to the termination. Very gradual changes in characteristic impedance will NOT cause a discontinuity. In fact, "tapered" transmission lines can be used as smooth impedance matching devices. Such things as the slant wire feed and the delta match, both variations of the tapered transmission line, were universally used in the broadcast industry and amateur radio for much of their early history. (There's an ancient local A.M. broadcast station in Fairbanks that until just a couple of years ago used a slant-wire-fed grounded tower! I had the dubious honor of working on the thing at one time.)

Anyway...where were we? Oh yes...discontinuities and partial reflections. We need to set the record straight right here and say that these are NOT inherently bad things! We can USE reflections on a transmission line to do all kinds of useful and wonderful things. We can't just IGNORE them, but we don't need to wring our hands over them, either! Things are generally

SIMPLER when there no reflections to contend with; but this by no means suggests that a MATCHED transmission line system is necessarily any *better* than an unmatched one. We'll talk a bit about the CONJUGATE MATCH before too long. As a prelude to this, however, let's modify our experiment one more time.

Let's remove the light bulb from the double-throw switch, and connect a shorting bar to those terminals, instead. Switch the switch to the transmit side. Send a one-second burst, turn off the transmitter, and then throw the switch to the other side. What happens when the pulse returns from the distant land and encounters the shorting bar? Why, it gets TOTALLY REFLECTED back out to the far end again! In fact, it will keep bouncing back and forth between the two ends of the transmission line forever. Actually, we could REMOVE the shorting bar and get the same result...an OPEN transmission line is just as reflective as a SHORTED one. As long as there is NO RESISTANCE in the termination, the reflection is total.

Now, we hope you have understood that all the previous discussion assumes an IDEAL transmission line. We always have to study IDEAL components in order understand the real-world editions thereof. Actual, practical transmission lines have resistive losses in them, which complicates the matter a little bit. In reality, an R.F. burst would never even make it to the far end of an 11.16 million mile transmission line. (Well, actually, it WOULD, but it would be less than the cosmic noise in the wire by the time it got there!) In reality, H.F. radio signals start running into trouble after a couple of miles, even in the best transmission lines humanly makeable. (I understand someone was able to make Ethernet work over a mile of rusty barbed wire, but this is NOT recommended practice!)

Now for the FUN Part

Hopefully you've been able to follow, and actually ENJOY some of this transmission line stuff, because we're *just* about ready to get to the real meat.

We've intentionally separated our FORWARD and REFLECTED signals for all the previous discussion. This is easy to do with short bursts, for (hopefully) quite obvious reasons.

However, amateur radio transmissions do NOT consist of such short bursts of R.F. (relative to the length of the transmission line, that is. A CW "dit" is MUCH less than a second long...but typical ham radio transmission lines are MUCH less than 11.16 million miles long, as well!) In typical communications service (as opposed to RADAR), any reflected signal on a transmission line is almost assuredly going to coincide with, or overlap, the outgoing signal. This opens up ENTIRELY new phenomena...as well as potential for confusion.

Whenever two electrical signals overlap each other in a conductor, you have the potential for *interference* to occur. If you remember from our chapter on antenna fundamentals, *interference* can be either constructive or destructive. Interference can occur in wires, just as it can in free space, with much the same results.

Allow me to introduce one more term that will help tie all this together: the Superposition Theorem.

Now, the Superposition Theorem is one of those physical truisms that seem so obvious it shouldn't even need mentioning, but it has *profound* implications. Stated simply, it's this:

At any point in time, any given location on a wire must have one and only one voltage.

Seems pretty obvious, doesn't it? Or to state it even more stupidly: You can't have two voltages in one place at the same time.

How does this truth affect life on Earth as we know it?

If we have two waves traveling on a wire...one going East and one going West...at ANY point on the wire, the waves MUST add or MUST subtract. There are no other options.

Now, whether they ADD or SUBTRACT depends on their relative *phasing.* For the case of total reflection, we have a few options. An OPEN transmission line termination (no termination) will return a reflected radio signal IN PHASE with the forward signal. The two signals will SUPERIMPOSE, or ADD at the point of reflection. Since the forward and reflected signal amplitudes are equal, the VOLTAGE at the termination point will be twice what it would be if no reflection existed. You can actually see this with a Lecher Wire. Remember the Lecher Wire at the start of the chapter? You just KNEW we'd come back to that sooner or later, didn't you? Well, here we are!

What about the case of a dead short at the termination?

Again, we have total reflection, but the reflected wave is 180 degrees OUT OF PHASE with the forward wave. So the SUPERIMPOSED voltage will be the DIFFERENCE between the forward and reflected signals, which are, as mentioned above, EXACTLY equal (but opposite). The resulting voltage at that point will be zero, as the Superposition Theorem tells us it must be. But we already know that, because we ALWAYS have zero volts across a dead short! So, whether we're treating our transmission line as a "lumped constant" (Ohm's Law) device or as a "distributed" (wave) device, we come up with the same answer!

Which brings us to another DEEP truth about physics. Our Universe is *staggeringly* consistent. If we can't arrive at PRECISELY the same answer to a problem by approaching it from two different angles, we're doing something WRONG! You can ALWAYS double-check this stuff. Don't take my word for it. MEASURE it yourself!

Now this process of superimposing an East traveling wave and a West traveling wave on a single pair or wires generates what is known as a STANDING WAVE. It's fairly obvious why it's called this; the relative values of voltage (SUPERPOSED VOLTAGE, that is, remain stationary relative to position along the line. You can see mechanical standing waves on any vibrating object, a plucked guitar string, for example. Or you can wobble a curly telephone cord back and forth and generate nice standing waves (if you can still find a phone with an actual cord!) You can easily measure electrical standing waves with a Lecher Wire...in fact, that is its main function.

Now, here's something very interesting and important.

Remember how we demonstrated that a FORWARD moving wave (traveling wave) has real energy? We lit up a light bulb with it. Remember how we demonstrated that a REFLECTED traveling wave has real energy? We lit a bulb with that too.

But guess what? A Standing Wave has no energy! It is a pure mathematical construct! It is analogous to isobar lines on a weather map. They INDICATE where pressure air pressure variances occur but they are NOT air pressure in themselves.

Now a system that SUPPORTS standing waves does indeed store energy. But this energy is in the form of forward and reflected REAL energy waves. The STANDING wave is just the visible, but powerless ("Wattless") MANIFESTATION of the two traveling wave components.

And this one point is where most of the Amateur Radio Stupidity Exchange concerning transmission lines comes from. A standing wave in itself can do NOTHING good or bad to any piece of amateur radio equipment. Blaming "standing waves" for transmitter damage or other ills is like blaming the number Pi for the truck tire that ran over your foot. Yes, Pi describes the diameter and circumference of the truck tire that ran over your foot, but Pi is NOT a truck tire!

Does this mean that we ignore standing waves? Not at all! But we need to know that Standing Waves are an INDICATION...not the THING ITSELF. With the PROPER INTERPRETATION, they can tell us a few things. Unfortunately, most hams have *no clue* how to properly interpret standing waves.

Fortunately, we don't HAVE to! There are other MUCH more meaningful indications than standing wave ratio that we can use to know what's really happening. REAL things with REAL effects.

Conjugal Rights

The Superposition Theorem allows us to do some really amazing things with transmission lines. But to understand this requires that you have ABSOLUTE FAITH in Ohm's Law. We already showed how consistent our physical universe is. You don't violate physical laws...they violate YOU. They apply EVERYWHERE, from all viewpoints.

We talked briefly about characteristic impedance of a transmission line...how it's built into the physical construction of the line...how it's totally independent of length...how it doesn't care what's at the far end.

However, despite this seeming rigidity, the Superposition Theorem allows us to ALTER the impedance of a transmission line at different locations, using the magic of wave interference. Let's look how this works.

Let's return to the case of a transmission line with a dead short at the termination. We know the forward and reflected power are the same, but the voltages are exactly out of phase. (Grudgingly deferring to the SWR-obsessed, we have infinite SWR on this transmission line). Now, moving BACK from the termination by wave, we see something interesting. We have added an extra 90 degrees of phase lag to our reflected signal, but that OVERLAPS the outbound signal 90 degrees BEFORE the latter reaches the termination. So, what happens is the two overlapping voltages are now 0 (or 360 degrees, depending on how you look at it) apart. In other words, wave back from the termination, the voltages are IN PHASE, and therefore add.

We now have a maximum voltage point. But when we look at the POWER, something doesn't add up. Or does it?

How much power is delivered to the load? Well, a dead short doesn't dissipate ANY power, so the answer is zero. How much power is reflected? All of it. At any point along the transmission line, the reflected power equals the forward power, so the TOTAL power has to equal zero. But we're measuring a HIGH voltage wave back from the termination. How do we reconcile a high voltage with no power? The answer is Ohm's law. What circuit condition, in combination with a very high voltage gives us zero power? Infinite resistance! That's right. One quarter wave back from the termination, we have an infinite resistance load. Physically, it's a chunk of transmission line; electrically it's a chunk of air. Pretty amazing, isn't it?

How about if we go back a half-wave from the termination? Well, we get an additional 180 degree phase change between forward and reflected voltages. The forward and reflected voltages cancel, and we get zero. Let's double check. Zero volts across zero ohms is how much power? Zero!

Transmission lines REPEAT the load impedance every half wave, and INVERT the impedance every quarter wave. And also every ODD multiple of a quarter wave. However, in every case, if we have either a dead short or an open termination, the total power is zero.

If we insert a transmitter at any point in the transmission line, how much power will the transmitter put out? ZERO!

What heresy is this??!! A transmitter's OUTPUT power is determined by the LOAD impedance? Are we nuts?

Well, do you believe Ohm's Law or not? How you answer the following two questions will reveal who the REAL heretic is!

How much power can a transmitter put into a dead short?

(Answer: Zero).

How much power can a transmitter put into an open circuit?

(Answer: Zero.

You CANNOT violate Ohms law. It violates *you* if you try.

Often I hear statements like "If you have a big mismatch, all that reflected power is going to come back and burn up your transmitter!"

Impossible. Absolutely impossible...at least in *this* world. And most likely in the next, as well. All that reflected power, as we've clearly demonstrated, prevents the transmitter from generating the power in the first place!

Engrave this on the inside of your eyelids:

WHERE A TRANSMISSION LINE EXISTS, THE POWER GENERATED BY ANY RADIO TRANSMITTER EQUALS THE FORWARD POWER MINUS THE REFLECTED POWER IN THE TRANSMISSION LINE. ALWAYS.

It's important to note the clause "where a transmission line exists," because, as we mentioned very early in the article, this is far from always the case. Think of all those hand-held radios out there with a whip sticking right out of the radio.

Are we saying that it's impossible to damage any radio transmitter by having a "bad" load? No, not at all. You can torch almost any transmitter by putting a dead short on it. And you can fry most modern radios by having an open circuit on them, as well, mainly by over-voltage of the output transistors. But it is NOT the SWR that does the damage! NEVER NEVER NEVER. A transmitter always sees an IMPEDANCE; it never sees an SWR. And don't ever forget it.

We've talked about reflections. We've talked about MULTIPLE reflections. And it is with regard to multiple reflections that things get really useful and clever.

The conjugate matching theorem tells us that maximum power will be transferred between a generator (transmitter) and a load when the load impedance is the COMPLEX CONJUGATE of the source impedance. This is a good thing to know. Without going into a lot of esoteric math, what the conjugate match theorem tells us is that you can match ANYTHING to ANYTHING with just two components, one parallel and one series. And sometimes less, if you're lucky.

When it comes to transmission lines, it translates into this: Any reflection in a transmission line can be compensated for with an equal and opposite reflection elsewhere in the transmission line.

We should, in all fairness, add one small caveat to this: The load impedance must have a real value of resistance less than infinity but greater than zero. What this means is that you really CAN'T match into a dead short or an open circuit...but you can come really really really close to doing it, if you have large enough matching components. The real point is that you only need TWO of them.

Let's look at a practical example to demonstrate this. Let's say we have a dipole antenna that has a radiation resistance of 50 ohms. To keep things simple, let's assume our antenna is perfectly resonant. (Reactive terminations of transmission lines can be a bit trickier to analyze). We want to feed this with 450 ohm ladder line. We know that we will have a 9:1 impedance mismatch at the antenna. (Assuming our transmission line is very good, we'll have the same mismatch at the INPUT end as well). Once again, in deference to our SWR worrywarts, we have an SWR of 9:1. Now, this is one case where this SWR information is good to know. What this tells us is that we have a WIDE RANGE of impedances to choose from, depending on our transmission line length. We know that if we pick a multiple of a half-wavelength, our transmission line input impedance will REPEAT the load impedance. So, if we cut our line to be a full wavelength long, we will have 50 ohms impedance, which will make most transmitters happy all by itself. What if we choose a transmission line length of wave? We know the impedance of a wave line INVERTS itself. The quarter wave transmission line is a very useful special case. If the load is resistive (which in this case it is), the input impedance is equal to the characteristic impedance squared, divided by the load impedance. (This is called the "geometric mean"). So this gives us 450 squared divided by 50= 202,500/50=4050 ohms.

Well, not too many transmitters are going to be happy with a 4050 ohm load...even if it IS purely resistive! So, this might not be too smart a choice of transmission line length.

On the other hand, what if we replace our dipole with the venerable Double Zepp, mentioned in the beginning of this fascinating chapter? As it turns out, the impedance at the center of a double Zepp is on the order of 2500-3000 ohms at resonance. Let's use a value of 2500 ohms, just for jollies. If we were to connect a 450 ohm line to the center of that, wave long, what might we expect to see at the input end? Using our same geometric mean formula, we have 450 squared divided by 2500, which gives us an impedance of 81 ohms at the input end. Oh, joy joy! This is well within the "happy" range of any typical ham transmitter. With no further adjustments whatsoever, our transmitter will put out 96% of the power that it would put into a perfect 50 ohm load...assuming the transmitter is truly optimized for 50 ohms. (I have to admit I cheated to come up with the answer...the venerable ARRL Antenna Book has all kinds of handy graphs to show power loss vs impedance mismatching and such. It's okay to use cheat charts and computers as long as you don't use them as a substitute for thought processes).

What have we done with the impedance inversion of the wave transmission line? We've performed a *conjugate match.* The impedance looking back TOWARD the transmitter with the wave section in place is the COMPLEX CONJUGATE of the antenna impedance itself.

Now, sections of transmission lines are not the only means of performing conjugate matching. In fact, using "series sections" as described in the above has become a bit of a lost art in most modern ham shacks. Standard practice now is to use a "lumped constant" antenna tuner, using one or more coils and capacitors to perform the conjugate match. As mentioned earlier, there is NO fundamental difference between lumped constants and distributed components as far as the physics is concerned. Any combination of distributed and lumped components may be used to achieve a conjugate match. In the above example, it might be practical to use a lumped component tuner to move that 81 ohms down to 50 ohms for the truly obsessive. More commonly, a lumped tuner would be used to tune out REACTANCES where the antenna is operated somewhat removed from its resonant frequency.

It should be emphasized that NO amount of twiddling of an antenna tuner at the INPUT end of a transmission line has any effect whatsoever on the standing wave ratio on that transmission line. The SWR is determined ONLY by the load impedance at the line termination. The antenna tuner only adjusts the impedance the transmitter sees.

Now, this fact brings up another very interesting point. Let's say we have a 100 watt transmitter, designed for a 50 ohm load. We have a wide range antenna tuner immediately after the transmitter. Beyond that, we have a length of transmission line, finally terminated in a severely mismatched antenna. Let's use our very first example, with a 450 ohm transmission line and a 50 ohm antenna. We have a 9:1 SWR on the transmission line. Taking a gander at another ARRL Handbook chart, we see that we will have about 60 watts of reflected power on the transmission line.

Now, remember what I had you engrave on the inside of your eyelids a while back? Transmitted power is equal to forward power minus reflected power.

Now, if we twiddle the antenna tuner so that our transmitter sees 50 ohms, we know the transmitter is putting out 100 watts. On the far side of the antenna tuner (away from the transmitter) we see 60 watts of power reflected from the antenna toward the antenna tuner. Does something seem amiss? Is our transmitter only putting out 40 watts? No...it's seeing 50 ohms...so we know it's putting out 100 watts (assuming the transmitter is functioning properly). Let's look at the FORWARD power on the transmission line. 160 watts! Well, how about that? Now the math works out...but WHERE does that extra 60 watts come from? Our transmitter can only put out 100 watts. What have we overlooked?

It's simple. It's a DOUBLE reflection. The 60 watts of REFLECTED power is RE-REFLECTED from the antenna tuner...actually added IN PHASE with the original forward power. But WHY the double reflection?

Without KNOWING it...when we adjusted our antenna tuner to make our transmitter "happy" we created a conjugate match on the other side of the tuner. It's actually a gross mismatch looking toward the transmitter...but it's a gross mismatch in the exact Complex Conjugate of the impedance looking the other way!

Actually, in this example, we have TWO complex conjugate pairs...one at the junction of the input of the tuner and the transmitter...and another at the junction of the antenna tuner's output and everything after it!

Again, this is stuff you can CONSISTENTLY DEMONSTRATE on the work bench. I always love showing a room full of skeptical "SWR Gurus" how the forward power on the output of a tuner EXCEEDS the power capacity of the transmitter!

Well, I suppose I could go on and on about this absolutely intriguing subject, but instead I'll refer you to two pieces of required reading:

1. "My Feedline Tunes My Antenna," By Byron Goodman, W1DX (SK). Originally published in QST in 1956, it has been reprinted several times since. A genuine classic, and a fine example of clear analytical thinking...a rarity in ham radio today.

2. "Reflections" by Walt Maxwell, W2DU. This is the most eloquent and detailed work on the subject ever written. Most of the material in this EPILOGUE chapter was stolen, not in prose, but in principle, from Walt's writings. This originally appeared in a series of QST articles in the 1970s, but has been consolidated in a couple of excellent books, Reflections and Reflections II. I understand there's a Reflections III coming out soon.