

# SWR - the persistent myth

*What you always wanted to know about SWR, but were too scared to ask!*

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## *True or False ?*

- *An antenna must have a SWR of 1:1 to radiate efficiently.*
- *For every watt of reduced reflected power achieved an extra watt of forward power enters the antenna and is radiated.*
- *Reflected power is absorbed by the transmitter and causes damage due to excessive dissipation in the amplifier output stage.*
- *An antenna must only be fed with a feed line that is an exact multiple of half wavelengths.*
- *A quarter wave base fed  $\lambda/4$  vertical antenna only requires 3 or 4 radials to radiate efficiently.*



## King SWR

### *How did you score ?*

If you answered *False* to all the questions you were correct. These are just some of the erroneous statements made over the years in amateur publications.

## *VSWR & SWR - what's the difference ?*

© VSWR is short for *Voltage Standing Wave Ratio*

© SWR is short for *Standing Wave Ratio*

In reality the two are exactly the same. The reason we often see *VSWR* written is because it is more practical to measure RF waves by detecting voltage rather than RF current. Most measuring instruments measure the voltage and then convert to power. ( $P = V^2 / R$ )

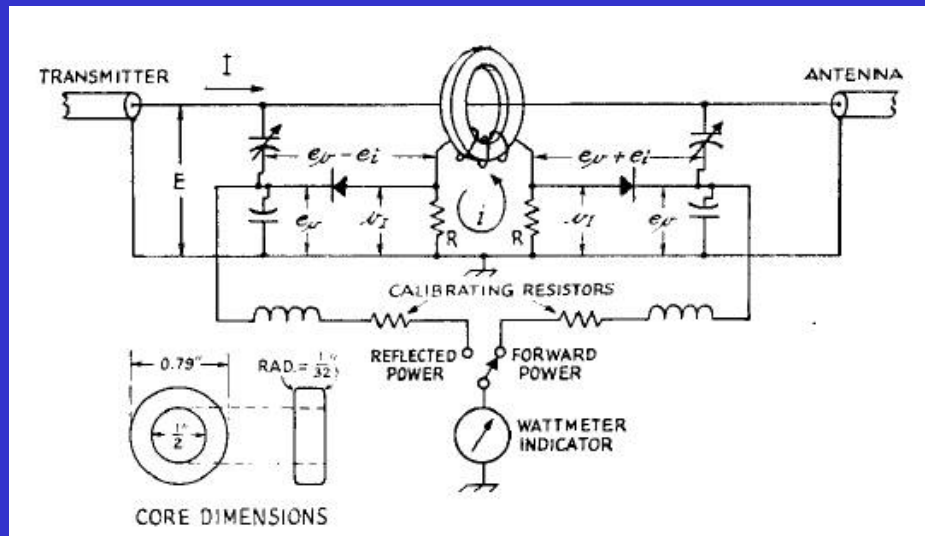
If the measurement were made by measuring the RF currents flowing we could use *ISWR* as the notation.

Knowing the line impedance and the applied voltage we can calculate the value of current since  $I = V / Z$ .

# Measuring Forward & Reflected Power

Measurement of RF power flowing in a coaxial transmission line is performed with an item known as a *Directional Coupler*.

*Bruene Bridge*  
*SWR meter*



In amateur circles this is normally known as a *SWR Meter*.



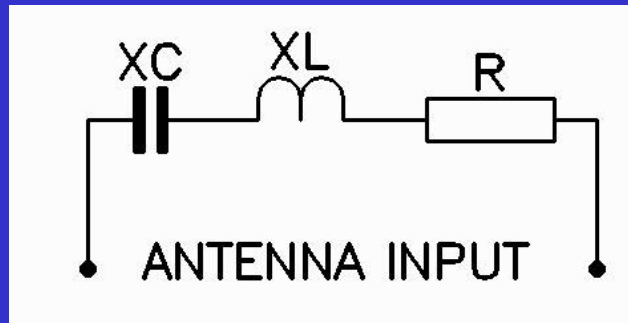
*Lab grade Narda microwave Directional Coupler. 1 to 12.4 GHz*

## *Before the SWR Meter - The Dark Ages !*

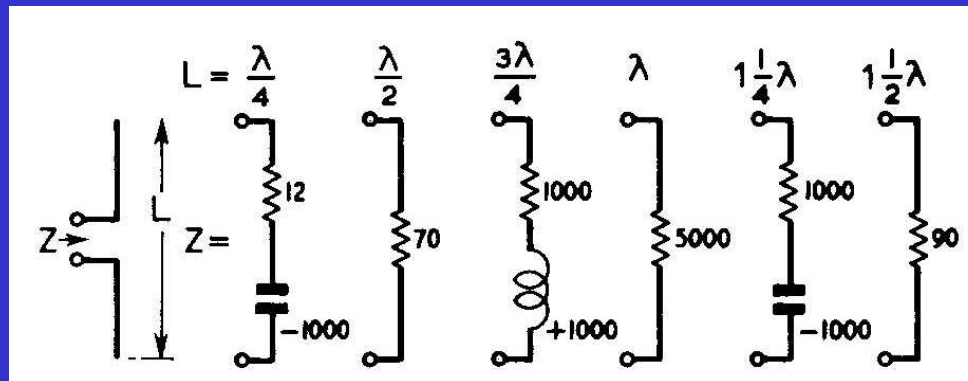
- The Directional Coupler and hence SWR meters are relatively recent inventions. Prior to their invention in about the late 1950s by Warren Bruene (W0TTK) of Collins Radio, transmitter output power was determined in a different way.
- Until about half way through World War 2 no commercial RF power meters existed, and these were only dummy load types.
- RF power measurement was performed with an *Aerial Ammeter* which measured the RF current being generated by the transmitter. The operator simply tuned for maximum current into the feed line. *(Maximum Smoke !)*
- In actual fact this was a better system because maximum current equals maximum power. Today, because we can measure SWR, we spend far too much time worrying about it - instead of operating in blissful ignorance!
- A low SWR does not mean the antenna is radiating efficiently, it can mean quite the opposite. If the SWR stays low over a large frequency range, something is very wrong!

## Antenna Equivalent Circuit

- An antenna is a complex device exhibiting resistance and reactance, hence we refer to it as an *impedance*.
- The resistance is made up from two types of resistance connected in series, one a *real resistor* and one an *imaginary resistor*. This is what we measure when we evaluate the *feedpoint resistance* or impedance.
- The imaginary resistance is the *radiation resistance* and is due to the transformation between the antenna and the *free-space impedance* of  $377 \Omega$ .
- The real resistance is due to RF current losses in the material, the *ohmic resistance*, and is due to skin resistance and other factors. It can also be caused by *ground current* in a radiator over a lossy ground.
- Reactance occurs when the antenna is operated away from its *resonant point*. At resonance the antenna behaves like a real resistance.
- A  $50 \Omega$  antenna does not measure  $50 \Omega$  when measured with a ohm-meter, it is either a short or an open circuit. Only a *Dummy Load* measures  $50 \Omega$ .



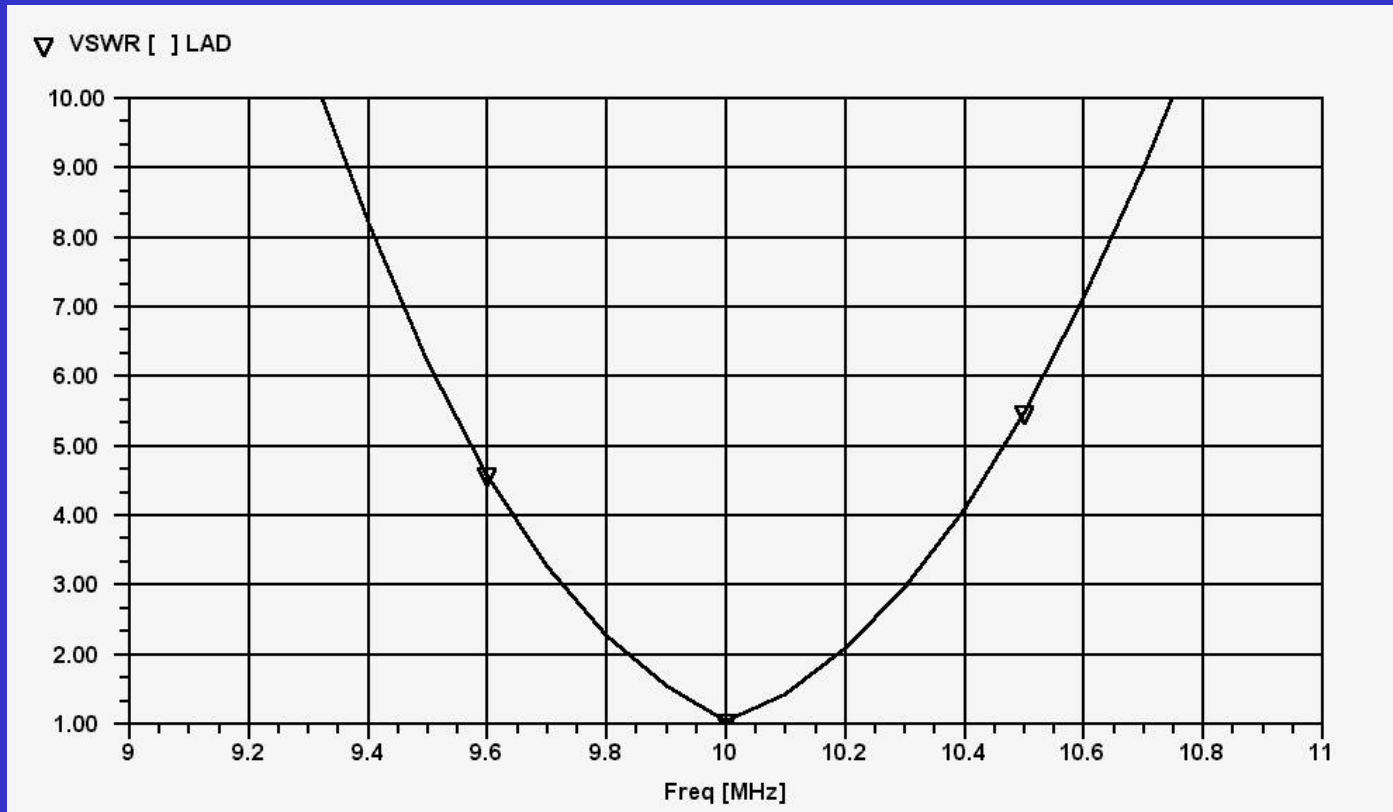
- At resonance  $X_C$  &  $X_L$  are equal and opposite values and so cancel out, leaving just the resistance  $R$ .
- Below resonance only  $X_C$  is present and above resonance only  $X_L$  is present. Hence for these two conditions the load will appear to be either capacitive or inductive. *Note that power cannot be dissipated in a reactance because the voltage and current are  $90^\circ$  out of phase.*



### Impedance of various dipole types

All of the types shown radiate with equal efficiency when correctly matched to the feed line although their radiation patterns are different.





## Typical SWR plot versus frequency

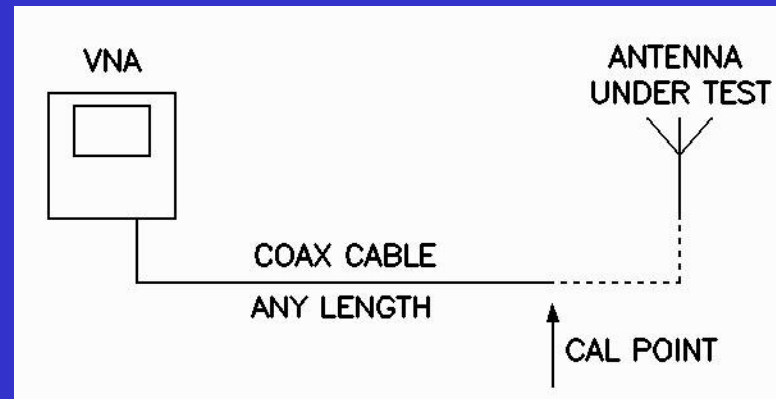
If your antenna doesn't behave like this then it probably has high ohmic losses which are dissipating the RF instead of radiating it !

## *So what exactly is SWR ?*

- SWR is the ratio between two different impedance's, one being the measuring impedance. This today is normally 50  $\Omega$ .
- If we measure in a 50  $\Omega$  system and the load impedance is 100  $\Omega$  then the SWR is  $100 / 50 = 2$ . This is written as ***SWR = 2:1*** because it is a ratio. When the load and the measuring impedance are the same then  $SWR = 1:1$ .
- If the load is lower in value than the measuring impedance we simply swap the two numbers around because SWR cannot be lower than 1:1. If the load were 25  $\Omega$  the SWR would be  $50 / 25 = 2:1$ .
- Hence, our SWR meter doesn't tell us much of any use, except that we are off the ideal case. All it tells us is the margin of error, but not which way to go to correct the condition. In order to ascertain this we need more complex equipment, such as a ***Vector Network Analyser*** or an ***Impedance Bridge***.

## Professional Antenna Measurements

Today the instrument most often used for antenna impedance measurements is the *Vector Network Analyser* (VNA). Using any arbitrary length of cable between the VNA and the test site we can *see* the exact impedance occurring at the antenna feed point.



Before use the cable is *normalised*. An open circuit, short circuit and a  $50\ \Omega$  load are connected in turn. The VNA stores the *Calibration Data* for later use. The cable length can be any value necessary to reach between the VNA and the antenna. Once the *cal-data* is stored it can be recalled as often as needed. The VNA resolves the resistive and reactive portions and displays the results. The antenna measurement is normally performed in an *anechoic chamber* - a RF *Dark-Room* - to exclude any strong transmitted signals.

## Matched Line Condition

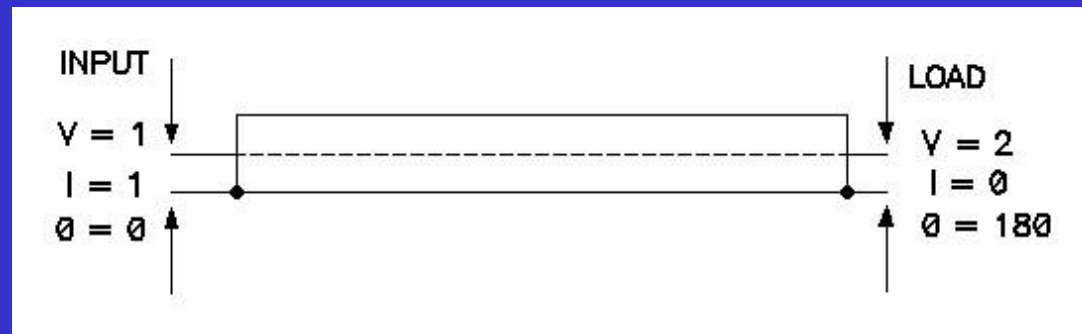
- In an ideal case the transmission line would have zero loss. This never happens in practice.
- When the source of RF energy, the line and the load are all of the same impedance (resistance) the line is *matched* and all the power sent from the source will be dissipated in the load.
- Because all the power sent down the line is accepted by the load there is no reflected power and so the SWR is 1:1. The RF current and voltage anywhere along the line are constant and in phase.
- In a practical transmission line there will be some loss (attenuation) so the power arriving at the load is less than the source fed into the line. In a lossy line some of the power is developed as heat in the line losses and the rest is accepted by the load.

## Mismatched Line Condition

- In a mismatched line the load is a different value to the transmission line impedance and not all the power sent down the line is accepted by the load.
- Some of the power is reflected away from the load and it travels back down the line to the source.
- *Note that the power level existing at the load end of the line is not the same as the power fed into the line by the source. It can be more and it can be less, depending on the phase relationship due to the mismatch condition and the attenuation (loss) of the line.*
- If the line has loss the power sent by the source will be attenuated by the line loss.

## Open Circuit Line

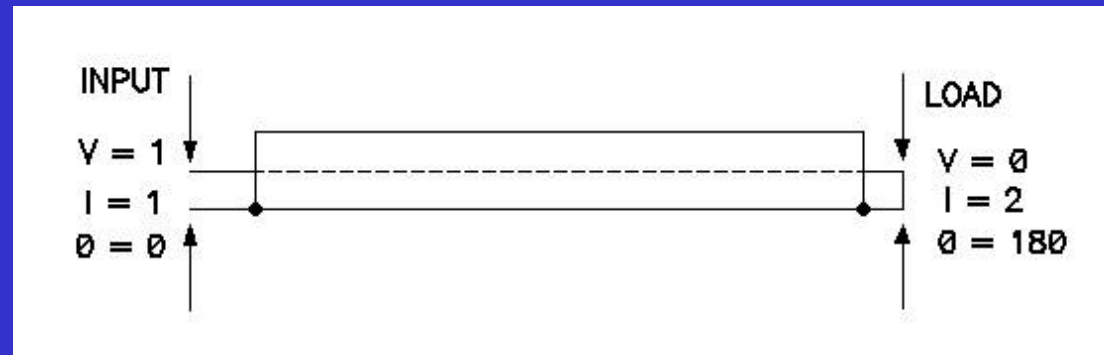
- In an open circuit line (at the load end) the electromagnetic wave travels forward from the source along the line until it arrives at the load.
- Before it reaches the load the voltage and current are in phase and a constant value.



- At the open end the current falls to zero and the collapsing *magnetic field* causes the voltage to rise to a value of twice that of the matched line condition.
- The phase of the *current* reverses by  $180^\circ$ . (Lenz's Law)
- All of the power arriving at the open end is turned around (reflected) and travels back towards the source.
- In this condition the SWR is infinite.

## Short Circuit Line

- In a short circuit line (at the load end) the electromagnetic wave travels forward from the source along the line until it arrives at the load.
- Before it reaches the load the voltage and current are in phase and a constant value.



- At the shorted end the voltage falls to zero and the collapsing *electrostatic field* causes the current to rise to a value of twice that of the matched line condition.
- The phase of the *voltage* reverses by  $180^\circ$ .
- All of the power arriving at the shorted end is turned around (reflected) and travels back towards the source.
- In this condition the SWR is infinite.

## Open & Short Circuit Line

- For power to be dissipated we need voltage and current to be present.

$P = VI \cos \theta$  where  $\theta$  is the phase angle between voltage and current.

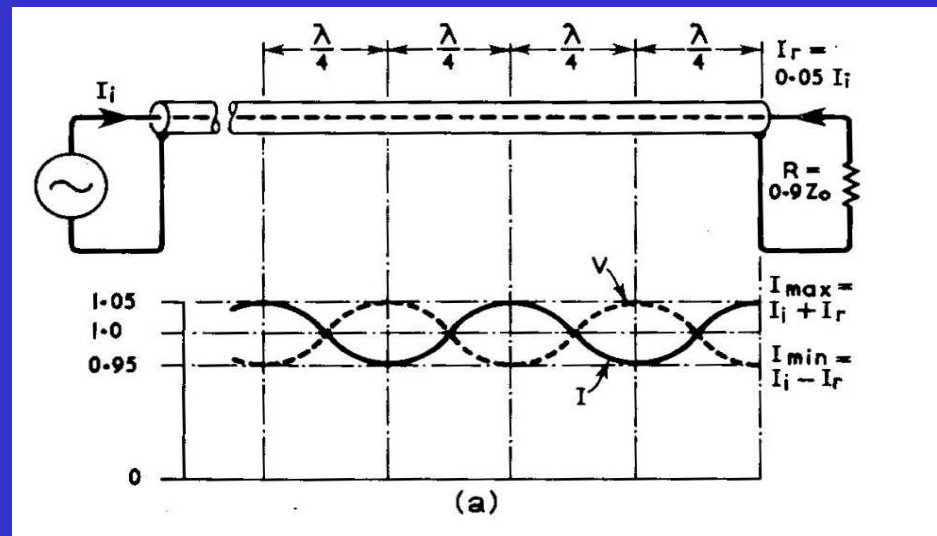
- In the open circuit condition although the voltage is 2-times the normal line voltage there is no current flowing.
- In the short circuit condition although the current is 2-times the normal line current there is no voltage present.
- For both of these cases the resultant voltage and current are  $180^\circ$  out of phase.
- Hence, no power is *dissipated* at the end of the line and all the power is reflected back towards the source. No power is *lost* because of an infinite SWR.
- The reflected wave contains *real power* since  $P = VI \cos \theta$ . When  $\theta = 0^\circ$  the result is 1, when  $\theta = 180^\circ$  the result is -1. The minus sign denotes the wave is traveling in the opposite direction.



## Standing Waves on a mismatched line

It is the  $180^\circ$  difference in the reflected wave current and voltage that sets up **Standing Waves**. The two electromagnetic waves existing on the transmission line are separate entities but they interact with one another.

- As the two waves travel up the line (the forward wave) and down the line (the reflected wave) the voltage and current vectorially add. At the sum points the voltages and currents rise to a maximum. At the other points they vectorially subtract to give a minimum voltage or current.



- The standing waves of voltage or current maximum occur every  $180^\circ$  ( $\lambda/2$ ).

## Higher and lower value for $Z_L$

- For the case where  $Z_L$  is higher than the transmission line impedance the voltage and current behave in the same way as when the far end is open circuit. The voltage rises to a higher level, the current falls to a lower level and changes phase by  $180^\circ$ .
- For the case where  $Z_L$  is lower than the transmission line impedance the voltage and current behave in the same way as when the far end is a short circuit. The current rises to a higher level, the voltage falls to a lower level and changes phase by  $180^\circ$ .
- In both these cases the power remains constant and the phase between voltage and current in the reflected wave is  $180^\circ$ .

## Reflection Coefficient & SWR

It is more convenient to use an alternative method of expressing SWR. This is the *voltage reflection coefficient*  $\rho$  (rho) since we normally measure RF voltage and not current.

$$\rho = \frac{\text{SWR} - 1}{\text{SWR} + 1} \quad \& \quad \text{SWR} = \frac{1 + \rho}{1 - \rho}$$

For a SWR of 3:1  $\rho = 0.5$

$\rho$  is the magnitude of the reflected voltage where the forward voltage is 1. Since  $P = V^2 / R$  to express as power we square the value of  $\rho$ .

SWR = 3:1 is the result of a reflected power of 0.25 times the forward power (25%).

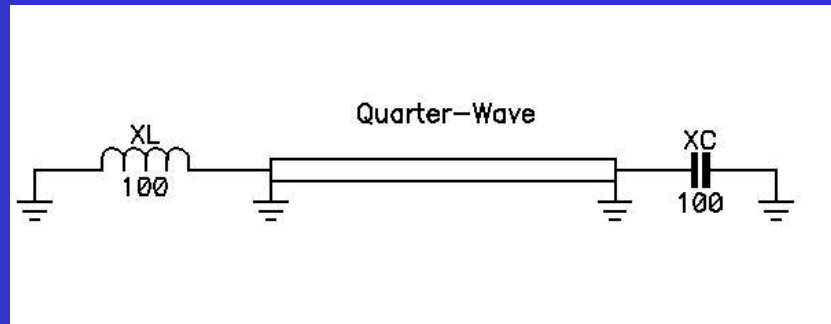
## Property of a Half Wavelength Transmission Line

- In a half wavelength line ( $\lambda/2$ ) the impedance appearing at the far end is the same as the impedance at the sending end.
- The phase of the voltage and current at the far end is  $180^\circ$  out of phase with the sending end.
- However, the phase relationship between voltage and current at any point on the line is always  $0^\circ$  if the line is matched.
- The reactance appearing at the far end of the line is the same as the sending end. If a reactance of  $+100 \Omega$  is connected at the sending end we will see the same  $+100 \Omega$  at the far end.
- The  $\lambda/2$  line is a non-inverting line.

# Reactance Inverting Properties of a Quarter Wavelength Line

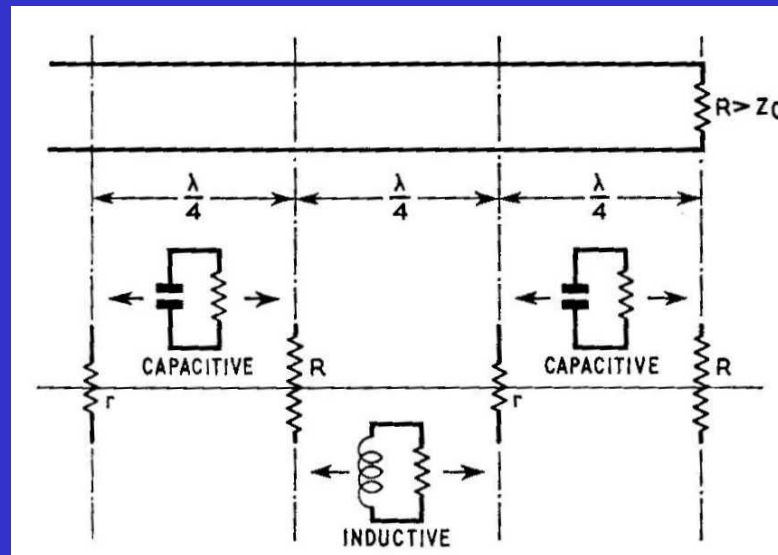
A  $\lambda/4$  section of transmission line inverts reactance and resistance.

$+j100\Omega$



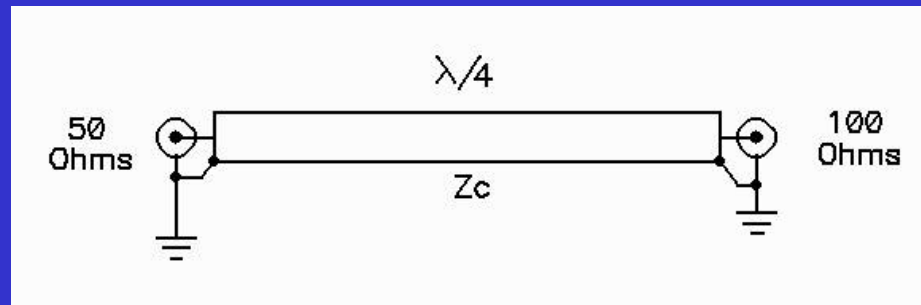
$-j100\Omega$

The reactance at one end of the line is inverted and appears at the other end of the line. This is a very powerful tool. In a long transmission line the reactance is inverted many times.



## Matching with a quarter wavelength line ( $\lambda/4$ )

Where we need to match between two similar value impedance's we can use a  $\lambda/4$  section of line, either coaxial, micro-strip or balanced wire lines.



The impedance of the line required ( $Z_C$ ) is given by the formula:

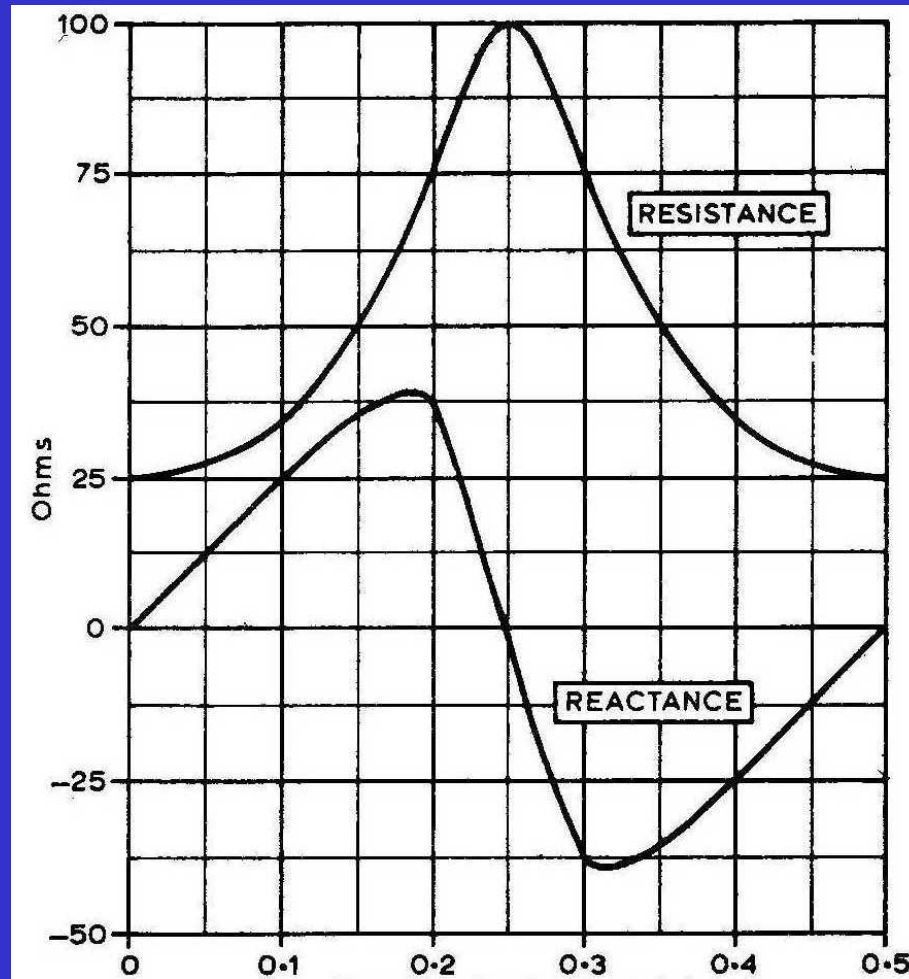
$$Z_C = \sqrt{Z_1 \times Z_2}$$

Where  $Z_1$  &  $Z_2$  are the two impedance's to be matched. In the example we need a line of  $70.7 \Omega$  and  $72 \Omega$  coax would be suitable

If coaxial cable is used we are limited to the impedance's we can match between because of the small number of different impedance lines manufactured.

If open wire balanced lines, micro-strip or coaxial air lines are used we have more choices because the line can be made any impedance required.

## Resistance & Reactance curves

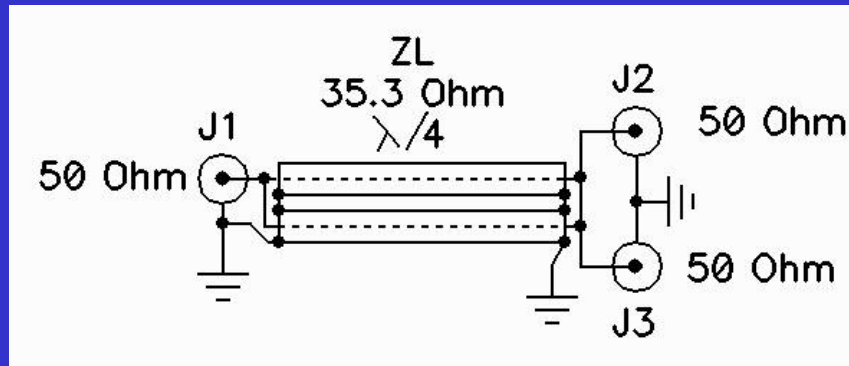


Wavelengths from Load

**25  $\Omega$  resistive load connected to a length of 50  $\Omega$  coax cable.**

## Special Quarter Wave Impedance Converters

Although the number of different impedance coaxial cables is limited we can use some sneaky methods to achieve a good match.



In this scheme we parallel two 72  $\Omega$  cables to achieve an impedance of 35  $\Omega$  needed to match between 50  $\Omega$  and the 25  $\Omega$  presented by two 50  $\Omega$  antennas connected in parallel.

***Note that each impedance presents a SWR of 1.4:1 to the 35  $\Omega$  line but the net SWR is 1:1.***

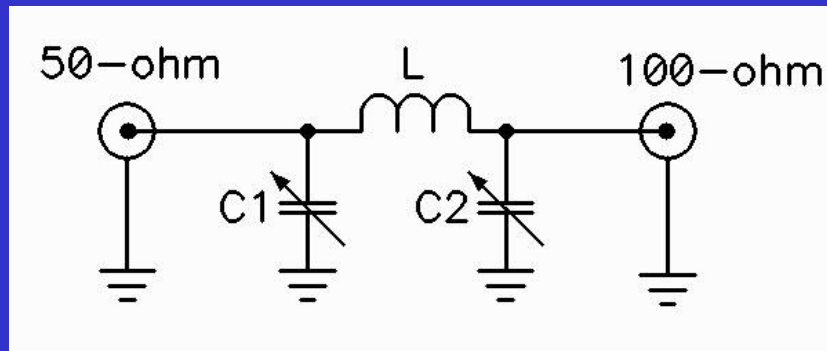
We have deliberately introduced a SWR to effect the matching. This is the basis of all impedance matching networks. There is always a high SWR somewhere in the network, it can be as high as 100:1 in some methods.



## Inverting Reactance with other methods

A transmission line of  $\lambda/4$  electrical length can be simulated by a lumped network of inductors and capacitors.

If the network is designed so that a phase shift of  $90^\circ$  occurs from end to the other we have the same electrical parameters as a real  $\lambda/4$  line. The most popular network is the Pi network ( $\pi$ ).



By selecting the values for the components we can design any impedance line desired with any electrical length between about  $0.1 \lambda$  and  $0.75 \lambda$ . In the example we require a network of  $70.7 \Omega$  characteristic impedance.

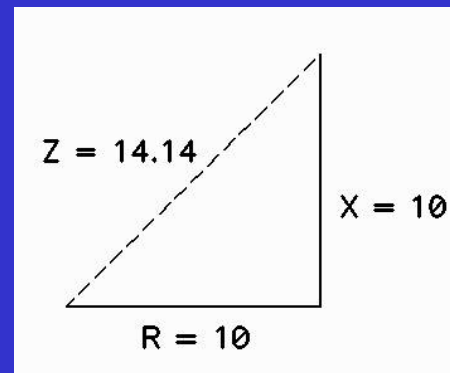
## Handling Resistance & Reactance - the j notation

When we have resistance and reactance (impedance) we cannot simply add the two values together. If an impedance consists of  $R = 10 \Omega$  and a reactance of  $+10 \Omega$  the answer isn't  $10 + 10 = 20$ , but something different.

We can solve this graphically by drawing two lines at right angles to scale and then constructing the missing side of the triangle. For the example we find the resultant impedance is  $14.14 \Omega$ .

To find the result by calculation we

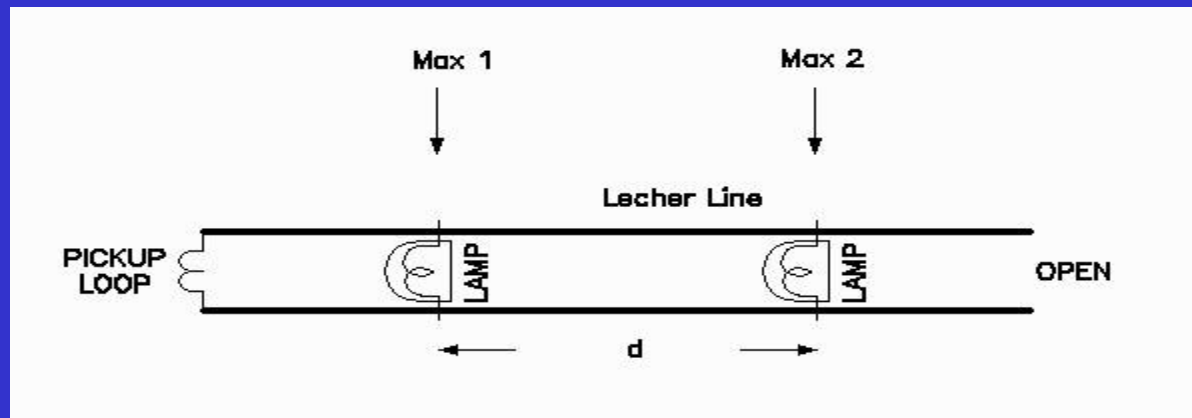
use the formula:  $Z = \sqrt{R^2 + X^2}$



We write the values using *j notation*, where an inductive reactance is  $+j$  and a capacitive reactance is  $-j$ . For example,  $100 + j25 \Omega$  is an impedance consisting of a resistor of  $100 \Omega$  connected in series with an inductive reactance of  $25 \Omega$  and this is the same as an impedance of  $103 \Omega$ .

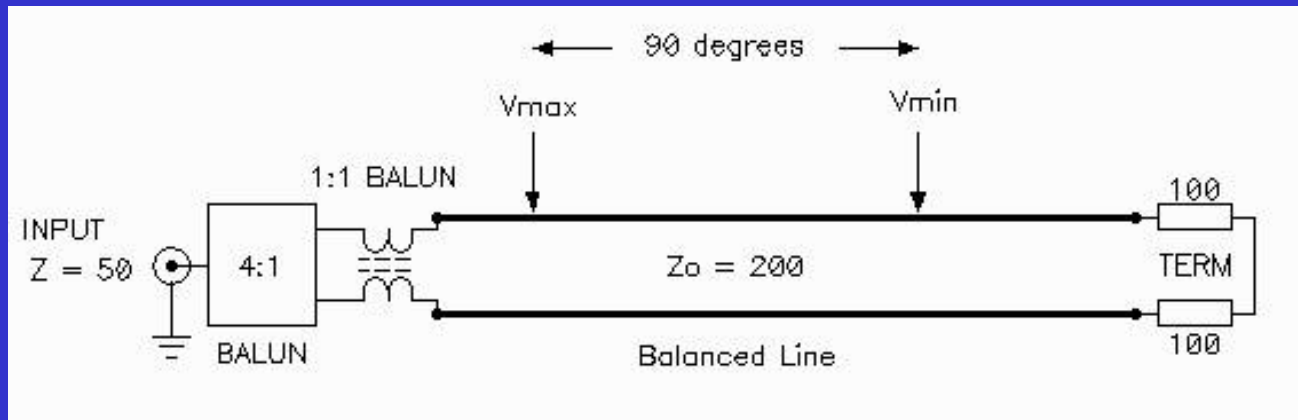
## Measuring Wavelength with an open circuit line

- A useful property of an open circuit line is that we can use the standing waves to determine the wavelength and hence frequency. This is an item of test equipment called a **Lecher Line**. (*Dr Ernst Lecher, Vienna 1856 - 1926, paper published in 1890*)



The standing wave voltage maximum points occur every  $\lambda/2$ . By accurately measuring the distance between two adjacent voltage maximum points gives us the wavelength. With care an accuracy of 1% or better is possible. (*Lecher used this technique in 1910 to measure a 300MHz oscillator!*) Today the **Slotted Line** is used at microwaves to measure frequency and SWR.

## Measuring SWR on a balanced line



If the line is perfectly matched the RF voltage anywhere on the line is constant. If the line is mismatched Standing Wave voltage maximum and minimum points will exist. By measuring the values of these we can use the formula below to calculate the SWR.

$$\text{SWR} = V_{\max} / V_{\min}$$

If  $V_{\max} = 1.5\text{V}$  and  $V_{\min} = 0.5\text{V}$  then  $\text{SWR} = 3:1$ . *(If the line is perfectly matched the voltage would be 1V all along the line. The  $\pm 0.5\text{V}$  difference is due to  $\rho = 0.5$ ).*

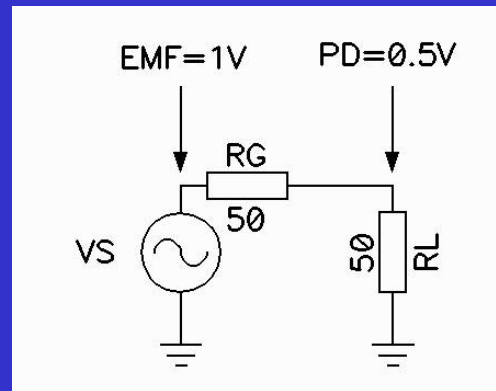
This is how SWR was measured before Directional Couplers for coaxial lines were invented. If the voltage is constant we say the line is *flat*.

## *So what happens to the reflected power ?*

- Many amateur articles are insistent that the reflected power is *absorbed* by the transmitter and causes damage or extra heating in the amplifier network components. It is simple to prove these arguments wrong.
- The reason they assume this occurs is because they treat the transmitter as a *Signal Generator*.
- In a signal generator a resistive attenuator network is placed between the oscillator and the output connector to ensure the load always sees a constant resistance (impedance).
- The reflected power from the load is totally absorbed by the attenuator network and dissipated as heat.
- RF transmitters do not work this way, they are *Conjugately Matched* not resistively matched as the signal generator is.

## How to prove a transmitter is Conjugately Matched

- If the transmitter behaved as a signal generator it would have a source resistance ( $R_G$ ) of  $50\ \Omega$ . The signal generator develops an open circuit output voltage we call the EMF. When the load is attached the output voltage falls to the PD value and 50% of the power is dissipated in the output resistance of the signal generator and 50% in the load.



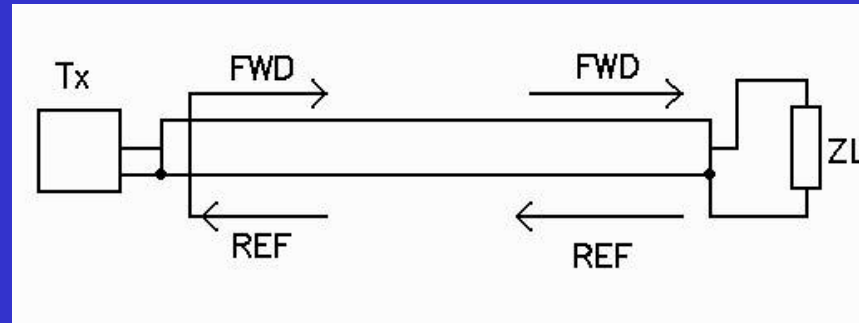
*$R_G$  and  $R_L$  are connected in series and act like a potential divider network*

- This means the highest efficiency it can have is only 50%. Transmitters often exhibit efficiency figures of 60% or higher.
- Hence, the transmitter does not have an output resistance of  $50\ \Omega$ , but something quite different.
- Audio amplifiers designed to drive low impedance speakers have an output source impedance of as little as  $0.01\ \Omega$ , transmitters are similar.

## Conjugately Matched Devices and Reflected Power

- In a conjugately matched power source the output network is designed to transfer maximum current (and hence power) into the load or transmission line.
- Although they are designed to operate into a given impedance (typically  $50\ \Omega$ ) they do not look like a  $50\ \Omega$  resistive load when we *look back* into the output terminal.
- Depending on how you analyse them they can be considered as a *Current Source* or a *Voltage Source*.
- A current source has an output impedance of zero  $\Omega$  and voltage source an output impedance of infinite  $\Omega$ .
- Hence, they present a very high SWR to any power which is reflected back towards them, the same as an open or short circuit antenna.

## Reflected Power Diagram



- Many amateurs regard the power reflected from the antenna as *reflection loss*.
- The reflected power from the mismatched load end of the transmission line is repelled (*re-reflected*) by the conjugately matched transmitter.
- Upon re-reflection the phase again undergoes a  $180^\circ$  change (*just like that which occurred at the antenna*) and now the power is *in-phase* with the forward power.
- Hence, the re-reflected power and the forward power from the transmitter add to give an increase in the power entering the transmission line. This is known as *reflection gain*.
- With a SWR of 3:1 on the line the forward power increases by 25% to an indicated 125% of the nominal power. (*Many amateurs have observed this with their SWR meter but believe this is an incorrect measurement*).

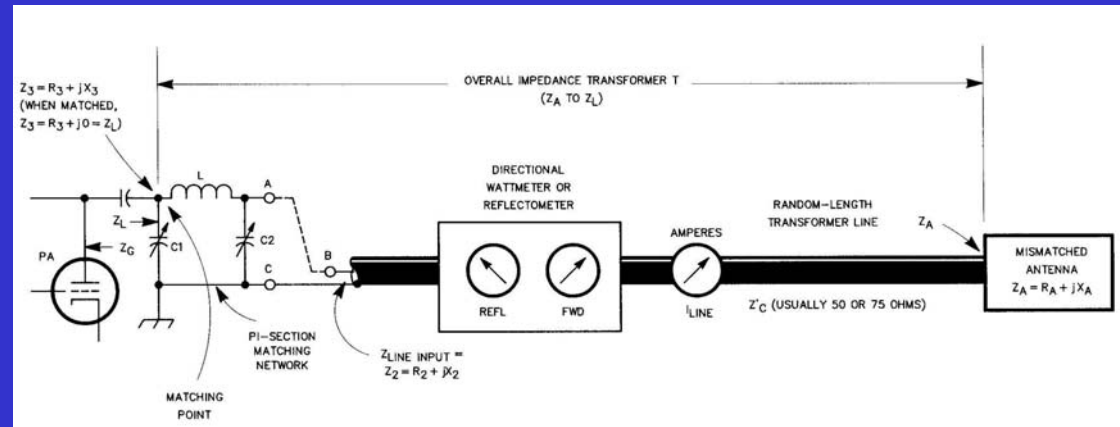


## Reflection Gain

- The *re-reflection* of the original reflected power cancels out the *reflection loss* and gives rise to an increase in the forward power. Suppose the transmitter is rated at 100-W into a 50  $\Omega$  resistive load and the line SWR is 3:1.
- The forward power is now 125-W into the transmission line. Assuming the line has no loss, this same 125-W will appear at the antenna terminals.
- The antenna needs to send back (*reflect*) some of the power when a SWR occurs. Since with a SWR of 3:1 the power to be reflected is 25-W and there is 125-W occurring at the antenna mismatch, the antenna needs to accept 100-W and reject the remainder.
- Hence, the full 100-W transmitter rated power is *accepted and radiated* by the antenna and the excess 25-W is reflected back to the transmitter.
- Although the SWR is 3:1 the full 100-W is radiated and no power is *lost*. Therefore there is no reduction in field strength. Using the SWR meter we can determine the radiated power. It is :  $P_{\text{rad}} = (P_{\text{fwd}} - P_{\text{ref}})$

# Valve Transmitters

- In a valve transmitter we have an adjustable matching network between the valve and the output terminal. Often this is a  $\pi$  network. A practical  $\pi$  network can match over a 100:1 impedance ratio with negligible loss.
- By adjusting the anode tune and load capacitors we can establish maximum power transfer (maximum current) into the antenna feed line by canceling out the reactance seen at the input to the line.

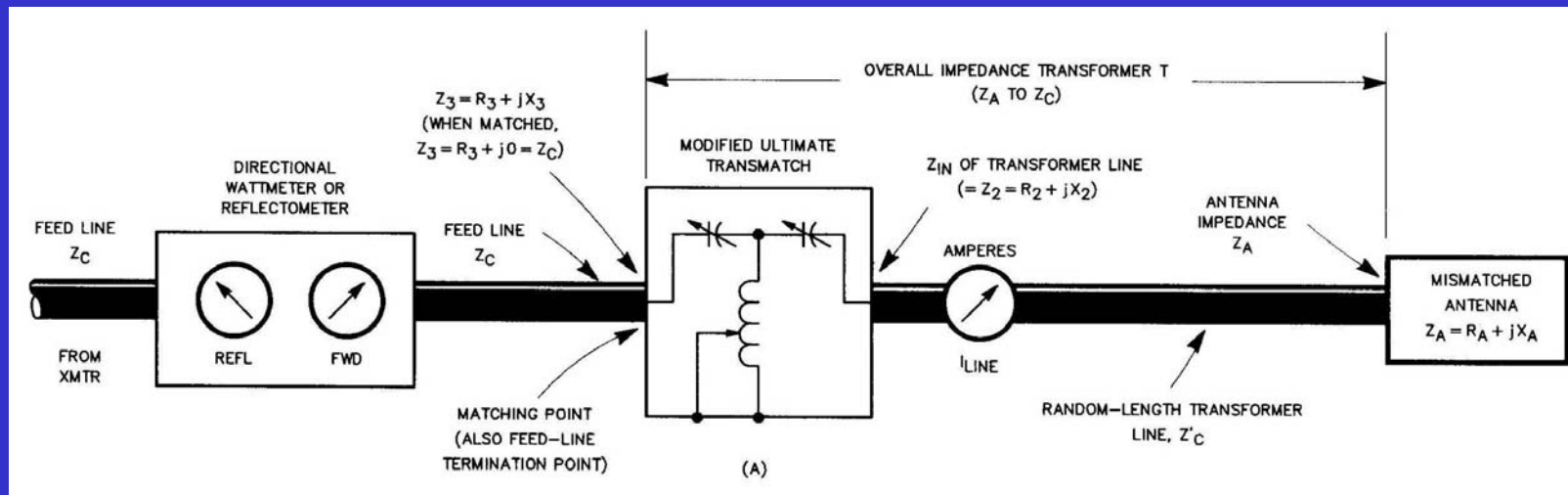


- Any reactive component reflected back down the feed line from a mismatched antenna will be inverted every  $\lambda/4$  but can be corrected by adjusting the capacitors if they have sufficient range.
- A typical valve transmitter with a  $\pi$  network can match over about 3:1 to 5:1 SWR with minimal power loss. This allows us to work over a wider portion of the band with little effort.

## Solid State Transmitters

In a solid state transmitter the output network is *fixed tuned* and no adjustment is possible by the operator. It will only deliver its full power into a pure  $50\ \Omega$  resistive load - *is this progress?*

- If the SWR presented to the transmitter is excessive the RF amplifier will not be able to deliver maximum power into the feed line. Typically when the SWR is about 2:1 the internal reflected power detector will begin to *back-off* the drive. At a SWR of 4:1 it is almost totally shut-down.
- To correct this we need to insert an additional matching network, called an *Antenna Tuning Unit (ATU)* or *Transmatch*.



## Practical transmission lines with some loss

- All the cases up until now have assumed zero line loss. In a practical feed line some loss will be present. If the line has loss then the indicated SWR at the line input will measure less than the SWR occurring at the antenna.
- If the line has infinite loss then all the power input to the line will be dissipated as heat and none will arrive at the far end. It behaves like a *Dummy Load* and the SWR indicated is 1:1. *(30m of RG-58/U at 432MHz has  $\approx 30\text{dB}$  of loss and behaves like a dummy load).*
- For cases where the loss is less then we need to consider what the SWR meter will indicate if placed at the transmitter end of the line.
- If the line has 3dB loss and 100-W are sent from the transmitter end only 50-W will arrive at the antenna. Assume the antenna SWR is infinite. Hence, 100% of the applied power will be reflected back. This is 50-W.
- The reflected power traveling back to the transmitter is also reduced in level by the 3dB line loss and only 25-W arrive at the SWR meter. It uses the 100-W and 25-W to compute the SWR and arrives at a value of 3:1. But the real SWR is infinite.

## Percentage Reflected Power and SWR

Some measurements which will be useful.

<b>% Reflected Power</b>	<b>Indicated SWR</b>
1%	1.22:1
2%	1.35:1
4%	1.5:1
11%	2:1
25%	3:1
33%	4.2:1
50%	6:1
67%	10:1

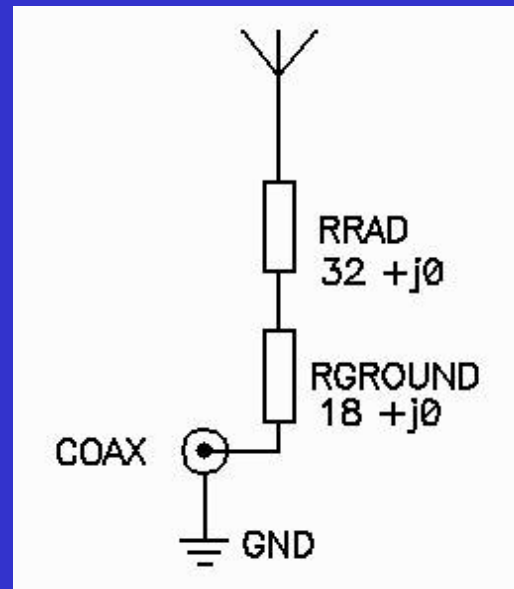
*If the line has 1dB of attenuation and the antenna end is either open or short the indicated SWR at the transmitter end is 9:1.*

*If the line loss is 6dB the indicated SWR is 1.7:1 for the same fault condition.*

***We can use this method to measure the line attenuation !***

## Vertical antennas - how many radials are needed ?

A  $\lambda/4$  vertical fed at the base requires a minimum of 60 radials of about  $0.4\lambda$  in length to radiate efficiently, 120 radials would be better. The deciding factor is the ground *loss resistance*. Dry, sandy ground has a higher resistance than moist soil and requires more radials.



The ground loss resistance is effectively in series with the antenna. A  $\lambda/4$  vertical exhibits an impedance of  $32 + j0 \Omega$  at resonance. If the ground loss resistance is  $18 \Omega$ , due to too few radials, the feed point impedance is  $32 + 18 = 50 \Omega$  and presents a perfect 1:1 SWR to the feed line. Although this looks good we need to appreciate what is actually happening!

The power is divided between the antenna and the ground loss resistance. 36% of the power is wasted heating up the ground and only 64% is available for radiation.

*In this case the SWR is too low because a high percentage of the power is wasted in the ground resistance. It also stays low over a wide band because the ground loss is shunting the feed point.*

Increasing the number of radials lowers the ground loss resistance to about  $1 \Omega$  and now 98% of the power is radiated and only 2% is lost in the ground. The feed point is now  $33 + j0 \Omega$  at resonance. (SWR = 1.5:1) Reducing the antenna height by about 5% increases the feed point impedance and a good match to  $50 \Omega$  is possible.

A better method is to increase the vertical height to about  $3/8\lambda$  where the feed impedance is about  $500 \Omega$  and the ground loss is now insignificant, so fewer radials may be used. In this method we now need to match from the  $50 \Omega$  feed line to the higher impedance with a network.

## *True or False ?*

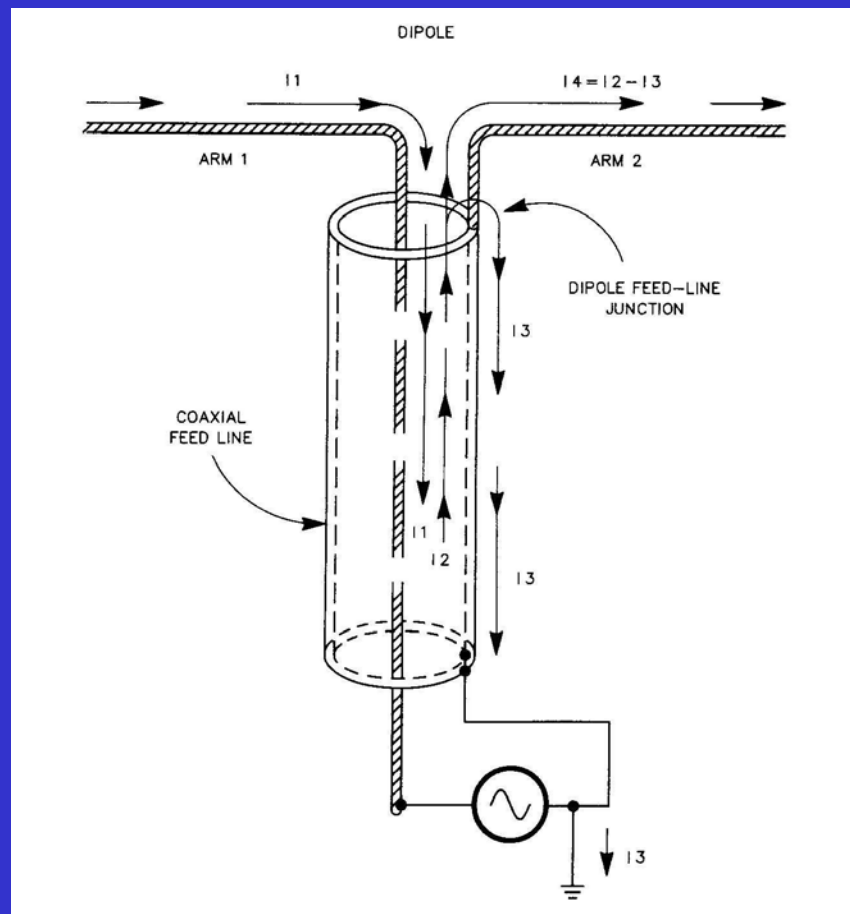
- *A high SWR on the feed line causes power to be radiated from the outer of the coax cable which causes TVI.*
- *An antenna tuning unit does not tune the antenna.*
- *A high SWR causes excessive harmonics to be radiated.*
- *It isn't necessary to employ a balun with a dipole fed with coaxial cable.*
- *In multi-Yagi arrays the length of the cables running from the power splitter to the individual Yagis must be exact multiples of a half wavelength.*



## Again all these statements are incorrect !

- The RF currents flowing in a coaxial cable (both forward & reflected) are all contained *within and between* the inner and outer conductors. ***No current flows on the outside of a coaxial cable due to a mismatch.*** Similarly with open wire balanced lines no RF is radiated because the currents are equal in value and flow in opposite directions and so the magnetic fields cancel.
- One thing that causes RF current to flow on the outside is direct radiation from the antenna if the coaxial cable is placed close to radiating elements. Re-routing the coax can eliminate this effect.
- RF currents will also flow on the outside of the coaxial cable if a balanced antenna (dipole etc) is fed without a Balun. These currents have nothing to do with SWR, they are still present when the antenna is perfectly matched to the cable.
- These RF currents flow back down the outside of the cable and confuse the SWR meter when they reach it. ***In one case observed the SWR meter indicated more reflected power than forward power - an impossible case!*** To correct this we need to fit “***RF choking networks***” of ferrite beads on the coaxial cable close to the SWR meter. In RF design labs this is a common technique to obtain a true indication. Even ***lab-grade*** power meters sometimes need this technique.

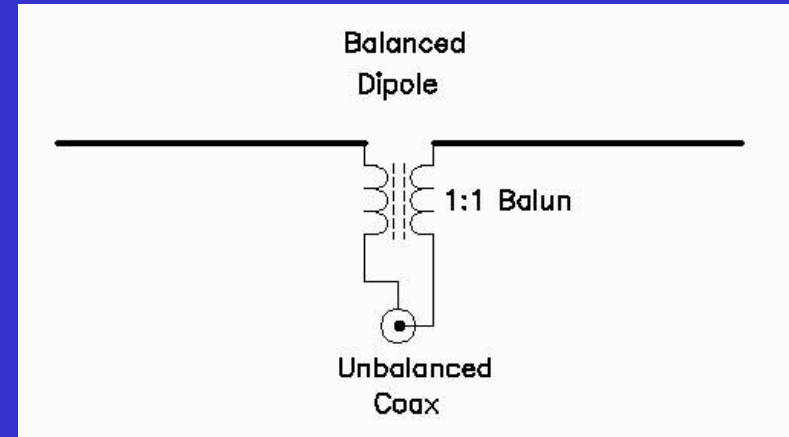
## Unbalanced Coaxial Cable Current without a Balun



A balanced antenna fed with an unbalanced feed line generates an extra current path on the outer of the coax. This flows to ground and is wasted power.

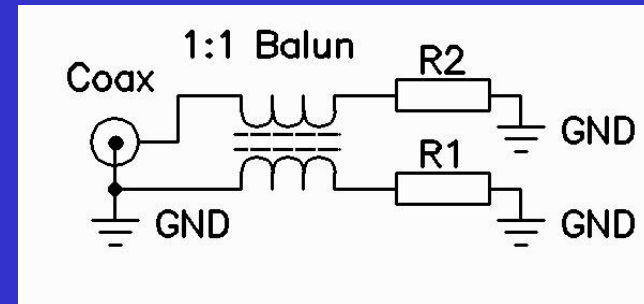
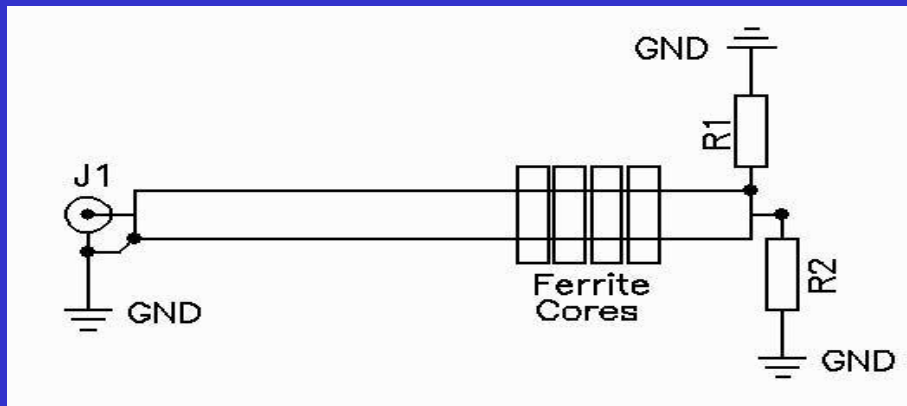
# Baluns

- There are two different types of Balun. One type is a *Voltage Balun* the other is a *Current Balun*. Of the two the Current Balun is far superior. The best example is the W2DU *Coaxial Choke Sleeve* design loaded with ferrite beads or toroids.



- The W2DU 1:1 balun is simple to make and low cost. It can cover a very wide bandwidth with almost perfect amplitude ( $\pm 1\%$ ) and phase balance ( $\pm 1^\circ$ ).
- The power rating is purely that of the coaxial cable it is made from. The example shown for 144 MHz uses PTFE cable and handles 1 kW without any significant heating. The power dissipation in the ferrite beads is negligible.

## W2DU Balun Test Circuit



### Physical Test Circuit

### Equivalent Circuit

- To test a W2DU balun to prove it is a **Current Balun** we use the circuit shown. If the values of R1 & R2 are the same the voltage across each will be the same with a  $180^\circ$  phase difference. (Measured with a RF Vector Voltmeter).
- If we change R1 to be twice the value of R2 then the voltage across R1 is now twice that across R2 because the RF currents are still the same value. The phase difference is still  $180^\circ$ .
- If the ferrite cores did not **choke** the RF current on the outer of the coax no current could flow in R1 because the other end of the line is grounded. The W2DU balun behaves like a **Common-Mode** balanced transformer.

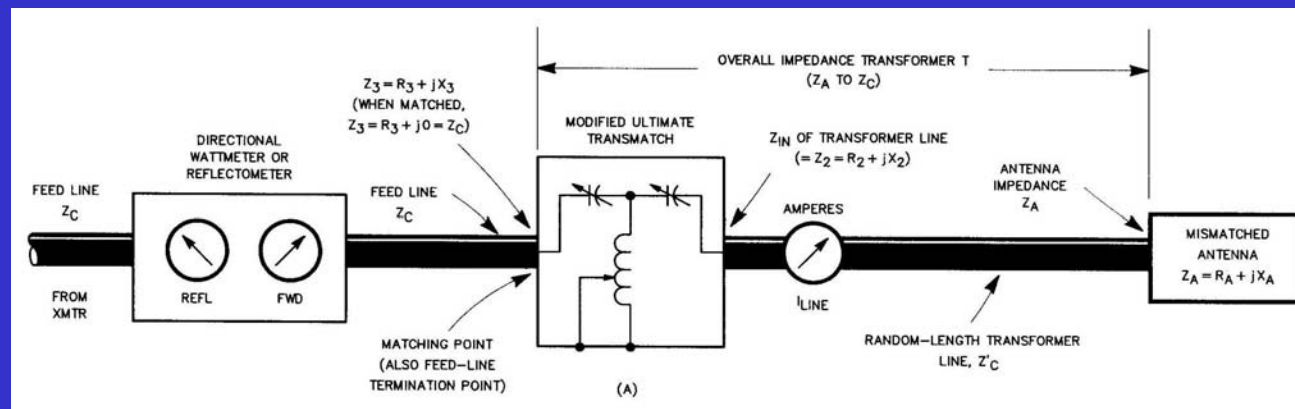
## Baluns - some incorrect assumptions

Baluns are also classified by the impedance ratio.

- A 1:1 balun transfers the impedance presented at one end to the other end. If the balun sees an antenna impedance of  $300 -j100 \Omega$  the same impedance will appear across the unbalanced feed line end. In a  $50 \Omega$  system this is a SWR of 6.7:1 and in a  $72 \Omega$  system a SWR of 4.6:1.
- Connecting a  $50 \Omega$  coax to a 1:1 balun does not *force* the antenna to look like  $50 \Omega$ , only a  $50 \Omega$  load resistor can do this. The coax will accept any impedance presented to it and simply convey this back to the sending end, with inversions in the reactive and resistive portions occurring every  $\lambda/4$ .
- A 4:1 balun if presented with the same  $300 -j100 \Omega$  by the antenna will cause  $75 -j25 \Omega$  to be presented to the unbalanced coax cable. In a  $50 \Omega$  system this is a SWR of 1.7:1 and in a  $72 \Omega$  system this is a SWR of 1.4:1.
- Both of these assume the balun is perfect, which is rarely the case in practice. Some error always occurs in the transformation process. Voltage baluns are far more likely to cause an incorrect transformation.

# Antenna Tuning Unit

- An ATU does in fact *tune* the antenna, despite what many amateurs believe. To understand this this have to examine the reactance problem in more detail.
- We have seen that a  $\lambda/4$  line inverts reactance whereas a  $\lambda/2$  line does not. If the transmission line is exactly  $\lambda/2$  in length (or multiples) the impedance and reactance occurring at both ends of the line are identical. If we need a reactance of, say,  $+100 \Omega$  to be placed across the antenna feed point to correct a SWR, then it is more convenient to place this at the transmitter end where we can adjust it if necessary.
- If the feed line is not an exact  $\lambda/2$  it doesn't matter because we can vary the value and sign of the reactance to compensate. If the feed line happens to be odd multiples of  $\lambda/4$  then we simply change the sign of the reactance from  $+100 \Omega$  to  $-100 \Omega$ .
- To be strictly correct *The ATU tunes the antenna AND the feed line*, because the two work in conjunction.

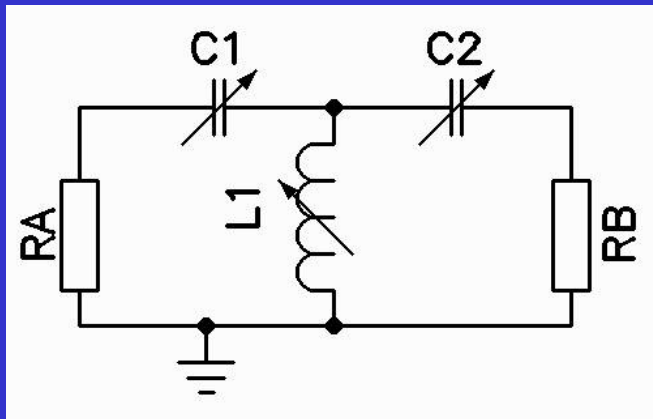


## Matching a feed line with an ATU

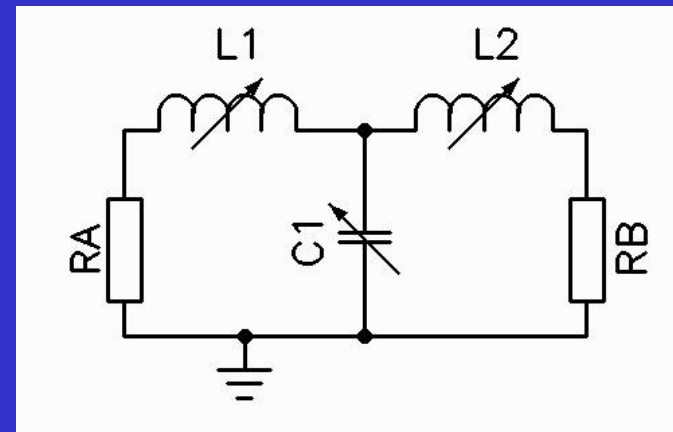
- When we insert an ATU between the transmitter and the input to the feed line we are introducing an additional *conjugate matching network*. This is a case of *two wrongs making a right*.
- By adjusting the ATU we make the transmitter *see* a low SWR. But the SWR occurring at the output terminals of the ATU is still the same as before. All we have done is to install a *one-way valve* to help prevent power flowing back into the transmitter.
- Any reflected power from the antenna is *re-reflected* by the conjugately matched ATU and it is sent back to the antenna reinforcing the forward power.
- What is important is the insertion-loss of the ATU. If this is more than the power increase obtained from the transmitter when the ATU was used then we are no better off, or we could be worse off compared to the high SWR condition without the ATU.
- *If a 100-W solid state amplifier backs off the power to 80-W when a SWR is present and the ATU has an insertion loss of 1dB (20%), then we are no better off with the ATU in circuit. We still only have 80-W entering the feed line but 20-W is now being turned into heat in the ATU.*

## *ATU types - the good and the bad !*

- There are two main types of ATU, the Pi network and the T network.
- The normal Pi network behaves as a low pass filter and hence reduces the harmonic levels passed to the feed line.
- The normal T network behaves as a high pass network and does not significantly reduce harmonic levels. (*In fact it can accentuate them with a particular phase angle of reflected power!*) This can make the SWR appear higher than it actually is.
- The alternative T network topology acts as a low pass filter but has less matching capability and is more bulky.



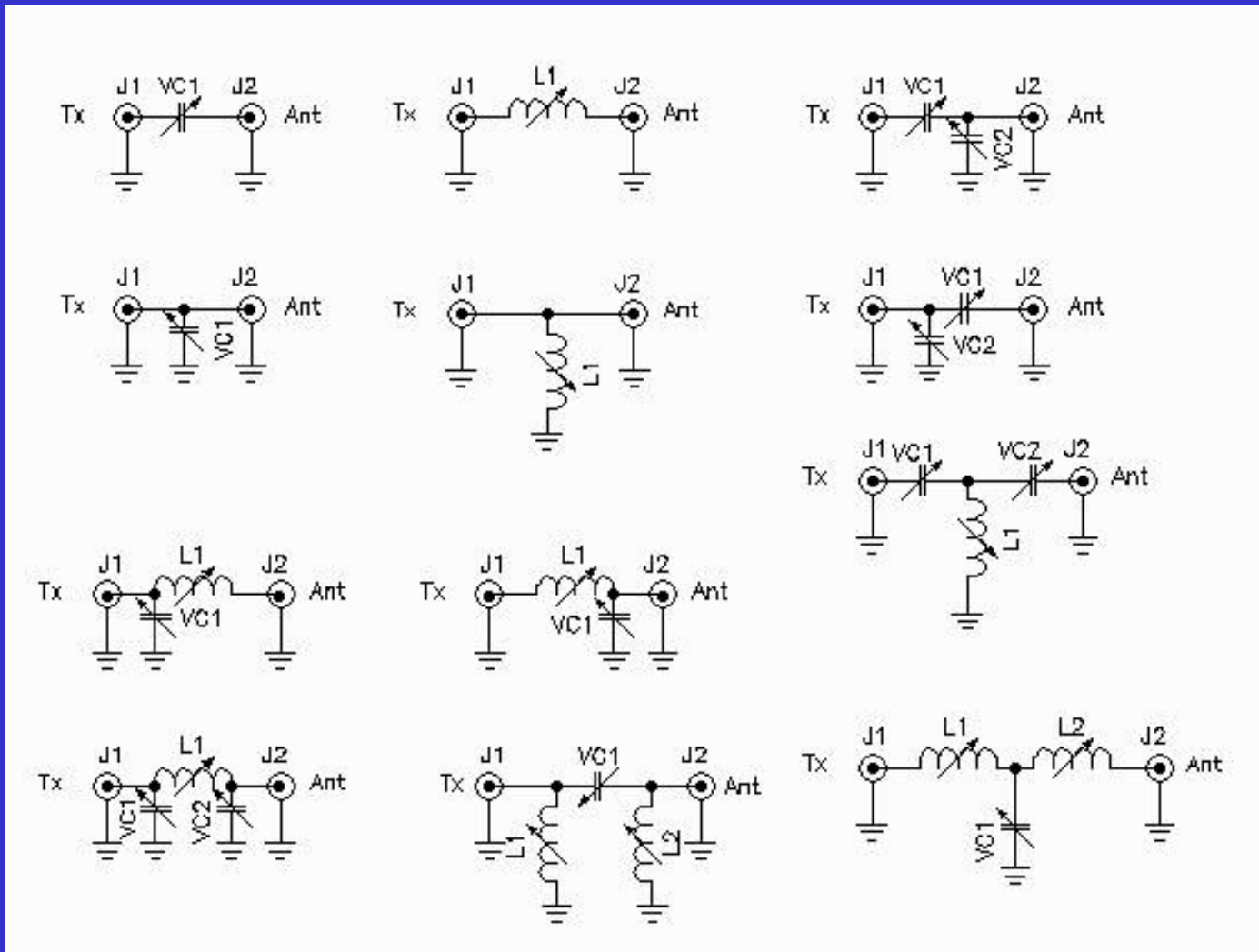
**Standard T network for an ATU**



**Alternative T network**



# ATU Circuits - All the possible combinations !



No commercial ATU caters for all these combinations, some are very limited. A homebrewed ATU can be configured to any circuit required by suitable switching.

## Solid State Transmitter & SWR “Power Back Off”

- Manufacturer’s of solid state transmitters (and Linear Amplifiers) normally design the *SWR protection* to begin reducing the power when the SWR exceeds a certain level, often as little as 2:1.
- The reason usually given for this in the manual is: *To reduce the possibility of damage to the power transistors*. Normally this is an incorrect statement.
- *The manufacturer’s of the power transistors test them at 30:1 SWR at all phase angles at maximum power and an elevated supply voltage (about 25% greater than normal) in a “load pulling test jig” to ensure they do not become spurious or suffer damage. This is far greater than they will ever experience in practice.*
- Solid state transmitters, because they are fixed tuned, cannot tolerate large reactive currents and voltages being reflected back to the output stages. For the types using wideband ferrite transformers the ferrite cores can saturate because of the large reactive currents.
- When this occurs the intermodulation performance suffers and by reducing the power output they are held to an acceptable level.

## Solid State Transmitters With Built-In ATUs

The trend today is for manufacturer's to incorporate an ATU in the HF transceiver. *This is an admission of defeat!*

- The volume available for the ATU is often limited and so the inductors are wound on ferrite cores to reduce the volume.
- The Q it is possible to attain is well short of that of an external ATU using a high Q (physically large) air-wound inductor. The RF capacitors are also limited in Q. *Low Q means the resistive losses are high.*
- The result of this is that the insertion loss is often quite high, as much as 2dB in some cases. 2dB is 40% power loss in the ATU.
- The inductors because they are wound on ferrite cores are also capable of saturation with large reactive currents flowing. This *de-tunes* the network and causes an incorrect conjugate match. Above a certain SWR the amplifier simply gives up the fight and backs off the power to virtually zero!

*And you thought that modern amateur equipment is better than types made 30 years ago ?*

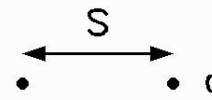
## Feeding a $\lambda/2$ Dipole

A wire dipole of half wavelength total length exhibits a feed point impedance of  $73.1 + j0 \Omega$  at resonance when mounted at least  $\lambda/4$  above ground.

- If the dipole is fed with  $50 \Omega$  coaxial cable and a 1:1 Current Balun and the SWR meter is  $50 \Omega$  then the indicated SWR is  $73.1 / 50 = 1.46:1$ .
- Many amateurs think this is still too high and alter the antenna length or bring the ends towards ground in an *Inverted V* configuration to lower the SWR to 1:1. Some of the power radiated is absorbed by the lossy ground adding extra resistance, which lowers the SWR. ***But up to 25% of the radiated power is now being absorbed in the lossy ground heating it up!***
- If instead they used  $72 \Omega$  coaxial cable with a SWR meter designed for  $72 \Omega$  the indicated SWR would be  $73.1 / 72 = 1.015:1$ , which is so close to 1:1 it is academic.
- If you have a dipole fed with  $50 \Omega$  coax and a  $50 \Omega$  SWR meter then when the SWR meter indicates  $\approx 1.5:1$  you are ***bang-on*** resonance.

## Balanced Wire Lines

- Balanced open wire lines can be made in any required impedance for little effort or expense. The higher the line impedance the lower the attenuation losses. 200  $\Omega$  open wire balanced line has an attenuation loss less than 25% that of average size 50  $\Omega$  coaxial cable. (The main cause of losses in coaxial cable are due to skin effect resistance due to the high current flowing and dielectric loss).

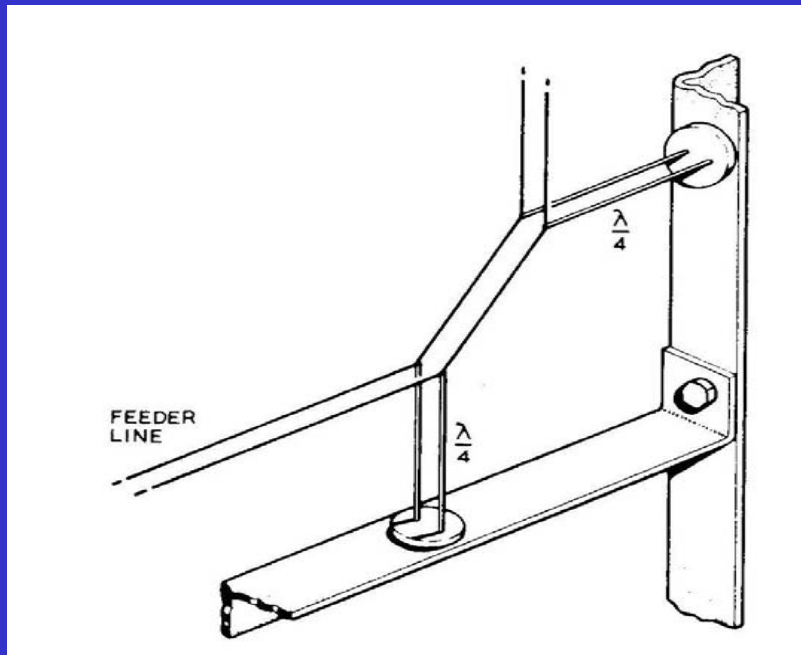


$Z = 276 \log (2S/d)$   
 $S =$  center-center spacing  
 $d =$  wire diameter

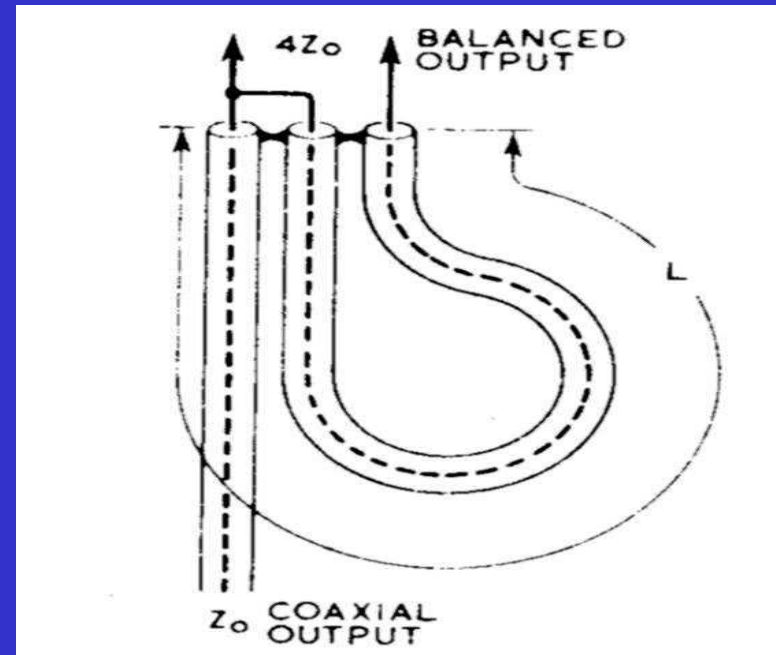
- The lower loss in high impedance balanced lines is mainly due to the lower RF currents flowing because the high impedance raises the line voltage ( $I^2 R$  loss). At a large physical spacing the breakdown voltage is also high and so they are very useful where high SWR voltages may occur. The RF voltage on a matched 200  $\Omega$  balanced line is only twice that of a 50  $\Omega$  line. At 100-W it is 141 V rms.
- A 200  $\Omega$  balanced line can easily handle 5kV of RF voltage (125-kW). The dielectric losses are also very small, air is an excellent insulator! At 1-kW the RF voltage on a perfectly matched 200  $\Omega$  line is 450V rms. With a SWR of infinity it is 900V rms.
- Open wire balanced lines with a balun at the transmitter end and an ATU allows more flexible matching over a much wider range (about 25% more) than with coaxial cable and lower line losses. The power rating is at least 4-times that of coaxial cable.

## Open Wire Line with Metal-Insulators

For VHF & UHF the lines can be supported by *Metal-Insulators*.



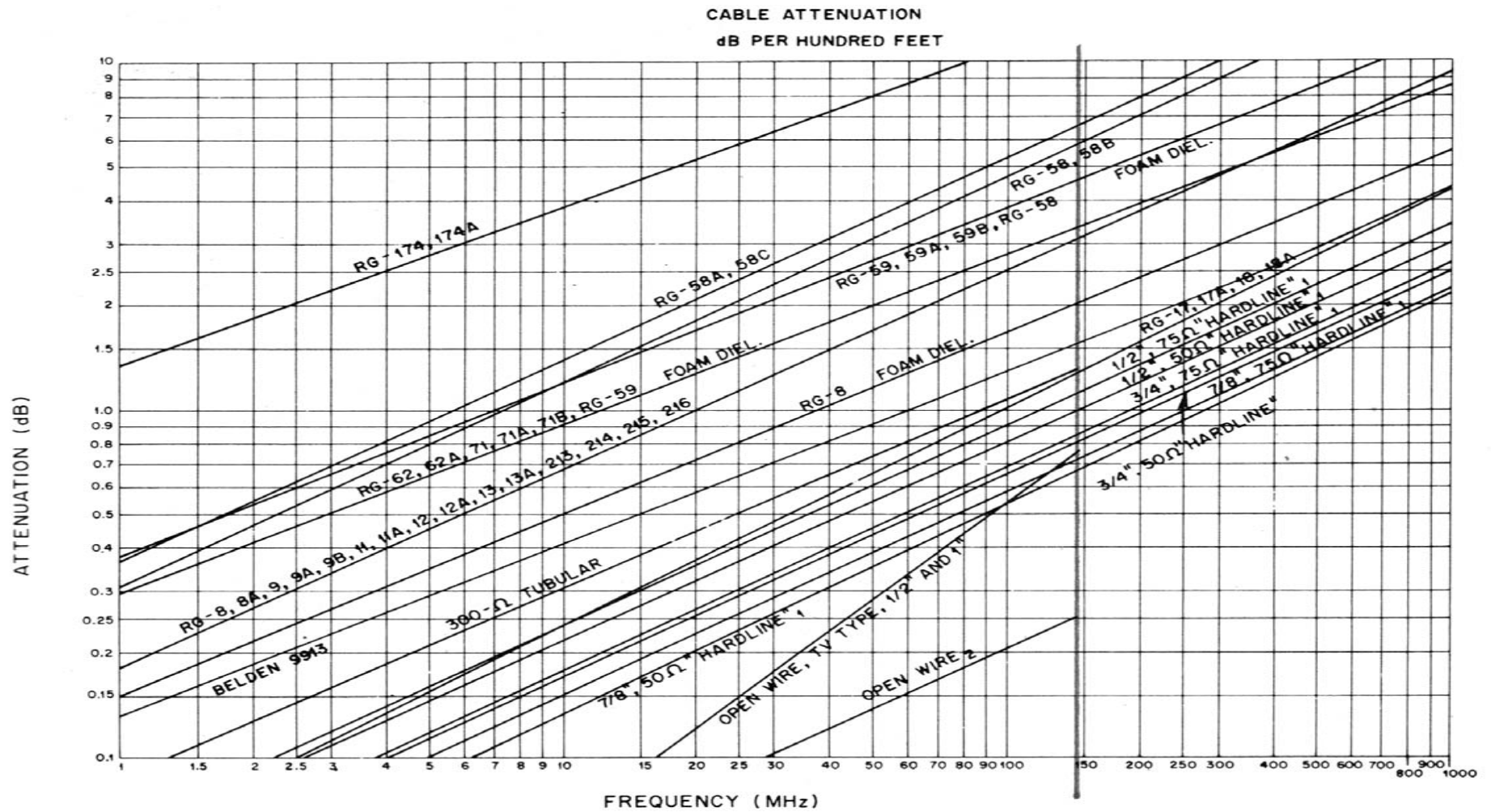
Shorted  $\lambda/4$  stubs support the open wire balanced lines



4:1 balun

*If a 144 MHz  $\lambda/4$  stub is used then the line will also work equally well on 432 MHz where the stub looks like a  $3 \lambda/4$  type.*





## ARRL Handbook Chart

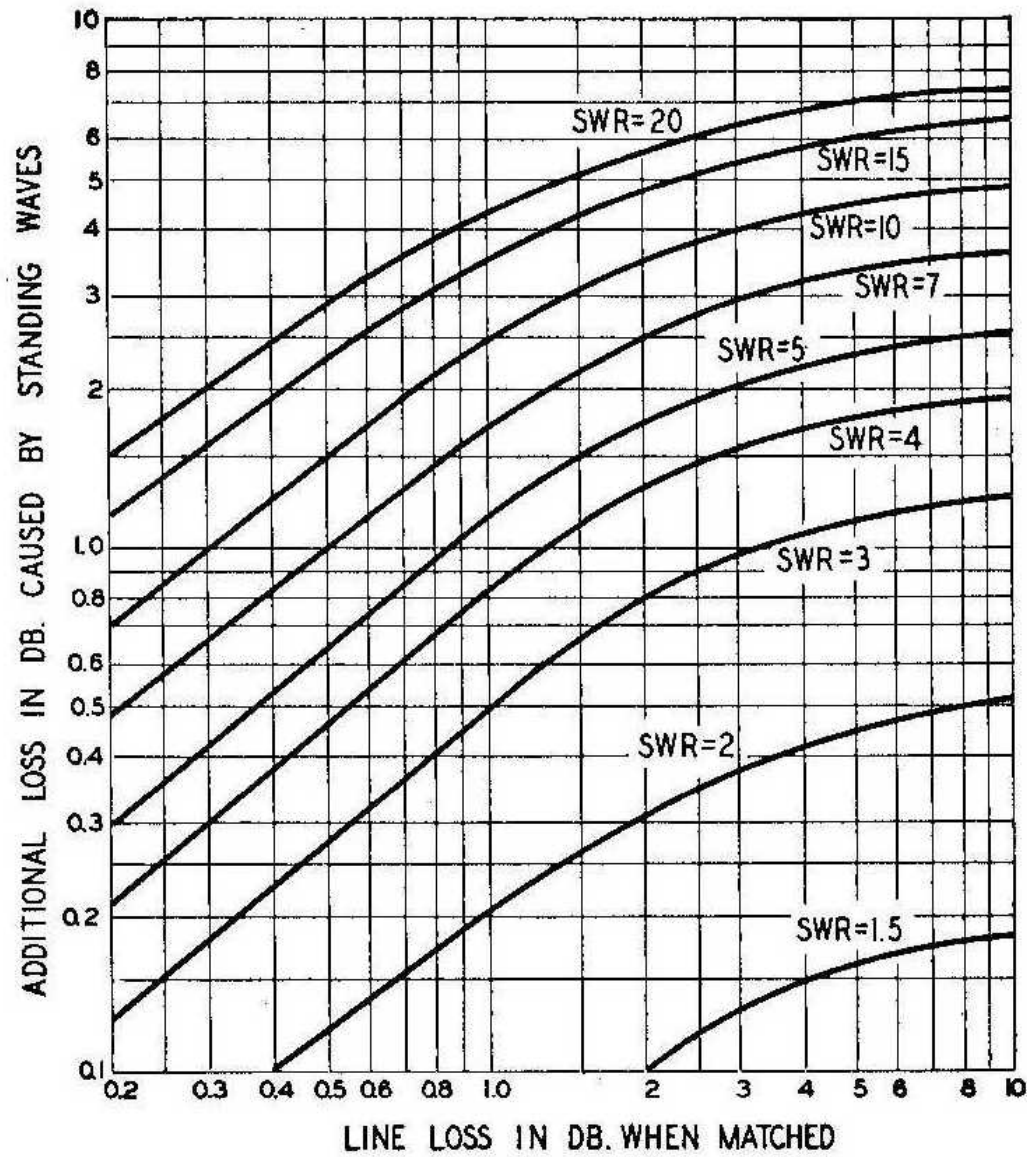
100 ft = 30.5m

200 Ω balanced line has a loss of only 10% of that of RG-213U and 30% the loss of 7/8" Hardline.

## Additional Feed Line Loss with a High SWR

- When a high SWR exists on a transmission line additional loss occurs. This is normally quite low. For a coaxial cable of 3dB loss and a SWR of 2:1 the additional loss is less than 0.4dB. (The total loss is 3.375dB).
- The additional loss in coaxial cable is mainly *dielectric loss* because of the higher RF voltage at the standing wave maximum points. This imposes an upper limit on the SWR the cable can safely handle. The other cause of loss is the higher current flowing at the current maximum points. The skin resistance causes power to be dissipated and hence the attenuation increases.
- For balance wire lines the higher RF voltage isn't normally an issue but the skin effect loss due to the higher current can be a problem.
- If the extra loss amounts to 0.5dB the radiated signal is reduced by an additional 10%.
- A typical amateur receiver S meter is calibrated in 6dB per S point.
- For an extra 0.5dB of feed line loss the distant station will measure a reduction in signal level of 1/12th of an S point, which is insignificant and probably impossible to discern. Fading (QSB) on a long path is likely to be at least 3dB so the reduction in signal strength will be unnoticed.





**ARRL Handbook Chart**

*What is the correct length of cable between the transmitter and the antenna ?*

The simple answer is:

*Whatever the physical length required to cater for the cable run.*

- There is no *special condition*, the cable simply needs to be long enough to reach from the transmitter to the antenna, with adequate mechanical strain relief. We do not need  *$\lambda/2$  multiples* or any other *magic number*.
- If the cable can be re-routed to shorten the length then the attenuation will be lower.
- If the cable run is long then consideration of an alternative cable type (lower loss) or transmission line type should be made.

## Blindly Following Myths

- If you blindly follow some of the articles published about the *correct cable length* then you are potentially wasting a lot of money and power!
- If you believe that an antenna must only be fed with exact multiples of a half wavelength then your cable run is probably too long. If you move frequency by 1% then the feed line is no longer a true  $\lambda/2$ . This also confines us to less of the available band because we are hung up about SWR. The 80m band covers 3.5 - 3.8MHz, a bandwidth of 8.2%.
- The Velocity Factor of the lower cost coaxial cable can vary by as much as 10% from the nominal value. *Amateurs who believe they have a true  $\lambda/2$  by simply measuring the length in reality are often a long way from the true case!* The only way to be sure is to measure the cable *electrical length* using complex test equipment and trim it to the correct length.
- *What do you do with the extra coax? Coil it up and waste space?*
- If the cable required between the antenna and the transmitter happens to be just too short to comply with the *half wavelength rule* then you have added an extra half wavelength of cable.
- If the band is 80m you will have a lot of spare cable - about 26m - which wastes power. At R10-00 per metre this is R260-00 wasted and the power into the antenna is less than possible. Shouldn't power be dissipated in the antenna and not in a *Dummy Load* ?

## Harmonics

- One of the claims made by some published articles is that a high SWR generates excessive harmonics that cause TVI. This is normally incorrect.
- 99% of all TVI cases are due to *fundamental-overload* or *swamping* because the TV receiver has insufficient immunity to strong out of band signals.
- In valve transmitters working into a SWR as high as 5:1 the harmonic rejection is largely the same as into a SWR of 1:1 because the Pi tank can be adjusted to cater for the reactive load.
- *The harmonics fall to minimum at resonance of the Pi tank network. This occurs at the maximum anode current dip.*
- What can be a problem is a Voltage Balun with high reactive currents flowing. In these the ferrite becomes non-linear due to saturation and this generate harmonics.
- A common problem is the incorrect indicated SWR when significant levels of harmonics exist due to insufficient harmonic filtering at the transmitter.

## Harmonic Antennas

- If the antenna is a half wavelength dipole it looks like a low SWR at the fundamental frequency and at odd harmonics.
- A 7 MHz dipole is also a low SWR at 21 MHz (where the antenna is  $3\lambda/2$ ) but a high SWR at 14 MHz where it appears as a full wavelength and looks like an impedance of 5,000  $\Omega$  (SWR = 100:1). Hence a 7 MHz dipole can be used on two bands with low SWR - 40m and 15m - but not on 20m.
- The SWR meter is a wideband device and sees the power due to the reflected 14 MHz power (2nd harmonic signal) as a large reflected power. Hence, it shows a high SWR.
- If the 2nd harmonic level is -20dBc this is 1% reflected power and the SWR meter shows 1.22:1 although the antenna is perfectly matched at the fundamental frequency.
- *By adding a low pass filter between the transmitter and the SWR meter to eliminate the 14 MHz energy the SWR returns to a low value with a negligible loss in transmitted power.*

## Feeding Multi-Yagi Arrays

- Many published articles insist that the electrical length of the cables running from the power splitter to the individual Yagis must be exact multiples of  $\lambda/2$ . This is another false assumption.
- Whereas all the cables must be the same *electrical length* (not necessarily the same physical length due to variations in the Velocity Factor of the cable) the relationship between the length and the number of electrical degrees (wavelengths) is not critical.
- As long as the phase and amplitude at each antenna is the same all the Yagis will be fed in phase.
- It is immaterial what the electrical length is. It may be that a cable length of  $5\lambda/4$  is sufficient to cater for the cable run and this will give the same amplitude and phase at each Yagi as any other electrical length.
- Shorter cables means more power into the antenna.

## Using a low SWR for the correct reason

There are only two special cases where a low SWR is essential. Both of these apply to broadcasting stations.

- In television transmitters standing waves on the feed line cause multiple over-lapping pictures to be displayed on the receiver, this is known as *ghosting*. This is due to the time delay caused by the reflected wave traveling from one end of the transmission line to the other and then back again. The way broadcasters overcome this is to use *Isolators* and *Circulators* to dump the reflected power on its first return into a dummy load. In this case the reflected power is *lost* but the transmitter always sees a low SWR.

- *This proves that the re-reflected power is radiated by the antenna !*

- In FM stereo transmitters the standing waves due to the reflections cause inter-channel interference which transfers left and right channel energy to the opposite channel. Again isolators and circulators can eliminate this effect, at the expense of lost power.



## Check your 50Ω SWR meter !

Using low inductance resistors (carbon composition) we can check if our SWR meter indicates correctly. (Make the resistor leads as short as possible). Use a relatively low frequency to reduce the effects of lead inductance. Set the transmitter to about 1-W output.

- Connect two 100 Ω / 2W resistors in parallel to make a 50 Ω load. Measure the SWR, it should indicate exactly 1:1.
- Connect four 100 Ω / 2W resistors in parallel to make a 25 Ω load. It should indicate exactly 2:1.
- Connect one 100 Ω / 2W resistor to make a 100 Ω load. It should indicate exactly 2:1.
- If the SWR meter passes this test then make up more load resistors to cater for 3:1, 4:1 etc and check these points.
- Many amateur SWR meters indicate incorrectly even with a pure resistive load, and we haven't considered the reactive components here!
- If the indicated SWR increases with higher power then the meter is defective. This points to a lack of directivity and hence the ability to distinguish between forward and reflected power. Very few amateur SWR meters have the necessary directivity to make accurate measurements when the forward power is high.



## More checks on your feed line and SWR meter

- If inserting an additional  $\lambda/2$  length of coaxial cable causes the SWR to change there is something wrong. Adding an extra  $\lambda/2$  should not change the line impedance or SWR. Either there are RF currents flowing on the outer of the coax, or the SWR meter is defective or both.
- Similarly, adding an additional  $\lambda/4$  in series - if the line is not matched by an ATU - should not change the SWR. Although the  $\lambda/4$  section inverts the resistive and reactive portions and the impedance and sign of the reactance are different, the SWR is the same value.
- Hence adding any random length of coax should not significantly alter the indicated SWR.

## Summary

High SWR on a transmission line is not a problem at the power levels used by amateurs. In fact it can be a blessing in disguise because we can fit a shorter antenna into the available real estate.

- For most flexibility when using non-resonant wire antennas the use of an ATU will allow more bandwidth to be covered.
- Open wire balanced lines offer more flexible matching and lower transmission losses, much lower than coaxial cable can offer. The power rating is also much higher.
- Any SWR less than about 2:1 is perfectly acceptable and any further reduction yields an insignificant increase of radiated field strength. Typically at best 1/6th of a S point.
- Finally - **Do not believe everything you read in articles!**