Reflections on Reflections

At the talk on aerial matching that I gave recently, I promised to write it up for BarsCom, as the subject is quite complex (not to say argumentative!) and some slightly more permanent reference seemed worthwhile. Well, the article was started - but it just grew - and grew! Perhaps this is not really surprising, as the talk was my attempt at explaining the main (and mainly agreeing!) points of several competent reference and technical books (and many articles) on the subject, plus my own experience in this area, and we did cover quite a wide range of aspects during the talk.

I should add at this point that the revision I needed for the talk, and for this article, has been fascinating, and certainly helped improve my own understanding of what goes on when feeding an aerial with RF power, although there are still many areas where I have to have faith in what I'm being told by the truly expert! (The trick is to know who are the real experts, and who aren't.) I hope this article helps you as well in a better understanding of this mystery, and perhaps it will encourage some discussion and further questions about the subject.

Because of "Topsy-like" growth of this article, it became clear that the best thing to do was put it on our website, rather than in BarsCom, so that is what has been done. What follows, therefore, are the main points from my talk, including some miscellaneous aspects that may have only been touched on, but are worth repeating or amplifying. This write-up also includes comments and information that you didn't actually hear at the talk! You will also find some repetition or re-phrasing of certain statements - this is partly because some aspects re-occur under different headings, and partly to emphasise points without referring back to another paragraph - that's my excuse anyway.

First, however, I'd like to give some details of books that I think are "top of the heap" and the most worthwhile for further reading, if you wish to delve further into this black art. I have to acknowledge that apart from some early work training, much of my knowledge and the content of the talk, and therefore much of this article, has been based on these books, and particularly the one by M. Walter Maxwell, W2DU, plus my own practical experience "in the shack".

I also wish to acknowledge at this point that drafts of this script have been "vetted" by Nick Shepherd, VE3OWV, who was a founding member (one of the "Gang of Four") of our club when living in Braintree, though now resident near Ottawa in Canada. With his own professional background he has been able to give a number of very helpful and important additions, as noted later, but any errors or statements that you don't agree with are my responsibility alone.

The "most recommended" books:

The most venerable - **"The ARRL Antenna Book"**. Anything from the early 90's onward is particularly good.

The English equivalent - **"hf antennas for all locations"** by L.A.Moxon, G6XN. An RSGB production.

"Reflections" by M. Walter Maxwell, W2DU. Published by the ARRL.

"Building and Using Baluns and Ununs" by Jerry Sevick, W2FMI. A CQ Communications Ltd publication.

I think all these can still be bought via the RSGB, or second-hand at rallies if you are lucky. Many other books and magazine articles on this subject have been published over the years, but the above would be good basic additions to any amateur radio library.

Additionally, may I recommend you to the web site "www.w2du.com", which is Maxwell's up-to-date view on this whole subject. He includes his background and engineering history, which alone makes very interesting reading.

Scope of the Talk

The area of concern for the talk was the transmitter, the feeder and the aerial (or, for the talk, dummy loads of various non-inductive resistive values). In addition, the use is assumed of a Standing Wave Ratio Meter (SWR meter), located between the transmitter and feeder, and (if or when needed) an Aerial Matching Unit (AMU), fitted between the SWR meter and the shack end of the feeder. The feeder could be coaxial cable or open-wire, and the aerial anything you are hoping will radiate a signal. My demonstration used an HF transmitter on 7MHz, and coax feeder, but the principles apply to VHF and UHF as well.

The questions I considered most important, and tried to answer in the talk, included:

When **DON'T** I need an AMU between transmitter (Tx) and aerial?
What problems can arise from **not** using an AMU?
What are we trying to do when using an AMU?
What does an AMU actually do?
What conditions exist in a "matched" transmitting system (Tx, AMU, feeder and aerial)?
Are these conditions detrimental or beneficial to Tx operation?
How can I be sure the AMU is doing its job correctly?
Is it necessary to achieve a 1:1 SWR (at the AMU/Tx interface)?
When should I use a Balun - if at all - and why?

It had been hoped to cover the designs and main features of AMUs in general, and look at SWR meters and the problems and misleading readings that can arise in their use, but time ran out, although members were able to look at some useful examples of AMU. There are also some unusual uses of the SWR meter that are very handy, but rarely covered in books on this subject. Perhaps these aspects could be covered at a future operating meeting, if required.

When don't I need an AMU?

If your aerial is resonant at the operating frequency (ie by definition it is non-reactive and purely resistive) and its impedance matches the feeder impedance, which in turn is that required by the transmitter output, then the whole system is "matched" to the Tx. Consequently, there is no need to use an AMU, as it adds no benefit. If the Tx has adjustable PA tuning (with an adequate range of L and C), this can be used to match into an aerial/feeder that is mismatched, so a separate AMU is not normally needed either. Note that in the above situation, it is not unknown for the AMU, if left in circuit, to cause some power loss.

What problems can arise from not using an Aerial Matching Unit?

If the aerial is not resonant - and it can only be resonant at one frequency or certain harmonic multiples thereof - it will present a reactive (inductive or capacitive) load to the feeder. This load will now be a vectorial combination of the resistive and reactive components of the aerial, and will have an impedance value that is different from the impedance at resonance. Mathematically, this value is usually shown in the form of "R + jX". Don't worry about this!

This mismatch at the aerial end of the feeder will now result in a mismatch at the Tx end of the feeder, although the actual values of "R" and "jX" will usually be different from those at the aerial end. The mismatched feeder will "transform" the values, depending on the electrical length of the feeder. A true and precise half-wavelength of feeder (allowing for feeder velocity factor), or its multiples, will present the same result at the Tx as seen at the aerial - but all other lengths will change the results. The above statements relate to use of a feeder of the correct "system" impedance, eg 50 ohms used with a Tx of 50 ohms output impedance, although - uniquely - the half-wave of feeder can be of any practical impedance without affecting the result. See later for comments about the use of "non-standard" impedance feeders.

Note: This unique property of a half-wavelength of feeder can be used to remotely measure conditions at its far end. It does not allow any meaningful measurements eg of the impedance of the aerial, if any RF currents flow from the aerial along the outside of the feeder and back to the Tx - assuming coax cable is being used. (If twin feeder is used, "parallel" currents on both wires together give the same problem.) This is because the connection of the feeder to the aerial, and further connection via the Tx to earth, provides an unwanted path for some of the RF energy, which changes the aerial matching conditions. More on this under "Baluns".

For a Tx with a very limited range of output tuning or totally pre-set tuning per band, as with many late-model valved Power Amplifiers (PAs) and all solid-state PAs (as far as I know), this mismatch fed back to the Tx detunes the transmitter output circuitry, which will alter the "loading" on the active device. Depending on the character of mismatch seen, the output stage will either try to draw excess DC current from the power supply, or it will reduce its current demand. Either condition will reduce the power obtained, assuming that the Tx was initially tuned for optimum (not necessarily maximum) power output into a dummy load of the correct impedance - normally 50 ohms when using coax cable feeder. The mis-tuning will alter the PA output impedance, reduce the PA efficiency and cause excessive voltages and currents to appear in the output circuitry, in turn causing voltage flashovers or over-heating of coils and joints. The output stage is said to be "under-coupled" or "over-coupled" when in this state.

Now, as I understand the situation (and assuming the use of zero-loss feeders, tuned circuits and aerials):

According to Maxwell, W2DU, amongst others, when power is reflected by an aerial mismatch back to the Tx, the reflected power causes changes to the output tuning and therefore the operating conditions within the Tx PA, resulting in the transmitter output being reduced by exactly the amount of power being reflected from the mismatched load. Total reflection of the incoming reflected power at the Tx output tuning will send the original reflected power back to the load, adding it in phase with the reduced Tx output power, so that what arrives at the load is the equivalent of full Tx output power. The aerial (load) will fully absorb the power representing the reduced Tx output power and radiate it, but continue to reflect back to the transmitter the rest of the power, maintaining the status quo, as it were.

This effect is **NOT** the same as that resulting from a retuned Tx PA, nor its equivalent - the tuned Aerial Matching Unit - in that it is not creating a "conjugate match" in the system. (For a definition of "conjugate match", see W2DU's book or web site.) The aerial is **NOT** being "tuned to resonance", which would allow it to absorb 100% of the Tx output instead of reflecting some of it. The total forward power being sent to the mismatched load is no more than the original power that the Tx can supply into a proper matched load, but the actual radiated power is reduced by the amount of the reflection.

Some authorities state that some or all of the originally reflected power from the mismatched load will be absorbed by the Tx Power Amplifier. This can only occur if the Tx PA, seen from the feeder/load direction, looks like or close to the nominal system impedance, although apparently this condition is unlikely to occur, even when the whole Tx, feeder and aerial system are correctly matched to a standard impedance.

However, the reflected power actually changes the operating conditions within the PA, creating a 100% reflection at the Tx output. It does therefore seem that the reflected power is not absorbed by the PA, but there is the equivalent loss of output power, due to the detuning and the Tx then cutting back on its output. (This "power output reduction" is not to be confused with the effect of SWR-sensing devices built-in to give PA protection.)

Despite the reduced Tx output and assuming that no RF is re-absorbed in the PA, the Tx PA can still be overloaded thermally because the change in operating conditions (loading) will make the PA less efficient, and this effect can be very large. Commonly, an "off-tune" PA will take a larger current from the supply than it does at resonance, while the RF output will have reduced. Consequently, and depending on the severity of it, a mismatch will cause increased thermal dissipation in the Tx PA stage, which can reduce life very severely. The change in loading can cause damage to the output circuitry, and it always reduces the power output, relative to that achieved into a good impedance match.

Note: The increase in power dissipation within the PA is not directly related to the amount of reflected power, being dependent on a number of operational factors within the PA. The possible damage to the PA also depends in part on the margin of safety built into the PA eg how close to maximum permissible power dissipation the PA is when operating normally and at maximum efficiency.

It is for these reasons that modern transmitter PAs include protective circuitry that detects any mismatch condition and reduces PA power input (and output) to a safer level. Erring on the side of caution, this circuitry usually cuts back the power input (and output) to a much greater degree than the mismatch itself would cause, so that with a SWR ratio of as little as 2:1, very little power output can be obtained from many transmitters.

HOWEVER - Don't alter the settings of this circuitry - it is an essential safeguard.

As noted above, a Tx with adjustable Power Amplifier (PA) tuning can first be tuned to match into 50 ohms, say, and then can be re-adjusted to compensate for the aerial/feeder mismatch, replacing the AMU in this respect. If the PA tuning is not readjusted, however, the same problems will occur as with fixed-tuned rigs.

Therefore, in summary, for any PA that is initially tuned into a "normal" load impedance (usually 50 ohms), a mismatch at the aerial will reduce the radiated power, and could be detrimental to the Tx, if an AMU is not used. I'll look at the percentage of RF power that could be lost later on. There's a little bit of maths involved, but nothing serious.

Note: The re-tuning of a transmitter PA mentioned above requires returning the PA conditions of input voltage and current, and power output, to the previously matched conditions, so requires metering (and tuning facility) that is not available on most modern rigs. If meter facilities exist, this operation can be done without the use of an SWR meter in circuit, and of course was the routine for many years prior to the introduction of SWR meters. Once SWR meters started to be used, they helped in this tune-up process by showing when maximum output power from the Tx had been achieved (see later for an experiment you can do that shows this), but the fact that the SWR was not 1:1 on the feeder didn't upset most amateurs at that time. It was only with the introduction of fixed output tuning for transmitters that SWR became a real problem.

Then, as SWR meters became more commonly used with tuneable PAs, a side-effect was that technical writers in magazine articles etc began, quite correctly, to advise readers that concerns about the reflected power from the load (aerial) being dissipated in the PA and causing over-heating were unfounded. This was technically correct because either the PA cut back its output power or its retuned output circuitry acted as a built-in AMU, causing the reflected power to be re-reflected back to the load in a way that allowed it to be fully radiated (this is explained further later on). What usually wasn't made clear was that the PA could still over-heat because of improper tuning and operating conditions, unless the output was retuned.

Many such articles didn't actually explain this - I quote Martyn Williams in an article in "AMATEUR RADIO" of May 1987, who said "Contrary to popular opinion, this (*reflected*) power is not lost and neither does it heat up your rig, but that is too deep a subject to go into now". I don't think that many (any?) writers of the time did actually explain the subject properly.

What are we trying to do when using an Aerial Matching Unit?

Basically, we use an AMU to provide conditions at the Tx output point that it wants to see, in order to provide optimum power output within the ratings of the Tx, with all that power being radiated by the aerial. This requires the AMU to do two things:

a) Cancel out any reactance that has been reflected from the load (aerial), and
b) Change the resultant resistive impedance to the value that the Tx requires at its output.

Simple, isn't it?

What does an Aerial Matching Unit actually do?

Firstly, in purely electronic terms, when correctly tuned the AMU provides what is called a "conjugate match" to the reactive impedance it sees coming into it, by looking like the exactly opposite value in vectorial terms - in effect, it neutralises the mismatch created at the load. The AMU then reflects the returned power back up the feeder, adding the reflected power **IN PHASE** with the power generated by the Tx, and creating a total forward power that is the sum of the original power plus the reflected power. (This ignores feeder losses - more later on this.)

Note: When RF power is reflected from a mismatch, the phase of either the voltage or current (relative to the incident wave) is changed by 180 degrees. (The same effect occurs for sound reflections, and for light waves.) When the AMU reflects the returned power back up the feeder, the phase is further changed, to make the re-reflected power have the identical phase to the original RF power from the Tx, which is why it can now add directly to the original RF power. What now travels towards the aerial is a power level greater than the actual Tx output!

Note: Apparently (according to Maxwell), the phase change caused by a correctly tuned AMU or re-tuned output circuit of a PA will also automatically correct for a reflected wave that is no longer 180 degrees out of phase with the original (forward) wave as a result of its journey back down the feeder. I assume this can occur from stray inductance or capacitance effects within the feeder, but have not found any information on this.

The mismatched load continues to reflect the same ratio (%) of power as before, but the resultant now is that the aerial (load) is actually absorbing 100% of the original power level (except for any lost to feeder losses). This power is now fully radiated (except for any lost due to any ohmic losses in the actual aerial). Although power is still being reflected back towards the Tx, no power gets back into the Tx itself, which because it is not being de-tuned is now able to provide 100% of its rated output power, without adverse effects. See Nick's further explanation, below.

A little bit of maths, mainly from "**Reflections**", and assuming a loss-less feeder and AMU, for each of the following cases:

a) A 100W output Tx, feeding a matched load, will see a 1:1 SWR. All the Tx power is absorbed by the load (aerial). No reflections, and no problem!

b) The same Tx, still outputting 100W, but with a 3:1 SWR load, **NOT** re-matched to the Tx impedance. From some simple maths, which is detailed later on, the reflected power from the load is 25% of the incident power ie 25W, and only 75W goes into the load (aerial).

Note: Here, I have to assume that the 100W output is the resultant of the original Tx output being reduced to 75W because of the 25W of reflected power, but with this reflected 25W of power added (re-reflected) in-phase with the "new" level of 75W to give the 100W output again - as described earlier. This aspect did not appear clear to me when first reading W2DU's book, I have to admit, but is clarified in a letter he wrote to QST in March 1985.

Another Note: The following description of (c) is nearly all Nick's (based on W2DU's original description) - it was a lot better than my own attempt to make this explanation understandable! I have altered the wording slightly in places to fit with the rest of the text, but not the meaning (I hope).

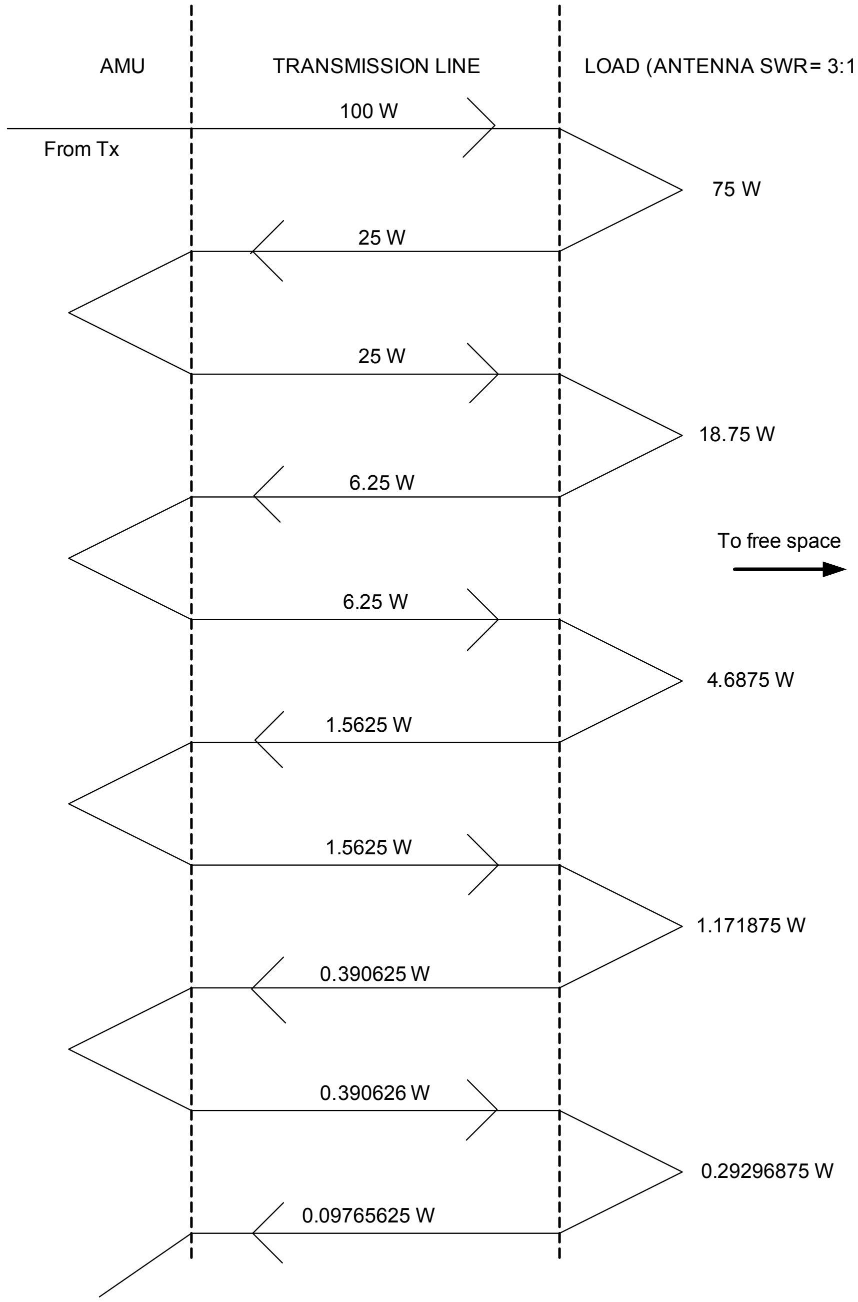
c) The same nominal 100W Tx and the same 3:1 SWR load (antenna), BUT with an AMU in line at the Tx end of the feeder ie between Tx and feeder. The AMU is adjusted so that the reverse (reflected) power as indicated on the SWR meter is zero. The indicated forward power should now be 100W once again. As far as the Tx is concerned it now sees a matched load because the AMU has been adjusted to provide a "conjugate match" to the complex impedance presented by the combination of the feeder and its unmatched antenna load.

Let's now assume that there is a directional wattmeter (SWR meter) placed somewhere along the feeder between the Tx/AMU and the antenna. The position is not important - it could be at the AMU end, the antenna end or somewhere in between. The reflected power sensed by this meter is clearly not going back to the transmitter because the SWR meter at the Tx end is reading zero reflected power, so where is it going? The answer is that it is reflected back up the feeder by the AMU action, and adds to (ie is in phase with) the original forward component of the Tx power as measured by the Tx-end wattmeter (SWR meter). Now, the antenna SWR is 3:1 so the reflected power is 25% of the forward power (= the voltage reflection coefficient squared), or 25W. (See later for the maths on this aspect.) Of the original 100W, 75W is radiated by the antenna.

This 25W of reflected power arriving back at the antenna (after re-reflection by the AMU) is still subjected to the 3:1 SWR of the antenna, so 25% of the 25W or 6.25W of that extra power is reflected by the load, while 25W - 6.25W = 18.75W now adds to the radiated power of 75W. The 6.25W of newly reflected power is again returned by the AMU in phase with the original forward power (and the previously re-reflected power), and when it arrives at the antenna 25% or 1.5625W is reflected and 6.25W - 1.5625W = 4.6875W is radiated in phase with the rest of the forward power.

The total amount of radiated power is therefore 75W plus the contributions from each of the successive reflections between the AMU and the antenna, with each reflection contributing successively less radiated power. In practice, a reasonable estimate of the total radiated power, after accounting for just the first six reflections, is 99.97558W. The same kind of reasoning shows that the in-line directional wattmeter reads the forward power flow as 100W + 25W + 6.25w + 1.5625W + 0.390625W etc. for a total of 133.33W, and the total reflected power flow as 25W + 6.25W + 1.5625W + 0.390625W etc. for a total of 33.33W. The forward to reverse power ratio is therefore 4:1 for the load SWR of 3:1. This is the same as the ratio of forward power to reflected power in case (b) above, ie 100W forward power to 25W reflected, the difference being that in case (b) only 75W finds its way out of the antenna.

Nick illustrates this sequence with the following diagram:



A Postscript - This is Nick's analysis (with some minor editing by myself to add information or relate to other parts of the article), based on W2DU's writings, of why the Tx PA (without re-tuning or use of an AMU) reflects all the power originally reflected from the mismatched load, rather than absorbing all or part of this power and dissipating it in the PA as additional heat:

The arguments W2DU presents are quite long and involved (and somewhat mathematical), and I have not yet been through the entire collection of articles in detail. (These are on W2DU's web site as mentioned above.) He is also mightily concerned with explaining the operation of non-linear class B and class C amplifiers, but the idea that reflected power is not absorbed by the final amplifier applies to any amplifier (unless of course it is a VHF/UHF amplifier with built-in feeder circulator and dummy load - in which case the reflected power doesn't reach the amplifier at all).

If an amplifier is operating into a matched load (non reactive ie resonant, if an aerial), the available output power is maximised and the RF output current and voltage are in phase, ie the amplifier sees a purely resistive load. The output power is given by values of Iout and Vout (where these are the RMS values). If the load is mismatched, for example by a mistuned AMU, unmatched antenna etc, then the load becomes reactive and the output voltage and current are no longer in phase. The available output power is now the vector sum of Iout and Vout, which will always be less than the in-phase product, even assuming that the magnitudes of Iout and Vout individually remain the same. In practice, one or both will usually be reduced anyway.

Now the generator (Tx PA) can only ever sustain the one set of vector products of current and voltage at its output terminals, so there is no distinction between a forward and reflected direction of power flow at the generator output. Therefore there is no separately identifiable element of power flowing back into the generator, and hence no absorption of reflected power by the generator. Since the generator is connected to a load and since what you get at the output terminals is all that you get, and ignoring losses in tuned circuits and feeders etc, then all of this (reduced level) power has to be dissipated in the load, even if this load is badly mismatched.

The amplifier efficiency can be compromised by the unmatched load because the internal dissipation is a function of the average DC current drawn from the power supply at a given supply voltage .If the supply current remains more or less the same between the matched and unmatched states, then the reduced output power in the unmatched state means less DC input power is converted to useful output and more is wasted as heat. Quite often the input current actually increases in the unmatched state, for example by non-dipped tuning of a valve PA stage. (For such amplifiers, at resonance in the PA anode tuned circuit the DC current should always be a minimum, the actual value then depending on the "load" control ie the degree of coupling to the load.) I suppose it could be argued that the increased dissipation is somehow equivalent to the "lost" RF power due to the mismatched load and reflections but I doubt that there's an exact relationship because the DC power input conditions vary in a somewhat uncontrolled fashion when the load goes off-tune.

(That concludes Nick's description of the effect of using an AMU, and related aspects of mismatched loads.)

My own note on this last point: Although W2DU states that the RF power output reduction is exactly related to amount of RF power reflected from the mismatched load, nowhere in his writings can I find any view that the increased dissipation in the PA is directly related as well. Indeed, a valved Tx PA that is even slightly off-tune, eg from a small load mismatch or finger trouble on the tuning controls, can incur a very large increase in DC input current, increasing the dissipation enormously, even ignoring whether it is putting out the same amount or ratio of RF power as at resonance (which is unlikely). I assume the same applies to semi-conductor PAs, but I have no experience of tuning these into a load.

To continue:

This multiple reflection and addition effect described above is possibly a little difficult initially to understand and/or accept! However, it shows that while the load SWR is not actually changed, its ability to absorb the full Tx output **IS** changed. The whole feeder/aerial system still has a 3:1 SWR, but is now essentially 100% efficient (neglecting feeder losses and aerial ohmic losses).

Now comes the aspect that caused even more disbelief during the talk - but bear with me! Let us first assume that the AMU (connected to the Tx via a length of feeder) is located at the aerial input, without any extra feeder. The AMU neutralises any reactance in the aerial, and converts the residual resistive impedance to match that of the feeder (50 ohms, say). By definition, if the aerial is now non-reactive, it is resonant at the working frequency. It will now take all the applied power from the Tx (apart from any power loss due to the AMU itself, and feeder losses), and radiate it all (subject to ohmic losses in the actual aerial). I think most radio amateurs would agree that the AMU is tuning the aerial.

This will apply, whether the aerial is physically longer or shorter than a quarter-wavelength or multiple thereof, which would certainly make it non-resonant in itself. Even an aerial that is half the size of a classic half-wave dipole will be nearly as effective as the full size aerial, because it is "taking" and radiating the Tx power, and still has a radiation resistance that is not very much lower than that of a full-sized aerial. (A G5RV on 80m is a classic illustration of this.) However, shorter aerials will become less efficient in radiation capability as their ohmic losses start to become significant when compared to the aerial radiation resistance, and that is the main reason for a reduced signal output with smaller "properly matched" aerials. (The polar radiation patterns will probably also change because of the different aerial size, but the same amount of energy will be radiated, minus the ohmic losses.)

Now lets assume the AMU is at the Tx end of the feeder. It is tuned in the same way as before (although probably with different tuning values because of the "impedance transforming" effect of the feeder), and creates the required conjugate match, reflecting the reflected power back up the feeder to the aerial. Again, the aerial is seen at the AMU input as non-reactive (resonant), and it will finally absorb the full Tx power, radiating it as before.

Adding the feeder to the system has changed the tuning values of the AMU, but not the conditions resulting, so the AMU is, again by definition, now tuning the aerial via the feeder system. There cannot be any reactance in the feeder/aerial system, as it has been "neutralised" by the AMU. The aerial HAS to be resonant, to fully accept all the power. The feeder is not radiating and is, strictly, not part of the aerial. The AMU is therefore tuning the aerial - again.

I suggest you consider the following. I think it can be agreed that the AMU, when located at the aerial, tunes the aerial to resonance. If it then located at the Tx end of a half-wave of feeder, which reflects exactly the aerial conditions, the same settings of the AMU should also tune the aerial as before. The AMU is now tuning the aerial via a feeder. Altering the length of the feeder will then change the tuning points of the AMU, but it is simply now allowing for the effect of the feeder on the complex impedance transferred from the aerial to the Tx end. The AMU is still bringing the aerial to resonance - not the feeder. It is fair enough to say that the AMU **IS** tuning the whole aerial **SYSTEM** and can properly be called an Aerial System Tuning Unit (ASTU) or similar - but it is still really only the aerial that is being brought to resonance. The feeder is not "resonant" - it is simply not reactive. However, whatever it is described as, the system works!

A Practical Demonstration

During the talk, I demonstrated this condition by use of an aerial ammeter, placed at the connection between feeder and aerial (mismatched dummy load). Without an AMU, the Tx end of the feeder "saw" a bad SWR (over 5:1). I therefore used a 6dB attenuator between Tx and SWR meter, which protected the Tx by absorbing most of the reflected power before it got back to the Tx. This also enabled the Tx output power to remain constant during the tests. The aerial ammeter readings allowed calculation of the RF power going into the (resistive) load, showing that it was taking about 60% of the Tx power, and reflecting about 40%. (Actually, the theoretical values should have been about 55% absorbed and 45% reflected, but to get this close is pretty good when dealing with RF!)

When the AMU was tuned and the Tx "saw" a 1:1 match, the aerial (load) current increased significantly, for the same output power from the Tx. Calculation showed that the new level of RF power into the load was better than 85%, but not 100%, of the Tx output power (after the attenuator). Sadly, I couldn't improve this figure by any AMU tweaking. However, I think the point was proven that tuning the AMU "forced" more power into the load ie matched it.

Later analysis (at home) showed that this unexplained loss was just under 1dB (1dB is about 20% loss), which apparently is typical of the loss caused by a good AMU design for this sort of mismatch. Recent ARRL tests on typical commercial AMUs under similar conditions showed losses of 1dB to 2dB in many cases, and sometimes worse, so 85%-plus final output power was reasonable, I feel.

An Experiment You Can Do In The Shack

It is possible to see the reality of the increased forward power, and the equally real continued and increased level of reflected power from the aerial, when using an AMU, by use of two good-quality SWR meters. Set up the system with the Tx, one SWR meter, the AMU, then the second SWR meter, some coax feeder of the nominal system impedance, and finally a dummy load matched to the Tx and feeder impedance (usually 50 ohms). You need to use at least 10 watts of RF power, to minimise "low power" errors in the SWR meters - but you may need to use a higher power level, depending on the SWR meters used (see comments later on this problem). Don't use the full power available from your Tx, though, as the tests will involve some reflected power getting back to the PA, even though this may be for a short period, and you don't want to overheat your PA. Also, the power level should be only enough to give up to 70% of full-scale reading on forward power on each meter when using a "standard" dummy load - any more and the second meter may exceed its FSD later on!

With the AMU out of circuit, note the power levels on both the SWR meters, for both reflected and forward powers. There should be no reflected power, and the two forward power readings should look the same. If they differ, you don't have matched SWR meters! For the average commercial-quality "amateur market" SWR meter, power measurement can easily be up to 20% in error in a plus or minus direction - and more (or less), if a previous owner has been tweaking any internal adjustments. However, not all is lost - just note the actual power readings for future reference.

Now change the load for a mismatch, to something around 200 ohms resistive and non-inductive. (I suggest this order of mismatch as an optimum for showing the effect but not getting large unwanted errors from losses in the AMU or errors in the SWR meters.) With the Tx on, check that the two SWR meters are showing the same forward and reflected power levels and SWR. If they aren't, they are not very helpful for this test, but again just note the actual readings. Your Tx may have reduced its power output, due in part to the protective circuitry, but don't alter any Tx settings. Keep this phase of the test as short as practical, to avoid over-heating the Tx etc.

Switch in the AMU (which is between the two SWR meters) and tune it for 1:1 SWR on the meter between Tx and AMU. Observe the power reading on this meter - it should now be the same as before with the 50-ohm load (if the Tx output returns to normal, as it should). Observe the readings on the SWR meter after the AMU. You should see that the forward power is now greater than that showing before, and in fact greater than the Tx output power (this is the reflected power being added to the original Tx power). This meter will still be showing reverse (reflected) power, which should also show a slight increase, maintaining the SWR at the previous value. As noted previously, tuning the AMU for 1:1 SWR at the Tx does not alter the SWR on the feed to the load.

If you are lucky (it depends very much on the meter quality and calibration), the forward power minus the reflected power on the second SWR meter should equal that of the forward power on the first meter - with a small caveat. The AMU will absorb some power, depending on its design and quality, and on the degree of mismatch it is dealing with. For a fairly small and resistive mismatch as described above, and a good design and quality of AMU, this loss should only be around 10% (less than 1dB). Feeder losses will also reduce the effects, but if a fairly short low-loss feeder has been used, this should not be of significance.

Incidentally, if you have a Tx PA with variable output tuning, the same effect can be seen with only one SWR meter. Tune the Tx for normal power output into a dummy load of the correct impedance (50 ohms, say), and then connect it to the SWR meter and thence to the same dummy load via some feeder. Check that the SWR is OK (1:1). Then substitute the load with a mismatched load, as above. Retune the Tx PA as you normally would, for correct conditions and normal output as indicated by its own metering, but watch the SWR meter as well. (Bi-focals might help!) The SWR will not change, but the forward and reverse power levels will both increase, as for the second meter in the test above. Hopefully, the optimum PA tuning as per its own metering will coincide with maximum forward power on the SWR meter - or be close to it. (See later for this test being used as an AMU tuning aid.)

My Own Results

When I did this test recently at home, to be able to quote some figures in this write-up, initially I used the same set-up as at the club meeting, with 10W of RF power from the Tx but no attenuator. The same SWR meters were used as at the club meeting, which are Daiwa crossed-needle meters - with two meters and power scales in the one display unit. Each indicator actually reads RF power, with two meter pointers for forward and reverse power which cross over and indicate SWR on a third scale.

The first meter read a correct level of forward power, but the second meter was reading 7.8W on the 20W range when the RF power was 10W into 50 ohms.

Note: The first meter had been "tweaked" some while ago to read power correctly at full-scale deflection (FSD) on all three ranges, in both forward and reverse directions, so I was happy with its readings in this series of tests, apart from any possible errors due to low power in the reverse direction. The second meter was badly adjusted on the ranges used, with serious errors, but these could be "corrected" and allowed for.

After the installation of a 200-ohm dummy load, a further check showed the second meter was reading the same amount of reflected power as the first meter - 1.9 watts. After tuning the AMU for 1:1 SWR on the first meter, and losing about 1 watt (10%) through the AMU (estimated from other tests), the second meter now read 8.5W forward power, with a reverse power of 2.0W. Adjusting "roughly" for AMU loss and meter "forward-power" error, this showed a probable forward power of almost 12 watts and a probable reverse power of at least 2 watts (although this seemed rather low).

I wasn't entirely happy with the accuracy of the SWR meters for low levels of reflected power, so this test was repeated with 80W of RF, as measured on a good-quality power meter. With a 50-ohm load, the first meter read 80W, and the second read 60W (75% of the correct value), on the 200W meter range. With the 200-ohm load but no AMU, the first meter then read 32W forward and 10.8W reflected power, the power reduction being partly due to the built-in safety system in the Tx. The second meter read 22W forward power (which corrected to 29.3W), and 5.2W reflected power - almost exactly half that of the first meter. (The meter errors can be - and were - different for each power range and direction of power measurement in this meter, and particularly at very low reflected power.)

Consequently, the SWR of the first meter read a reasonably accurate 3.9 (in theory it should have been 4:1 with the particular dummy load), while the second meter read an inaccurate 2.8. Using the meter reading, an SWR of 3.9 equates to a reflection of 35% of the forward power, so 35% of 32W is 11.2W - quite close to the actual reading and well inside meter reading limits and other meter errors. Using the theoretical SWR of 4:1, the reflected power would be 36% or 11.5W - not a lot of difference.

The AMU was then switched into circuit, already pre-tuned from the low-power test, and the first meter now read 80W forward and zero watts reverse power, as when the 50 ohm dummy load was in circuit. The power at the second meter was probably about 72W (due to AMU losses of 10%), but the second meter now read 78W forward and 21W reverse power. This corrected to 104W forward power. The reverse power was somewhere between 21W and 42W (assuming that the meter error is anything up to the 2:1 error previously noted). These readings clearly showed the large increase in forward power, which is now much greater than that actually provided by the Tx directly, and a reverse power that subtracts from the forward reading to show around 62W to 83W into the load. This suggests that the reverse power error in the second meter is reduced from 2:1 to just over 1.5:1 at the higher power levels, which is what would give about 32W actual reverse power and a load power of 72W.

I found these tests, and particularly the second set at high power, to be a very good proof of the earlier statements about forward and reflected power under these conditions - and also proof that too low a test power can give less-than-ideal results. And next time I do such tests, I shall ensure both meters are properly calibrated first!

With regard to power and SWR measurements, do remember that SWR meters can be very variable in readings with different power levels, even if calibrated correctly at a specific power level (usually at FSD on each range). The reflected power being a lot less than the forward power, there may be a significant error in the measurement if it is too low in level. (Some further comments on this appear later on!)

What conditions exist in a "matched" system (Tx, AMU, feeder and aerial)?

With the set-up demonstrated at the club, using a dummy load of nearly 300 ohms (six 47 ohm resistors in series), I also inserted a second SWR meter between the feeder and the mismatched load. Without use of the AMU, this showed over 5:1 SWR, as did the first meter at the Tx output. The AMU was then tuned for 1:1 SWR at the Tx output (AMU/feeder input), improving the power transfer to the dummy load, as seen by the increased RF current.

The SWR shown on the second SWR meter, between AMU and load, did not alter at all.

This was regardless of the AMU tuning or resultant input SWR. This emphasises that while using an AMU can reduce the input SWR to a better (lower) value, it can have absolutely no effect on the SWR existing on the feeder or at the aerial. I feel it is worth repeating this point - using an AMU (at the shack end) **DOES NOT AND CANNOT** reduce the SWR on the feeder. It would, of course, if the AMU were fitted between feeder and aerial, but this is a most inconvenient location, and not really practical if adjustments are required, as is usual.

Are these conditions detrimental or beneficial to Tx operation?

Obtaining a good match at the Tx output is very beneficial, as previously described. The Tx output is tuned correctly, and does not receive reflected power that could cause a change of PA tuning and consequent over-heating. The aerial receives and absorbs (radiates) all the power that the Tx can properly produce (within its ratings), subject to three caveats.

The first is that the AMU will dissipate some power - but this loss may only be very high under extreme SWR conditions when, without the use of an AMU, very little power would be radiated by the aerial. Typically, half or more of the Tx power (3dB+) can be lost in some AMUs in such extreme conditions, but better some radiated power than none! However, it may be worth trying different designs of AMU in such circumstances, if available, as designs vary in efficiency under different conditions, and one may be much less (or more) lossy than another at times.

The second caveat is that the feeder will always lose some of the RF power fed to the aerial. The better the feeder design and quality, the lower this loss will be. However, reflected power has to travel back down the feeder and then get returned again because of AMU action. The resultant increased peak currents (and, to a lesser degree, the resultant voltages) that result from wave interaction within the feeder (giving the SWR that can be measured) will cause increased loss of this reflected power, due to the feeder ohmic and dielectric losses. (The original Tx power is attenuated also, but only for one direction of travel.)

The higher the SWR, the greater the losses will be, due both to increased current and voltage peaks and to more reflection round-trips of significant power levels, so this can become a serious cause of power loss overall. As demonstrated at the meeting, using an AMU does NOT reduce the SWR on the actual feeder. For most operations on HF, however, with modest feeder lengths, loss due to high SWR is not a major concern, typically amounting to less than 1dB extra loss in the system. Operation at VHF and even more so at UHF can be seriously affected by high SWR, because of inherently higher basic losses in the feeder, and this must be considered very carefully in station design.

The third and minor caveat is that all aerials have resistive (ohmic) losses, which will cause some loss of the RF power that is absorbed from the feeder. Generally, this should not be a major problem (except for electrically short aerials), and in any case does not affect the use of an AMU.

Overall, therefore, using an AMU is a necessity in most cases, and not detrimental in any practical way. However, I recommend switching an AMU out of circuit when the system is "matched" without its use, as it is otherwise still circulating RF power and may cause some loss that is not desirable.

How can I be sure the AMU is doing its job correctly?

You will find that although in many cases there is a clear and unambiguous set of tuning adjustments of the AMU for a particular aerial, feeder and frequency combination, sometimes this is not so. There may be several apparently similar sets of adjustments of the L/C combinations, each giving a good SWR, though not always quite 1:1.

Unfortunately, although some settings may in fact give adequate results, it is also quite common for one or more of these "good" settings (or, indeed, the only L/C combination that seems to give a good SWR) to be useless. Instead of coupling the RF power into the feeder, the AMU is in fact circulating the RF around its coil and capacitor combination, with the "Q" of the circuit increasing the peak currents and voltages to levels that might seem appropriate to a transmitter power of 10 to 20 times that actually being used. This situation can easily, and very quickly, burn out the AMU, melting the coils and soldered connections, and arcing-over the capacitors and switches. (I once melted the plastic-insulated wafer switch of a commercial AMU rated at 150W, when using less than 15W of RF, because of this effect. I was able to replace the switch with a more robust type, but such damage can be very expensive, and difficult to repair.)

It is therefore very worthwhile (indeed, almost essential) to have a means of monitoring the effectiveness of the AMU in actual use. There are three main methods which have been in use more or less from the early days of "wireless" - though none the less effective for that - plus, nowadays, a fourth and readily available alternative.

I demonstrated one method - the RF ammeter in series with the feeder, AFTER the AMU. It doesn't really matter where in the feeder you place it, although the amplitude of the readings may vary along the feeder, but in the shack is the most convenient place. (You need two meters, one in each wire, for twin-feeder, but only one for coaxial cable.) You are not concerned with the absolute value being measured, only in obtaining the maximum value that is possible from using any tuning combination of the AMU, for a given Tx RF power level. Under mismatch conditions at the aerial but with the AMU in use, this value should always be greater than the value obtained with the same RF power from the Tx, without the AMU in circuit. A possible problem with using a current meter is that it will respond to both the forward and reverse powers that are flowing. I have never seen any description of what will actually be indicated under such conditions - but it works well enough for our needs, by showing an overall increase in the power in the feeder.

RF ammeters are rare nowadays, delicate and easy to burn out, and expensive. Also, you may need several meters with different full-scale readings, as the amplitude of current will vary along the feeder, depending on the SWR, and also vary with the frequency and RF power level being used. As an alternative, it is possible to "tap off" some RF from within the coax feeder after the AMU, via a suitable value of resistance, rectify it with a small signal diode, and apply the resultant DC to a microammeter - making a modest RF voltmeter in fact. This works, but the same degree of amplitude variations occur as with ammeters, and making sure that the meter is not overloaded at any time is a bit of a chore (although you will only need one meter plus a variable resistance to change its FSD reading, which is handy). Also, this method, and the ammeter method also, can only monitor the effect of tuning the AMU - important though that is.

The cheap, fairly easy and most useful alternative is an RF radiation field "sniffer". This is basically a diode detector circuit with a small aerial attached, rather like an un-tuned crystal set, put outside the shack where it can receive some RF directly from the Tx aerial. At its simplest, the unit has a sensitive microammeter in circuit, visible from the shack, and you simply tune for the maximum reading and choose the AMU setting that gives the best SWR and highest RF reading. However, as with the coax-fitted RF voltmeter, the meter reading will vary widely for different conditions, and it isn't easy to control. More sophisticated units may have a small DC amplifier built in, and feed a DC signal back into the shack, where the meter is more easily observed. Extra circuitry can then be used to prevent damage to the meter due to overloads.

The fourth method, which is certainly the easiest for most of us nowadays, is to use a second SWR meter (in-line power meter) AFTER the AMU, observing the forward power level and tuning the AMU for maximum RF output, while obtaining a minimum SWR on the first meter. You needn't worry about the reverse power on the second meter - the SWR is not going to change, although the reverse power will vary with AMU tuning as well. A "cheap and cheerful" ex-CB meter can often be used for this purpose! I have used this method to tune aerials, and with a little care it is possible to tune the AMU for virtually 1:1 SWR at the Tx output by only tuning for maximum forward power on the second meter (and this avoids having to have split eyeballs for observing two sets of meters simultaneously). You might then say "why have two SWR meters then?" - but the first meter gives the confidence that you are actually achieving a good SWR, while the second shows that you are getting a true maximum RF output.

Using some form of RF output monitor will not only make using an AMU much easier and less frustrating at times, but an "outside" type, although more complex, may in the long term help detect incipient faults developing on the aerial/feeder system, which could be reducing your signal without being obvious from the shack. Effectively, it is looking at your entire transmission "system", which is a big advantage.

Is it necessary to achieve 1:1 SWR (at the AMU input/Tx interface)?

Put simply - **NO!** When using an AMU at the Tx end of the feeder, it is only necessary to reduce the SWR down to a level that the Tx is happy with. In general, an SWR of less than 1.5:1 will almost always suffice. See below for further comment on this.

If one is using an AMU at the aerial feed-point to match into the feeder, then achieving a low SWR into the feeder is possibly essential for critically marginal use eg moon-bounce, and certainly commendable, although trying to achieve better than 2:1 SWR is usually a waste of time and effort. A second simple AMU at the Tx end of the feeder can then be used to reduce the SWR still further, and possibly allow operation over a wider range of frequencies, if desired. Using an AMU at the aerial feed-point, however, is usually a single-band and even single-frequency system unless some complex remote switching etc is used.

However, **UNLESS** using very long lengths of feeder, or very lossy feeder (or a combination of both) for the frequency or frequencies being used, a SWR on the feeder of as much as 5:1 is really of little or no consequence. Above 10:1 it can become a bit of a problem, but the problem is not so much high loss due to the SWR, as an inability of the average AMU to bring that SWR down to a workable level at the Tx output (plus extreme losses in the AMU). Tuning a G5RV is a typical situation where very high SWRs may be met on some bands - but some design or other of AMU will usually tune it sufficiently.

Changing the feeder length will also help at times - you may hear stations saying that they have altered their SWR by adding/subtracting a length of feeder. They haven't - but they may well have found a length of feeder where the transformation by the feeder of the "R + jX" value (as mentioned above) changes it to a value that the AMU can cope with. (There is another cause of an apparent change of SWR with feeder length change - see later.)

Provided the Tx is happy (remember the little built-in gizmo that may reduce power rather severely?), an SWR of less than 2:1 is often acceptable at the Tx/AMU interface, while a 1.5:1 figure is almost ideal. Virtually all transmitters will accept a 1.5:1 SWR without the safety system starting to cut back on the power output. By all means tune it for 1:1 if you can without too much trouble, but don't get up-tight if you can't quite get there. A quick QSY along the band to get onto a DX station's listening frequency is going to upset any previous tuning, but unless the shift is a long way, it is unlikely to degrade the SWR enough to warrant re-tuning and causing extra QRM on the frequency. (Very high "Q" aerials eg loops do limit the amount of shift, sometimes to only a few kHz, before the SWR becomes unacceptable - tough!)

Which reminds me - if your aerial shows a low SWR right across a band, with hardly any variation, it may be that the feeder and/or aerial is extremely lossy. If you were to obtain a 1:1 match with an AMU at 3.65MHz, say, but the SWR was still less than 3:1 at the band edges (without re-tuning the AMU), I would be very suspicious that you had some unexplained resistance in the system, reducing your Tx power. An SWR of 5:1 would be quite normal at the band edges on 80m, because of its large percentage bandwidth to frequency. Higher bands should not show such variations, as the frequency shift in percentage terms is generally less - 10 metres excepted - but 3:1 or more at band-edge may still be expected on most bands.

Don't forget - even with a perfect 1:1 at the Tx/AMU interface, the feeder SWR stays just as high as it is seen to be without the AMU. All you are doing, and all you normally need to do, is reduce the SWR at the Tx/AMU interface enough to make your transmitter happy.

Some (Simple) Maths!

Here seems as good a point as any at which to define the actual reflected power levels arising from a mismatch at the aerial, to which I briefly referred much earlier. As I haven't mastered the art of using symbols or sub-scripts on my word processor, I have to use alternative ways of showing formulae! My apologies.

The Greek symbol for Rho looks like a poorly written lower-case p (which I will use instead). This is used to denote the magnitude of voltage (or current) reflection coefficient in the equation:

p = {(SWR - 1) divided by (SWR + 1)}

This is the relative amplitude of reflected to forward voltage or current - a **RATIO** that doesn't change with changes in the power being used. It actually applies to the SWR seen at the aerial (or mismatch point), but is usually only measured in the shack. Consequently, as power losses in the feeder reduce the reflected RF power and therefore the apparent SWR at the shack end of the feeder, the true value of "p" will be under-calculated. This keeps the average amateur happier.

Now, power is derived from the usual power calculation formula by squaring either the voltage or the current value. Thus, (p.p) ie p-squared, gives the power ratio, or:

p.p = magnitude of power reflection coefficient (power reflected by mismatched load), and

(1 - p.p) = power absorbed by a mismatched load.

Thus, for 1:1 SWR, p = 0, p.p = 0, and (1 - p.p) = 1 or 100% into the load (because for an SWR of 1:1, {SWR - 1} is zero).

For an SWR of 2:1, p = (2 - 1, divided by 2 + 1) = 1/3 or 0.333. The square of this is 1/9, or about 0.111. Thus, about 11% of the forward power is returned as a reflection - less than 1dB loss of power. The aerial will accept about 89% of the original power (before use of the AMU). As the average AMU will lose about 1dB of power in normal use, it is arguable whether using one to correct for less than 2:1 SWR is worthwhile, unless the Tx needs it to give full output power.

For an SWR of 5:1, the reflected voltage coefficient is 4/6 = 2/3 or 0.666, and the reflected power is about 44%, leaving only 56% entering the aerial (nearly a 3dB loss).

For quick reference, therefore, and ignoring feeder losses:

A 2:1 SWR gives 11% reflected power, 3:1 SWR gives 25% reflected power, 4:1 SWR gives 36% reflected power, and 5:1 SWR gives 44% reflected power. A modest 1.5:1 SWR gives 4% reflected power. An "almost perfect" 1.1:1 SWR is less than 0.25% reflected power, while 10:1 SWR (easily found on a G5RV!) gives a whopping 67% reflected power.

Possible Damage to Your PA!

It can be seen that a 2:1 SWR is actually a small problem in terms of power lost to the aerial (just over 0.5dB in fact), but even this SWR can adversely affect some solid-state transmitters, as they tend to be highly-protected ie whereas the 2:1 SWR would only reduce the radiated power by about 11%, the safety circuitry may well reduce the input and output power by 40% to 50%!

If the Tx PA power INPUT under reflection conditions is maintained, however, the increase in heating in the PA from inefficient operating conditions can be quite significant. Assuming a Tx PA with 66.7% efficiency, it may take 150W DC and put out 100W of RF (say). The PA is coping with 50W of heat. If the detuning effect of reflected power reduced the RF output to 75W (say), while maintaining the same power INPUT, the dissipation would increase to 75W - a whopping 50% increase. (This degree of reflection corresponds to a 3:1 SWR.)

The 5:1 SWR is clearly even more serious, resulting in the radiated output being nearly halved and nearly half the Tx output power being reflected back, upsetting the PA output tuning and thus reducing the RF power output by the same amount. For a maintained 150W input to the PA, the RF output would now only be just over 50W, and nearly 100W would be dissipated in the PA.

In practice, for the greater values of SWR seen at the Tx output, it would be unlikely that the PA would be able to maintain the power input that was originally obtained when matched into its correct impedance, although sometimes the power input can actually increase above that for matched conditions. In any case, you can see the potential for disaster, I hope.

However, even if this high SWR exists on the feeder into the shack, use of an AMU can bring the **EFFECTIVE SWR** down to safe levels for the Tx. All (or virtually all) of the reflected power is then sent back to the aerial and absorbed and radiated by it - it is the SWR seen by the Tx after adjusting the AMU that matters, not the actual SWR on the feeder/aerial.

Many amateurs are besotted by the idea that they have to achieve 1:1 SWR, although this may actually not be possible with a given aerial, feeder and AMU combination. Very often, 1.5:1 can be achieved, but no lower. From the above equation, an SWR of 1.5:1 gives a "p" of 1/5, and "p.p" of 1/25 or 4%. Thus, a 1.5:1 SWR represents reflected power of only 4%, and this amount is not likely to cause significant de-tuning of the PA output or over-heating of the TX, unless it is already working at or beyond its design limits. Why strain for perfection?

Incidentally, one cause of being unable to achieve a perfect 1:1 SWR can be a high harmonic (or spurious) content in the Tx output. Looking at the 1.1:1 figures, you will see that this represents only 0.25% power reflection. If your Tx output actually had spurious or harmonic output of 0.25% of the total Tx power (250 milliwatts for a 100W Tx), this RF would almost certainly be totally reflected by the aerial, as it is on a frequency or frequencies not acceptable to the aerial. This spurious RF power cannot be "tuned out" by the AMU at the same time that it is tuning out the fundamental RF power reflection, and this would prevent you ever seeing lower than 1.1:1 SWR.

Nowadays, most commercial transmitters would have harmonics etc at least 40dB down on the fundamental, because of good output filters and design. With a 100W output, this would give only 10 milliwatts of unwanted RF, but with older rigs, or nowadays with over-driven amplifiers or even with an over-driven or poorly-adjusted PA, the spurious outputs can be relatively very high. It is not the absolute level that is important when measuring SWR (apart from meter error problems), but the relative levels of wanted and spurious RF in the output from the Tx. Home-brew and QRP rigs can be particularly bad offenders in this matter, because they tend to have rather basic tuning and output circuitry in many cases.

When should I use a Balun (if at all) - and why?

If a "balanced" aerial eg a dipole, is fed from the Tx with coaxial cable, the RF current initially is confined within the coaxial cable. The current flows (at a given instant in time) up the surface of the inner conductor, onto one leg of the aerial. By electromagnetic interaction on the aerial, the return current ought then to flow from the other leg of the aerial, down the surface of the inside of the sheath of the coaxial cable, and back to the Tx. If it always did this, there would be no trouble that needs a Balun.

Immediately, however, it can be seen that there is another return path for the RF ie down the surface of the outside of the cable. This current is totally random in its magnitude, depending on the conditions at the aerial feed-point, the resistance and impedance of the outer surface of the sheath, the length of the feeder, and the conditions at the shack end of the coaxial cable. This current eventually gets back to the Tx output circuitry, to complete the RF path for all the power, but it can cause all sorts of problems on the way. RF burns from the microphone or other Tx fittings are one symptom of this condition (although this is not the only cause of such effects), and random Tx or AMU tuning and output variations are another.

The length of the feeder can be critical. If it happens to be electrically a quarter-wavelength long on the outside (for coax cable), from aerial to effective earth (or Tx output), the effective (nearly) short-circuit at the earthy end is transformed to a very high impedance (not quite an open-circuit) at the aerial. Under these conditions, virtually no current can flow down the outside of the coaxial cable feeder, and the aerial is fed in a truly balanced manner. If the length is a half-wave, however, this presents the aerial feed-point with a very low impedance, and a maximum of current will flow down the outside of the feeder. The aerial feed is very unbalanced under these conditions.

Does this matter? After all, the same power is still going to the aerial, assuming it is properly matched (although the problem can exist whether an AMU is used or not, and regardless of the SWR at the aerial feed-point). Apart from the "RF burns" and other minor problems, the real problem is that the current flowing down the outside of the feeder will interact to some degree with the aerial itself. For most aerials, the effects of such interaction will be complex and variable in magnitude. What it will almost always do is distort the polar pattern of the aerial because of direct radiation of RF from the feeder.

This "extra" radiation is generally in the vertical plane because of mainly vertical feeder runs, and can be a very effective second aerial. However, what this does is completely ruin the front-to-back (or side) ratio and the vertical lobe pattern of the main aerial, whether a dipole or a beam of any polarisation. It can also give rise to greater problems with multi-path reception of a signal, because of unwanted sensitivity to polarisation. The effects will be there for both transmitting and receiving.

So why is a "Balun" an answer to such problems?

A "Balun" gets its name from being used to connect a balanced (BAL) aerial system to an unbalanced (UN) feeder or interface - sometimes seen as BAL-UN. It is NOT pronounced "balloon", as some foreign stations would have you believe! "Bay-lun" is also frowned on by purists. And an UN-UN (think!) is not an onion!

A Balun is primarily a device for preventing RF power from flowing down the outer of the coaxial cable feeder from the aerial connection point, thereby forcing the RF power to go where it is meant to go. Baluns come in various forms and designs, with pro's and con's for each. I didn't have much time in the talk to consider these aspects, but did refer to a couple of the simplest and most effective designs, commonly called "Choke Baluns" (because that is what they do to the RF!). One type is a short length of the feeder, with a number of lossy ferrite "beads" along its external length - the number and type of ferrite beads depending on the frequencies in use. To be effective, this "choke" must be situated very close to the aerial feed-point. I understand that Maxwell, W2DU, is the inventor of this type of Balun.

An alternative and quite effective design is a number of turns (perhaps 15 to 30) of the feeder on a former (usually of about 2" - 3" diameter) or "loose-wound" in a coil, typically of about 6" diameter, and again installed very close to the aerial feed-point, although this is sometimes difficult. Size, the frequency or frequency range in use, availability of the materials, cost and weight are the major considerations in deciding on which design to use.

Baluns can also be used to transform impedances, simultaneously with the balanced to unbalanced function. Usually, such Baluns are based on a ferrite-cored transformer design. This impedance transformation can be a fact, but it can also be very misleading, as the correct (or assumed) impedance transforming action is only likely to be effective if the impedance on each side of the Balun (input and output) is actually as designed for and specified. This is why a Balun is usually specified as, for instance, a 50 ohm to 200 ohm 4:1 Balun, rather than as merely a 4:1 Balun. Only rarely will an actual aerial/feeder arrangement present the proper impedance to be "transformed", and any other condition will degrade the Balun action. Many such Baluns for the HF bands are also frequency-restricted, working better at high or low frequencies, and poorly at the other end of the range.

The usual result of these limitations is increased losses in the Balun, especially if ferrite-cored, and its consequent overheating (plus serious loss of radiated power). The currents in the two legs of the feed to the aerial may not be equal either, which is not what is intended. Ferrite-based Baluns are to be avoided if possible - and they cost more than the choke types mentioned above! Unfortunately, such Baluns are usually to be found in most commercial designs of AMU, to assist in interfacing to balanced (twin) feeders, but their effectiveness is often of very dubious value. An interesting test in your own shack would be to use your AMU with the Balun connected to balanced feeders as normal (if you have same), and run full power for as long as you can eg in an extended QSO. Then feel the temperature of the Balun - if it is warm, you are losing RF power. If it is hot, don't use it at all!

There is a simple design of Balun, also using ferrite beads on the outer of coax, which can be used at the AMU output to interface to balanced feeders, which does not suffer from the transformer problems - which I did describe during the talk - but it cannot give any impedance transformation. If you are using balanced feeders into the shack, a properly designed unbalanced to balanced AMU, without a Balun of any form, is the best answer to matching and balancing the system.

It must be emphasized that the Balun in an AMU, even if working properly, is not always able to prevent unwanted currents flowing along the feeder from the aerial - you may still need a Balun up close to the aerial feed-point. (**Note:** With coax, the unwanted currents appear on the outside of the cable. With balanced (twin) feeders, the unwanted currents manifest themselves as parallel currents on the two wires, as if the feeder was a single wire. Both conditions are detrimental to aerial radiation patterns etc.)

You may wonder where this external current is coming from, if you have already fitted a choke Balun up at the aerial. It can come from the aerial radiating RF back onto the outer of the feeder - usually not a very large amount, and not sufficient to seriously degrade the radiation characteristics of the aerial (as described above for feeders not fitted with a Balun), but enough to upset SWR measurements.

It is external current on the feeder, by the way, that creates the strange effect of apparently being able to improve the SWR on a coaxial feeder (without altering any AMU tuning) by changing the overall length of the feeder. As you change the feeder length, so you change the conditions seen at the aerial, via the outer of the feeder (as described above). This in turn is seen as a change in aerial matching and SWR. Please note that you are not necessarily "improving" the match to the aerial - probably, you are merely altering the SWR appearance at the shack end of the feeder, and only for one specific frequency. To prevent this effect, a further "choke" Balun is needed at the shack end of the feeder, before the connection to the Tx and/or AMU, to block the flow of unwanted RF currents to earth.

Miscellaneous Matters - Items perhaps referred to, glossed over, missed out or thought of later!

Reflected Power is "Real" Power

I mentioned that reflected power is real power. Some "authorities" deny this, saying that reflected power is "wattless". Ignore and refute such ideas! They originate from incorrect evaluation of the voltage and current phase relationships existing within a feeder when reflections are present. The very purpose of an SWR meter is to measure the forward power and the reflected power, in a cunning arrangement of circuits that can separate out these two elements from within the feeder. If you used a very low-wattage load resistor in the meter for the reflected power circuit, ran high power and had a bad SWR, you'd soon see the resistor burn out! Wattless power can't do that.

A personal experience from when I worked on microwave radio systems:

These microwave systems used a 3-port circulator in the transmitter waveguide, which allowed the combined transmit power from 6 or 8 10W-output transmitters to feed the aerial (from port 1 to port 2), but any reflected power was fed from port 2 to port 3 and into a dummy load. This prevented any reflected power from returning to the transmitters from the aerial and giving the sort of trouble referred to earlier by Nick. This dummy load, which was normally made from a piece of tapered wood, coated in an absorbent (lossy) graphite and glued into a short length of closed waveguide, was usually rated at about 20W dissipation, as normally only a watt or so of reflected power was likely to be seen, at worst.

However, one night, vandals caused serious physical damage to the main waveguide run at a remote station, which caused a high SWR and a large value of reflected power appearing at the dummy load. This "real" power caused the dummy load to catch fire, creating a severe mismatch at port 3, which in turn reflected the power round to the transmitters on port 1. These immediately shut down and gave alarms to the control station. Luckily, we had spare waveguide and a dummy load at a near-by station, where I was working at the time, and an installation team was able to get the system working again within hours. However, to me the incident was absolute proof that reflected power in a feeder system is "real" power - it can burn!

Visualising Power Flows in a Feeder

It is very hard to visualise the flows of forward and reflected power in a feeder, and the interactions that produce a measurable SWR. Too often, because of simplistic teaching of current flows as being akin to water in a hosepipe, the concept of two power flows in opposite directions at the same time is impossible to grasp. I think that the best illustration to avoid this problem, as expounded by W2DU and others, is to consider a pond, into which you lob a brick, or several at short intervals. The initial ripples spread out until they hit the sides, whereupon they are reflected back toward their origin (more or less). They then pass through any ripples still moving out from the point of disturbance, without impeding them or being affected by them in any way. You see a whole pattern of ripples, moving both ways - which is more nearly what you get in a feeder with reflected RF. It is only a concept though - don't take it to heart too much!

Ready Reckoner Chart for Feeder Impedances

I handed out photocopies of a chart that I prepared for another talk (in 1991 it seems!), which is an enlarged and slightly modified version of one given in L.A. Moxon's book (referred to earlier). In the 1982 Edition, this chart is on page 55. The chart enables a quick evaluation of end-fed wires (and any simple dipole-type aerial where the length of wire from end to shack can be measured), as to what reactance and impedance will be "seen" at the shack end of the wire. A straight line from the length figure (RHS), through the frequency of interest, will meet the LHS at a point that will show whether the aerial will look inductive or capacitive, and whether it is high, medium or low impedance when resonated.

A capacitive aerial will tune to resonance with the aid of series inductance, and an inductive aerial will require a series capacitor for resonance (which is much the easier to arrange, of course). Low to medium impedance means from about 20 - 30 ohms to perhaps 300 to 500 ohms, and high impedance means up to perhaps five thousand ohms. (The extremes of impedance are always best avoided - especially the high end.)

Using this chart, it can be seen that an end-fed wire of 160 feet length (or, for instance, an equivalent length wire as one leg of a dipole of 120ft length per leg plus 40ft of open-wire feeder) on 1.9MHz will look moderately low impedance and need a series capacitor to tune it to resonance. This single wire "design" of 160ft is actually my own aerial at present, and indeed it needs about 350pf to resonate it on 1.9MHz, and then matches into 50 ohms almost perfectly, while only varying from about 40 ohms to 60 ohms impedance throughout the whole band, provided it is re-tuned as needed. The variable capacitor is the entire "AMU" in this case - I have calibrated its dial with frequencies across the band, and can pre-set it for resonance before QSY'ing (although wet weather can cause small changes at times). It is a simple matter to estimate the result for other wire lengths and frequencies, without having to "cut & try it".

Economic Feeders - or "Does the Impedance Really Matter"?

Provided the basic loss of the feeder is less than 1dB overall in matched conditions for the frequency used, the impedance of the feeder need not match that of the aerial nor of the Tx output, if an AMU is used at the Tx/feeder interface to give a good match for the Tx. (With higher basic loss, say 2dB or more - due to higher frequencies, longer lengths or poorer quality feeder - this is not a good idea, because the losses due to a high SWR become excessive.)

This impedance "flexibility" allows the use of feeders (coax cable, figure-8 "balanced twin", ribbon or twin open-wire etc) that have a useful characteristic (low loss, low cost, durability, flexibility or whatever), regardless of impedance, rather than having to use "standard" coax at exorbitant cost. Good quality ribbon feeder, low-loss 75-ohm TV coax, or even satellite-type cable can be as good as or better to use than RG58 or RG213 (say) in many cases, at a fraction of the cost. The lower basic loss of ribbon cable may more than offset the increased loss due to a high SWR. For the ultimate in this line, making your own open-wire balanced feeder out of 16-gauge copper wire and ceramic insulators for HF use is hard to beat!

Do use decent connectors though, and not the types used for satellite systems - soldered joints are essential in a transmitter feed line. Good-quality Belling-Lee coax connectors are actually very good for RF purposes, although nominally 75-ohm impedance - possibly because they are physically quite small - and if rescued from old TV leads can be very economic! They have been used successfully at up to 10GHz in radio amateur construction designs.

Three caveats to the above - firstly, SWR meters are usually designed to work with coax cable of a specific impedance - almost always 50 ohms, or sometimes 75 ohms. Using a meter connected to a feeder of the "wrong" impedance will usually cause incorrect SWR measurements, sometimes of rather large magnitude! As long as a 50-ohm SWR meter is used between a Tx with 50-ohm output Z and an AMU, with 50-ohm coax for the interconnections, this does not cause a problem in practice.

This does not preclude the use of the second "50-ohm" SWR meter for AMU tuning purposes, regardless of feeder impedance. All that this meter has to do is show when maximum RF power is being fed into the feeder, although the absolute power level it then shows may be incorrect.

Secondly, the use of unusual impedance feeder can significantly change the "R + jX" value seen at the AMU output. This may be beneficial, particularly if the aerial already has a severe mismatch compared to 50-ohms (eg the G5RV on some bands). It possibly could improve the match, rather than it getting even worse! However, it can also make it very difficult to obtain a good match, depending on the totality of effects, and on the ability of the AMU to "tune-out" the particular value of "R + jX" that it is seeing. Changes to feeder length, usually by only a small fraction of a quarter-wave-length, may help in such cases, or a different AMU design (Pi, T etc) or different values of L and C in the tuner may solve the problem. Some amateurs keep several different lengths of coax feeder in a "switch box", in series with the main feeder and after the AMU, so that if matching difficulties arise, they can simply add a range of feeder lengths to change matching conditions.

Thirdly - this use of non-standard impedance feeder is only between the AMU and the aerial. If you use it elsewhere you could have serious problems! I have, however, deliberately used short (under a half-wavelength) patch-leads of 75-ohm coax cable to improve the match of a 50-ohm feeder to the Tx, when I have not had a suitable AMU to hand. This can be particularly effective at VHF and UHF, as AMUs for such high frequencies are not so readily available commercially. Do make sure you permanently label such cables, as their misuse elsewhere by accident could cause real headaches!

Effect of Mismatches (SWR not 1:1) on Feeder Losses

With a 1:1 SWR, the feeder losses should be as per the specification for that feeder - at least when new - or as measured, using an RF source and a power meter. The r.m.s. values of current and voltage are the same throughout the length of the feeder, apart from a gradual reduction in RF power from Tx to load as a result of the inherent losses of the feeder, due to ohmic resistance and dielectric losses.

When the SWR increases from 1:1, the resultant interaction of forward and reflected powers causes both the peak voltage and peak current in the feeder to increase, relative to those found in a feeder with 1:1 SWR. The minimum current and voltage points (or troughs) are less than the values in a feeder with 1:1 SWR, but the overall result, because losses are related to the square of voltage and current, is that the higher peaks lose more power than that saved from the low values.

A feeder carrying reflected power therefore will attenuate the power in both directions ie from the Tx to start with, and from the load back to the Tx. The reflected power added in phase to the original power by use of an AMU is also attenuated proportionally, on its way back to the load, so the end result is an initial loss of "forward" RF power, and a multiple loss of reflected power, because of basic feeder electrical characteristics.

The effect is really quite minimal if the basic feeder loss is small (under 1dB, say), which implies either good-quality (low loss) feeder, or shortish lengths, or use of the lower frequencies - or any combination. At this level, a SWR in excess of 5:1 or even 10:1 is quite bearable at HF. Such high SWRs would probably not be acceptable for really marginal signal conditions, once the basic feeder losses exceeded 1dB. A basic feeder loss above 3dB is going to be a potential cause of serious power loss at any frequency, both in its own right and as the result of SWR losses. In practice, anything above 2:1 SWR on lossy feeders will give significant extra loss, and is best avoided.

SWR Meter Errors

Apart from the actual reduction in radiated signal that can result from poor SWR and high basic losses in the feeder, there is another problem. This problem is that an accurate measurement of SWR at the Tx depends in part on seeing the full value of reflected power, which doesn't happen. It also ought to allow for the reduced level of RF arriving at the load in the first place (due to the basic feeder losses). However, the SWR meter cannot allow for the reduced power level at the load, as it looks at the outward-bound RF at the Tx end, and it will also see a reduced level of reflected power, due again to feeder losses.

Consequently, the SWR meter's comparison of reflected power to the power arriving at the load is wrong twice, the two errors adding together to amplify the overall error. The overall result is that the SWR reading at the Tx end of the feeder will always be more optimistic that the reality. For example, with a basic feeder loss of 4dB or more, even an open-circuit or short-circuit at the load end of the feeder will be seen as not worse than 2:1 SWR!

This effect can be used to evaluate the loss of feeders, which can be rather handy. Basically, the procedure is to feed the aerial (without an AMU in circuit) with RF power at a frequency at which the aerial is not resonant ie one that will cause the aerial to reflect all, or almost all, the RF power. This is equivalent to making a short-circuit or open-circuit at the aerial feed-point, without actually doing it physically. In general, a frequency that is 10% to 20% away from aerial resonance should suffice for this test.

The SWR meter should, ideally, see something in excess of 20:1 SWR at the Tx end of the feeder. In practice, if the reading is 10:1 or more, the feeder has less than 0.5dB loss at that frequency. A 5:1 SWR indicates 1dB loss. 3:1 SWR is a little under 2dB loss, while 2.5:1 SWR is a bit over 2dB loss. A 2:1 SWR shows 4dB loss, and if you get any lower SWR it is probably time to make a serious examination of your feeder - unless the data for the specific type, length and frequency indicates that high losses are to be expected. The losses quoted above are for one direction of RF power transmission, although the SWR meter is reading the result of the RF making a round-trip.

I use a 4dB power attenuator between Tx and AMU when trying out new aerials, bands or AMUs, so that even if the real SWR is very bad, the Tx is not seriously affected, although it may reduce its output power slightly when it sees a 2:1 SWR. When I have achieved what seems to be a fairly good match, I then switch out the attenuator and give the AMU a further "tweak" to achieve a final and acceptable SWR.

Another SWR meter error that can occur is due to the characteristics of the metering circuits in the meter itself. These circuits use low-power "signal" diodes to rectify the applied RF, and these require a certain minimum value of applied voltage (power) before they conduct. The early part of their conduction characteristic (at low power levels), once they are actually conducting, is also non-linear. Basically, the typical SWR meter needs a fairly large applied power to allow the diodes to operate in their linear region and give consistent and reasonably accurate measurements.

This power level varies with each meter, but typically, a Tx power of 10 watts or more is enough for measuring forward power with a reasonable degree of accuracy - although most commercial SWR/Power meters for amateur use are only specified to +/- 20% (+/- 1dB) accuracy at full scale. However, unless the SWR is extremely high, the reflected power level is going to be a small percentage of the forward power, and although the metering circuitry is usually designed to allow for this, at fairly low SWRs and power levels the metering still becomes non-linear and very inaccurate. If you reduce the Tx power sufficiently, it is even possible to end up with the SWR meter indicating a perfect 1:1 SWR, even when at higher power it may be showing some disgusting value.

A simple check on your own meter is to measure SWR on a modest aerial mis-match (say, 2:1 or 3:1), at various Tx power levels. When the meter gives more-or-less the same SWR readings at all powers above a certain power level, that indicates you have reached the RF power level needed (for that degree of SWR) to make meaningful measurements. In practice, the result of this problem is that the apparent SWR always seems better than it really is. Annoying - or happy-making - isn't it?

Conclusion

That's it - more or less! I hope the talk itself, and the notes above, have been helpful in understanding what is going on when you use (or don't use) an Aerial Matching Unit, and what it can or can't do. Perhaps I have also been able to shine a light on the esoteric world of Baluns? Please let me have any queries you may have on this topic, and particularly on any aspects raised above. I will try to answer them, if possible, and if I can't, I will ask Nick!

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