Response to Dean Straw's "Hams and the Conjugate Match"

January 24, 2005, by Walter Maxwell, W2DU (Revised April 16, 2011)

(This notoriously infamous paper "Hams and the Conjugate Match," written by Dean Straw, originally posted on the ARRL Web Site and on Yahoo, is still available for downloading on Yahoo,)

Background for Understanding the Need for this Response

The text that follows includes the original wording of Dean Straw's paper, in black font, explaining why he considers the Conjugate Match only theoretical, and has no existence in the real world, plus his reason for deleting the section on Conjugate Matching from the ARRL Handbook that appeared in all editions from 1986 to 1994. I wrote the section he deleted at the suggestion of Technical Editor Jerry Hall, and at the request of Doug DeMaw, then Director of the ARRL Technical Dept. Both DeMaw and Hall considered knowledge of the conjugate matching principles important to the amateur community in understanding how the impedance matching of the pi-network output circuits and antenna tuners to the antenna feedline occurs. After both DeMaw and Hall retired, the unfortunate publishing of the infamous Bruene article in the November 1991 issue of *QST*, and Straw's belief that Bruene's invalid and unsupported definition of the Conjugate Match with RF power amplifiers is correct, resulted in the League's remaining (less than competent) Technical Department personnel reversing the Department's position concerning the conjugate match. The League's incorrect position still remains, and the Technical Editors refuse to discuss the problem.

Dean's many writings demonstrate that he's highly skilled in the area of antennas and transmission lines. I commend him on that, because his writings have provided important information in the education of communication engineers and radio amateurs alike. However it is evident from his paper that we are about to discuss, indicates his total lack of understanding of the practical application of conjugate matching.

My comments in response to Dean's paper appear in red, inserted at the appropriate places in his paper—there are many half-truths and factual errors in his paper that are addressed and corrected. However, while reviewing this response one point should be kept in mind. When an employee of a company publishes a paper, in general he is required to submit his material for approval to obtain company permission to publish to avoid errors that could reflect negatively on the integrity of the company. In my case, while an engineer with RCA from 1949 through 1980, I had to obtain approval from four divisions of the Company before even being allowed to submit the material for the series of articles entitled, "*Another Look at Reflections*" to the ARRL for publication in *QST* in the 1970's. Therefore, I believe it noteworthy that two of the RCA-engineering reviewers, one, Jack Young, Chief of in the transmitter design group of the Broadcast Division, complimented me on my presentation of the conjugate match, and then

both ARRL Technical Editor Jerry Hall and the then General Manager, John Huntoon did likewise. Although he had previously retired as Technical Director of the ARRL, the late George Grammer also complimented me personally on the quality **and accuracy** of my presentation of the conjugate match that appeared in those *QST* articles. (Without doubt, Grammer was the most competent RF engineer ever associated with the ARRL)

Had Dean's original manuscript been adequately reviewed by *qualified* editors to discover the factual errors it contains before placing it on the ARRL web page, the flagrant errors in his paper could have been avoided. As it is, these errors appearing publicly on Yahoo reflect negatively on the integrity and competence of the entire Technical Department of the League. Many people have expressed to me their concern over the League's unprofessional treatment of me regarding the conjugate matching controversy. (More on this later.) Several have demonstrated their concern by discontinuing their membership in the ARRL. Therefore, it is my hope that a positive result of this response will help re-establish the technical integrity of the League in the minds of those who have expressed their concern.

Before proceeding to Dean's paper it's important to define the Conjugate Matching Theorem as it appears in practically all communication engineering texts to see what a simple concept it is, and to provide support for my responses. From it we'll also try to discover why Dean believes it to be too difficult for some people to comprehend. The definition:

There is a conjugate match when the real (resistive) parts of the source and load impedances are equal and the reactive parts of the source and load are equal but of opposite sign.

A corollary to this definition:

There is a conjugate match if delivery of power from a source to a load decreases with a change in impedance of the load.

These definitions form the basis for the **Maximum Power-transfer Theorem**, which is, quoting from Everitt's *Communication Engineering*:

"**The maximum power will be absorbed by one network from another joined to it at two terminals, when the impedance of the receiving network is varied, if the impedances looking into the two networks at the junction are conjugates of each other."**

This condition is achieved when either the pi-network or the antenna tuner is adjusted correctly. It's that simple. It's important to note here that Dean's impedance-matching program 'TLA.EXE' performs this function mathematically, using an algorithm based specifically on the

conjugate matching theorem. However, because Bruene's incorrect definition of the conjugate match when the source is an RF power amplifier **is the original source of the controversy**, let's now put the Bruene definition to rest before discussing Dean's paper.

Bruene's definition of the conjugate match with respect to RF power amplifier is that R_S must equal R_L, where R_S is the dynamic plate resistance appearing upstream of the pi-network, and R_L is the resistance looking into the resonant pi-network. Bruene incorrectly calls R_S the source resistance of the amplifier. In general, R_S is greater than R_L, because plate current is zero for a portion of the cycle. Therefore, it is true there can be no conjugate match at the **input** of the pi-network. However, Brunei's definition of conjugate matching with respect to RF power amplifiers is **invalid** because the effect of energy storage of the pi-network tank circuit isolates the non-linear condition at the network input from the output, allowing the voltage-current relationship at the output to be linear. Thus the true source resistance of the RF power amplifier is at the **output** of the network, resistance R = E/I, the time-unvarying voltage-current ratio that occurs at the output of the network, not R_S at the input. Consequently, the **correct source resistance** for use in the definition of the conjugate match is **R = E/I**, not R_S, as Bruene claims. Therefore, the equality required for the conjugate match to exist in the RF power amplifier is $R = E/I = R_{LD}$, the load resistance external to the output pi-network. Thus it is evident that there **can** be a conjugate match at the **output** of an RF power amplifier, despite Bruene's claim to the contrary.

Let's now proceed to examine Dean's paper to learn the reasons why he disagrees with conjugate matching in general, and why his reasons are unfounded. As stated earlier, this paper is still available on Yahoo, by simply entering the title shown below.

Hams and the Conjugate Match

July 16, 2001, by R. Dean Straw, N6BV Senior Assistant Technical Editor,

ARRL Editor, *The ARRL Antenna Book*

In Chapter 4, "A View into the Conjugate Mirror" in the 2nd Edition of *Reflections* by M. Walter Maxwell, W2DU, (Sacramento: WORLDRADIO Books, 2001) on page 4-1, while discussing the concept of forward power measured by a directional wattmeter, Maxwell says:

> "The basis for understanding this rather subtle concept lies in the wave mechanics behind the principles of impedance matching introduced in Chapter 1 and defined in Chapter 2. As far as I know, the *wave* aspect of this subject has been presented in the literature only by Slater, Alford, (*Refs 35, 39,* and by this author in Chapter 23.)

Perhaps this restricted exposure may account for some of the confusion in this area among engineers and amateurs alike."

Actually Looking at the Cited Reference

OK, let's actually look closely at the historically important *Ref 35* cited by Walter Maxwell. From J. C. Slater, in *Microwave Transmission*, (NY: McGraw-Hill Book Co., 1942), p 47 to p 48, when discussing matching theory, starting at equation (5.20): "By a method entirely analogous to that used in deriving Eq. (4.65), we can show that the expression on the right of (5.20) is the impedance looking to the left from the arbitrary point where we are applying our condition, provided we replace the generator by an impedance equal to its internal impedance. Our result then, is that for maximum power transfer, the impedance looking to the right from our arbitrary point must be the complex conjugate of the impedance looking to the left from the same point; the reactances of the two half networks must be equal and opposite, an inductive reactance balancing a capacitive reactance, and the resistances must be equal. Obviously, our earlier theorem of (5.13) and (5.15), relating to a simple generator and load, is a special case of this more general theorem. The theorem we have just stated gives the general condition for impedance matching. If however the transmission line joining generator and receiver is resistanceless, so that there are no losses in it, we can prove a remarkable further theorem, no matter how complicated the line may be: if the conditions of the impedance match are satisfied at one point of such a lossless line, they are automatically satisfied at all points." At this point, let me interrupt quoting Slater directly to point out that his "remarkable further theorem" above is what later authors, including Walter Maxwell, refer to as the "Conjugate-Match Theorem." Later, on p 49, Slater says, after mathematically proving the "remarkable further theorem" in a series of equations (5.21) through (5.26):

"We have now shown that if the impedance match conditions are satisfied at one point of a uniform resistanceless line, they are satisfied at another arbitrary point of the same line. Thus they are satisfied at another arbitrary point of that uniform line. This however is the beginning of another section of uniform line; if the conditions are satisfied at the beginning of this section, by our same theorem they are satisfied at any arbitrary point of it, and by extension of this method they are satisfied at any point of the composite line, so long as each section of the line is resistanceless, so that by (5.22) the coefficients of impedance are pure imaginary."

So Far So Good!

So far, so good for the conjugate-match theorem. All the right words show up in this venerable text. But we need to look at the *whole* story to completely understand Slater. He continues, in his next paragraph (still on p 49):

"If there were losses in any section of the line, the corresponding impedance coefficients would have both real and imaginary parts, so that we could not perform the transformation from (5.25) to (5.24) by taking conjugates, and the theorem would not be true."

Any practical application in the real world involves lossy components, either in the transmission line or in any physical matching network. So, unless I've completely misunderstood Slater, it seems that for any practical application of the conjugate-match theorem, the conjugate-match theorem is *not applicable*.

Yes, Dean has **completely** misunderstood Slater; it will become clear as we continue that the conjugate match theorem *is applicable* **in every practical case** where all available power is being transferred from a source to its load.

In fact, logic dictates that a theorem that cannot be proved under specific circumstances (here, in the case of losses) cannot be called a "theorem" for this set of circumstances. Not to put too fine a point on it — the conjugate-match theorem is strictly theoretical, dealing only with lossless situations.

Unfortunately, Dean's 'logic' statement above is untrue, because, contrary to his statement, the conjugate-match theorem is **not** restricted to lossless situations, as I will explain.

Let's begin with a lossless network and proceed from there. When a network comprised of lossless reactive elements connects a source to a load is tuned to resonance a conjugate match exists everywhere in the network, at the input and output terminals, and in both directions, forward and reverse. Now let's replace the lossless elements with real elements, but with the reactance values of the elements remaining unchanged. In this case the loss resistances in the elements detune the network away from resonance; the input and output impedances are now reactive, and the conjugate match is destroyed, resulting in a conjugate mismatch, as Slater points out.

However, let's now assume the real network with resistive losses we just created is on our workbench. The reactive elements are adjustable. By simply adjusting the reactances of the network elements we can return (tune) the network to resonance, thus eliminating the reactances appearing at the input and output of the network, and returning the conjugate match that was destroyed by the losses in the individual elements. This procedure is called tuning to resonance, which is what we do when we tune our transmitters for delivery of the available power into their loads.

However, we must be careful to understand that during the conditions described above that although the conjugate match exists everywhere in the real network, it exists in only one direction—forward. If we reverse the direction of power flow without retuning, the resistive losses again introduce reactances that detune the network as they did when introducing loss into the lossless network, thus again destroying the conjugate match. But re-adjustment (retuning) of

the reactances of the network elements to again bring the network into resonance, the conjugate match again exists everywhere in the network, but in the reverse direction.

I have calculations prepared on Mathcad worksheets that prove the points I've discussed above, which I can furnish for Dean's review if he wishes. (These calculations will be appended to this paper.)

Is Slater the Only One?

And then let me ask a second question: Is Slater, whom Maxwell credits as being one of the pioneers developing the wave concept of the conjugate match, the only authority who states that the conjugate-match theorem doesn't actually come into play when losses are involved?

In my opinion, Slater doesn't say that the conjugate-match theorem doesn't come into play when losses are involved. Dean has misinterpreted Slater, as I explained earlier. In addition, we are not developing the **wave concept** of the conjugate match, we're only discussing the general concept of conjugate matching, a very simple concept compared to the wave concept.

No, Slater isn't alone. One of the most widely recognized authorities on transmission lines is Walter C. Johnson, author of *Transmission Lines and Networks* (New York: McGraw-Hill Book Co., 1950). His book was cited by Walter Maxwell as *Ref 18*, and it states on page 191, in Section 7.7, Impedance Matching:

> "Therefore, maximum power in the load is obtained when the load impedance is the complex conjugate of the generator impedance. This condition is sometimes referred to as a "conjugate match."
>
> Suppose that a generator is connected to a load through a lossless transmission line and a lossless matching device. None of the power is lost in the transmission system, and so, if the output of the generator is made a maximum by a conjugate match at its terminals, the power flow at all parts of the system must be a maximum. Then, if the system is opened at any point, the impedances looking in opposite directions must be the conjugates of each other. This can be made the basis for computing the matching elements to produce maximum power transfer."

Johnson in essence postulates the existence of a conjugate match everywhere, once a conjugate match has been established at the input of the line, by his stated condition that no power is lost and by stating that the transmission line is lossless.

Johnson doesn't explicitly state exactly what happens when components are actually lossy, the flip side of the conjugate match theorem. But then again, Johnson also does not dwell on the concept of conjugate matching elsewhere in his 354-page book. In the book's index, the term is

shown only for page 191, the quotation shown above.

From Dean's reference to Johnson above it is evident that he didn't read Johnson further than Page 191. On Page 192 Johnson says:

"Figure 7.13 shows a completely matched **low-loss** transmission system. (emphasis mine) At every point the impedance looking in opposite directions are conjugates. The characteristic impedance Z_0, being real, is of course its own conjugate. When matching devices must be adjusted by trial, the one near the load is first adjusted to provide a flat line, and only after this has been accomplished, the matching unit near the generator is adjusted for maximum power flow."

The 'adjusting' Johnson refers to corresponds to the tuning of the network to resonance I described earlier. There is a conjugate match **by definition** when the network is adjusted to deliver all of its available power from the generator to the load. Dean also failed to pursue the Johnson text to Page 248, to observe Section 10.8, which I quote:

"**10.8 Maximum Power Transfer.** The conditions for maximum power transfer from a source to a load were discussed in Sec 7.7 under the assumption that the source consisted of a constant emf in series with a fixed impedance, and that the load had an impedance which was adjustable in both magnitude and phase angle. It was shown that maximum power will be absorbed by the load when its impedance is made the complex conjugate of the source impedance. With a conjugate match the two impedances will have equal resistive components, and the reactances will be equal but of opposite sign. The efficiency is only 50 percent under these conditions, and this would be intolerably wasteful if energy were to be transferred in large quantities. Consequently, power systems are operated with load impedances much greater than the impedance of the source, thus improving the efficiency to a high value. No attempt is made to draw maximum power from the source. But if the power to be handled is comparatively small, as in a communication system, it may be more important to obtain maximum power from the available equipment than to economize on losses, and conditions approaching those of maximum power transfer are generally used." (End quote from Johnson.)

It is therefore evident that Dean is incorrect when he says "Johnson doesn't dwell on the concept of conjugate matching elsewhere in his 354-page book. Indeed, he does indeed, and in practical usage, not just theoretical as Dean asserts as its limitation. It is entirely possible that Dean avoided the additional information provided by Johnson, because it might conflict with his narrow belief that the conjugate match requires lossless elements, and thus open his mind to a broader concept than he is willing to acknowledge?

Any Clues Elsewhere?

So, let's go back to Slater to see if he gives us any clues about how we might look at things when we get to the real world — where real losses actually exist, both in transmission lines and in the matching networks used with transmission lines. Slater continues his analysis with a very interesting observation on p 50, middle paragraph (after he again had returned to the lossless line analysis), but as he now begins to looks at the situation from a different angle:

> "The lossless transmission line connecting them has the properties of a transformer. We may replace the line by a four-terminal network."

Aha! Here's the approach that ultimately makes more sense in the real world, the world we hams live in. Rather than trying to force things everything into the purely theoretical construct of a conjugate match, let's look at the transmission line as though it were a *transformer*.

And please note the following, because it is very important. This transformer can be either a *lossless* or a *lossy* transformer. We have a way to handle either variety, easily.

Not so fast, Dean, the lossy transformer, even when comprised of a transmission line, performs under exactly the same conditions as described above. When all available power is delivered through the transformer there is a conjugate match everywhere along the line in the direction of the power flow, whether the line is lossless or lossy. When properly adjusted there is a conjugate match at both ends of the transformer. Don't let the discontinuities at both ends of the transformer mislead you—**the conjugate matches are there**.

A Different Way of Looking at the Situation

The Black Box Concept

In a way, Slater advocates a kind of *black box* approach. Put a load impedance on the end of this black box (aka, transformer or transmission line) and you'll get some other impedance at the input, depending on the black box's exact transforming qualities.

And just to be clear about it, this is basically the approach I took when rewriting Chapter 19 ("Transmission Lines") of *The ARRL Handbook* (editions since 1995), and both Chapter 24 ("Transmission Lines") and Chapter 25 ("Coupling the Transmitter to the Line") in the 18th and 19th Editions of *The ARRL Antenna Book*.

The hyperbolic transmission-line impedance equation analyzes a transmission line just as though it were a transforming device. Here's what it looks like:

$$Zin = Z_0 \frac{Z_L \cosh \gamma\ell + Z_0 \sinh \gamma\ell}{Z_0 \cosh \gamma\ell + Z_L \sinh \gamma\ell}, \qquad \text{(Eq 1)}$$

Where:

Z_L = complex load impedance at load = $R_L + jX_L$

Z_{in} = complex input impedance at input of line

Z_0 = complex characteristic impedance of line = $R_0 - jX_0$

γ = complex attenuation constant = $a + jB$

a = matched-line attenuation constant, in nepers per unit length, where a is expressed in dB/100 feet – then a os 0.1151 a /100 in nepers/foot.

B = phase constant, in radians per unit length. Expressed in terms of wavelength and the Velocity Factor (VF) of the line becomes:

$$\lambda = VF \frac{983.5691272}{F_{MHz}}, \text{ in feet}$$

$$B = \frac{2\pi}{\lambda}, \text{ in radians/foot}$$

Going Through All the Steps

And yes, Eq 1 above is rather intimidating! It's difficult to get a "feel" for it without actually making computations using it. That is the reason I have been writing software that does all the nasty complex-variable computations in Eq 1: *TL* (Transmission Line), *TLA* (Transmission Line Advanced) or *TLW* (Transmission Line for Windows). The latter two programs are available from ARRL, bundled with *The ARRL Antenna Book*. The *TL* program can even be downloaded free of charge from: http://www.arrl.org/notes/1867/index.html - software. It's part of the software supplied for *The ARRL Handbook*. All these programs can also design antenna tuner networks.

The logical steps to analyze an antenna, transmission line and matching network down at the end of the transmission line in the radio shack are thus:

1. Determine the impedance at the feed point of the antenna at a particular operating frequency — this is the load at the output of the transmission line. The feed-point impedance can be determined using a computer model, a theoretical mathematical model or by direct measurement.
2. Specify the type of transmission line (this sets the complex Characteristic Impedance, the Velocity Factor and the Matched-Line Loss for the line).
3. Specify the physical length of the transmission line.
4. Now, compute the impedance at the input of the transmission line, using the hyperbolic transmission-line equation Eq 1 (probably using a computer program).
5. Design a matching network to transform the impedance at the input of the transmission line to

the impedance required by the transmitter (usually 50 Ω).

It should be noted here that the design of this matching network employs the principles of conjugate matching, whether or not the designer realizes the process of conjugate matching is involved, because it cannot be avoided. As stated before, and repeating for emphasis, **when the matching network permits delivery of all available power to the load, there is a conjugate match by definition.**

Unfortunately, following Dean's five steps above provides less understanding of the impedance-matching process than simply understanding the definition of conjugate matching that appears at the beginning of this response.

Actually, if the object of the exercise is simply to design a matching network, such as an antenna tuner, you could bypass steps 1. through 4. and simply *measure* the impedance at the input end of the transmission line down in the shack. That input impedance is what the antenna tuner sees at its output terminals.

What About a Lossless Line?

The hyperbolic transmission-line equation can easily handle a theoretically perfectly lossless line — simply set the matched-line attenuation constant α to zero. Simple as that. We have in Eq 1 a universal tool that ties together the theoretical and the practical.

How About a Really Big Black Box?

In fact, we could place our antenna, its environment and its feed line inside a *really large black box*. On the outside, this box would have two terminals, connected to the end of the feed line inside. Now, if you were to connect an impedance meter to these terminals you would measure a single, unique impedance at any given frequency.

For such a large black box, the concept of "conjugate match" has even less relevance — simply because the impedance measured at the terminals of this black box is totally determined by what's on the *inside* the box, not by anything external to the box (such as a transmitter's pi-network or an antenna tuner). We've done the ultimate in separating the antenna and feed line from a transmitter or an antenna tuner.

But what Dean is ignoring here is that when a source is delivering all its available power into the device inside the 'black box', the concept of 'conjugate match' has **complete and total relevance**, not less, and cannot be ignored as Dean has done. In addition, understanding the steps Dean suggests above requires more mental activity than understanding the simple basis

for the conjugate match.

Doing the Analysis Yourself

Actually working through steps 1. through 4. is valuable, however, because it can give you a much better idea about what you should reasonably expect in a system. That's precisely why I included in Chapter 25 of *The ARRL Antenna Book* tables for typical multiband wire antennas. The impedances at the feed point for a 100-foot center-fed dipole 50 feet in height are listed in Table 1, and those for a 66-foot long Inverted-V dipole, 50 feet high at its apex are listed in Table 2 in Chapter 25.

These tables also show the computed impedances at the shack-end of a 100-foot long piece of nominal 450-Ω "window" ladder line. You can use the free *TL* program mentioned above to do these computations yourself, starting from the feed-point impedance of each dipole.

Again, the impedance at the input of the transmission line (or the terminals of our large black box above) is what the antenna tuner has to transform into 50 Ω for the transmitter. And this antenna tuner, with its hopefully small, but nonetheless inevitable, real-world losses cannot create a conjugate match throughout the entire system, because of the losses.

As we've proven earlier, Dean's last sentence above is totally wrong, due to his misunderstanding.

One Last Consideration About the Conjugate Match

Consider the situation I posed in the July 2001 issue of *QST* in the "*QST* Workbench, The Doctor is IN" column, on p 64. (Yes, I've blown my cover—I'm one of a number of people who contribute answers to this column.) Rather tongue-in-cheek, I posed a hypothetical situation.

Let's say I bought a very unusual transmitter at a hamfest somewhere. Instead of working into 50-Ω like all my friends' transmitters, mine is designed to work into a 120 $-j$ 400 Ω impedance. Yes, this is a very weird impedance, but bear with me. Let's say that I want to operate on 40 meters one night, so I check my antenna system, just to be sure, with my trusty impedance meter.

At 7.1 MHz, I measure an impedance of 120 $-j$ 400 Ω at the input of the transmission line going to my *Super-Duper Signal Scooper* all-band antenna. Boy, am I ever lucky — that's just what I need for my transmitter! So I directly connect the end of the transmission line to my transmitter, and when I fire it up, I get full rated power output, at the rated distortion level. Everything is just fine and dandy.

Now, did you find any hint of a conjugate match mentioned anywhere in this hypothetical

scenario? Of course you don't, because there is very obviously no conjugate match involved here. There's no antenna tuner involved, and there's no pi-network in my unique, make-believe transmitter.

No hint of a conjugate match here? Obviously no conjugate match involved here? What kind of technical reasoning results in such incorrect statements as these? Wrong! There is no way Dean could get full rated output power into a 120 – j400-ohm line input impedance unless the output impedance of his transmitter was 120 + j400 ohms. He chose to completely ignore the source impedance of his transmitter. But you can't do that and successfully deliver power into a load of 120 – j400 ohms without considering the output impedance of the source. **Dean totally ignored the output impedance of his transmitter, which no competent RF engineer would even consider doing. His statement that no conjugate match was involved clearly proves his ignorance of the general subject of impedance matching.**

The definition of full rated power output means maximum available power with the drive level set for delivering a given full-rated power. According to this definition, when the maximum available power is being delivered, there is a conjugate match, period!

It's ironic that Dean's TLA.EXE excellent program cannot avoid or bypass using the principles of conjugate matching to achieve the match, because it uses those principles, and the numbers it yields indicate a conjugate match, even though Dean doesn't believe it does.

And unless you have a really unusual feed line with zero loss, and unless you have an antenna tuner with zero loss, you won't find a conjugate match in any other antenna system either because **a conjugate match doesn't exist in anything but theory**. (Emphasis mine)

Again, Dean is totally wrong!

Let me be clear: I agree that the concept of conjugate match is useful for introducing the subject of wave reflections to a very technical audience. I do not consider it the best way to present the subject to hams. Both I and other ARRL technical staff consider the concept of representing a transmission line as a transformer much more relevant to hams than the conjugate match.

We're not introducing or discussing the subject of wave reflections here for a technical audience—we're discussing the conjugate match for use by hams! And it's not complicated. For a ham to understand the procedure involved in impedance matching he should know that the resistive or real parts of the source and load must be equal and that reactances in both the source and load should cancel to zero to achieve resonance. Unless he understands these two simple points that comprise the basic and fundamental reasoning behind the impedance

matching process, he is ignorant of what is happening. **This process is called conjugate matching**. It is not necessary to introduce the subject of wave reflections to describe conjugate matching, as Dean implies in the paragraph above.

However, for those very technical hams, we have left references to Walt Maxwell's books and articles in *The ARRL Antenna Book*. That's only fair.

73,

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Some Background Information

I was trained at Yale University (1967, BS Engineering and Applied Science) as an electronics engineer. I worked for 25 years in industry, both as a bench engineer and as a manager, in engineering and technical marketing. I have been the editor of *The ARRL Antenna Book* since 1993, when I first joined HQ staff.

Although I consulted long and hard with all technical staff at HQ before doing so, I am the person who ultimately is responsible for removing "conjugate matches" from the ARRL books with which I have been associated; mainly *The ARRL Antenna Book* and *The ARRL Handbook*.

At the Dayton Hamvention in May, 2001, I had my first opportunity to meet Walt Maxwell, W2DU, in person. We discussed at some length the topic of conjugate matching. It was a useful and wide-ranging discussion, and I told Walt that we at ARRL took no "sides" on the personal controversy between him and Warren Bruene.

Dean made it very clear during our meeting at Dayton that the conjugate match was not involved in the every-day use of antenna tuners (a totally erroneous position statement), and that it had no place in the *ARRL Handbook*. I asked him if the League had any thoughts concerning the damaging effect its incorrect position on conjugate matching has had on my engineering integrity and my reputation as a reliable author, his response was that the League's position on conjugate matching isn't incorrect, and that I am simply wrong. End of conversation.

However, Dean's statement that "…we at the ARRL took no 'sides' on the controversy between Warren Bruene and me" is <u>untrue</u>, because they did—totally.

To understand why Dean's statement is untrue, the term 'totally' above needs a detailed clarification. To obtain the full appreciation of the unfair treatment I received from the League that 'took no sides'(?) in the controversy we must consider two eras—the time before Bruene (1972 to 1991) and the time after Bruene (1991 to date).

From 1972 to 1980 the League's technical editors sought my advice concerning antennas and transmission lines on a regular basis—on average from four to five times a month. During that period I was the engineer in charge of the antenna laboratory at the RCA Space Center, Princeton, NJ. This was the period when QST published my series of articles "Another Look at Reflections." The technical editors were so enthused by those articles suggested they be republished in book form, which resulted in the 1st edition of "Reflections —Transmission Lines and Antennas." By 1980, Technical Director, Doug DeMaw, had witnessed enough of my expertise to warrant appointing me an official Technical Advisor. The Technical Editors continued to seek my advice during the entire BB era, Before Bruene —but **none** AB, After Bruene. As I said earlier, DeMaw requested that I write a paper on Conjugate Matching for the ARRL Handbook. This paper appeared there from 1986 to 1994, when Dean deleted it from the Handbook, because he said "It has no place in the Handbook.".

In the November 1991 issue, *QST* published Bruene's infamous and invalid definition of the conjugate match concerning RF power amplifiers (that R_L must equal R_S), marking the end of the BB era, and igniting the protracted controversy, which has lasted for 20 years.

After reading the offending article I learned that Dave Newkirk was the editor who handled it. I called Dave and asked why he had not contacted me before publishing the article, because 1) the article contradicted my earlier articles published in *QST*, and 2) because I was the Technical Advisor on the subject involved in the article, who could have explained why the article should not have been published. Dave replied rudely that Bruene is right, that the material in my previous *QST* articles is wrong, and that the League was fortunate in having discovered my errors in my previous publications so they could be corrected. Dave also told me that the Technical Staff did not need the advice of Technical Advisors to tell them how to edit a manuscript.

I then composed a technical response to the Bruene article, applying references to well-known and respected engineering texts that support my position. I sent the response to the then Managing Editor of *QST*, Mark Wilson. No response. I then sent him a more detailed response. Again no response. I followed up the responses with three successive memos—still no response. So I called Mark on the phone, and asked him, "Is this a convenient time to talk?" He replied with, "What do you want to talk about?" When I told him he said, "You'll

have to talk with Paul Pagel about that," and he hung up without transferring me to Paul. I've always had a good rapport with Paul, so when I called him he said he wasn't allowed to talk with me about the conjugate match. It was evident I was hitting a stone wall—a total shutout—a 180-degree reversal of attitude toward me. And as I said earlier, I have never been asked to perform as a Technical Advisor since the end of the pre-Bruene era.

Sometime later I wrote to Dave Sumner to report the rude and unprofessional treatment I had received. Dave referred me to Dean Straw, saying he hoped Dean could assuage my concerns. I reiterated my position to Dean, which he rejected as wrong, and after further attempts to prove to him that my position is correct, he concluded our correspondence with "…we at HQ agree with Warren (Bruene) about how an amplifier works…and it means that we at HQ will not publish any further words on this subject, because League policy prohibits publishing controversial material. Please, Walt, I ask you to stop this campaign to "defend" conjugate matching. You risk losing your reputation and your credibility completely, and we all would be sad to see that happen." **Controversial material? Please remember it was Bruene who initiated the erroneous controversial material that WAS published in *QST*.** This is not taking 'sides'?

It is important to note here that several of Bruene's colleagues at Collins, including Jan Hornbeck and Warren Amfahr, had tried earlier to convince him that his position on conjugate matching with RF power amplifiers was wrong, but he stubbornly refused to agree with them.

In 1994 *QEX* editor Jon Bloom authored an article in *QEX* entitled, "Where Does the Power Go?," which contradicts my explanation of the reflection mechanics of wave interference that is the basis for matching impedances. As with the erroneous Bruene article in 1991, I responded to Jon, explaining why his explanation of matching principles in his *QEX* article was incorrect. As with Mark Wilson earlier, no response. Three follow-up memos—still no response from Jon. (I have since sent Jon a copy of Reflections 2—no acknowledgement of having received the book.)

During 1994 and 1995 Bloom supported a popular thread on one of the internet news groups concerning the conjugate match entitled, "Is Maxwell Wrong?," agreeing with those who considered my position wrong. The number of posters on that news group who displayed incredible ignorance of the subject was unbelievable. When the few who really understood the subject presented a correct explanation, the dissenters drowned them out. My reputation and credibility as a competent RF engineer were shattered World wide for publishing erroneous material in *Reflections,* with Bloom's approval.

In their attempts to assist me in my problem with the League, Jack Belrose, Ph.D. in Radio Science and Director of Canada's Radio Research Centre; John Fakan, Ph.D. in EE and consultant to NASA; and Al Helfrick, Ph.D. in EE, Professor of Electronics at Embry-Riddle University, and author of many articles published in both *QST* and the *IEEE*, these three pragmatic scholars sent correspondence to League personnel explaining their error concerning the conjugate match in relation to the loading of RF power amplifiers. In answer to Jack's correspondence Dean Straw replied, "You should go back to what you do best—modeling antennas." And Jon Bloom's response to Jack was, "Your understanding of the conjugate match is incorrect." John Fakan's letter was addressed to Mark Wilson—no response. As with my own letters to Mark, Al's letter also elicited no response.

Totally agreeing with Bruene, the official, publicly-stated position of the League is that **the conjugate match cannot exist when the source is an RF power amplifier.** To wit, during technical forums at ARRL conventions and hamfests, the League's technical editors replied "yes" to questioners who asked, "Is Maxwell wrong?" On one occasion in answering a questioner Dave Sumner himself stated that Bruene is correct and Maxwell is wrong. In the rather heated argument that ensued between them, Dave wasn't aware that his adversary, Warren Amfahr, W0WL, was one of Bruene's engineering colleagues at Collins Radio, who, along with other Bruene colleagues, have known all along that Bruene was wrong. Amfahr attempted to explain why, but Dave did not relent as the dialog became adversarial, stating the Leagues's position was based on knowledge accrued by the Technical Staff. At another ARRL Convention Amfahr approached Mark Wilson in an attempt to explain to him why the League's position is wrong, but Mark refused to talk with him.

From the revelations above it is clearly evident that Dean's statement that the League 'took no sides' in the controversy between Bruene and me is totally untrue. It is also clearly evident that contrary to Dean's statement that I'm simply wrong, my reputation as an engineer and my credibility as a writer have been damaged as a result of the actions of certain League personnel. Several people have told me that I have a clear case for a defamatory suit against the League, and have urged me to file. However, despite the unfortunate situation, I am not of a litigious nature, and suing the ARRL is unthinkable. On the other hand, just the thought of a possible suit might just motivate a certain few of the League personnel to recognize that withholding an indisputable scientific truth from the Amateur Community is akin to the Church's punishing Copernicus and Galileo for asserting that Earth is not the center of the universe.

The fact that ARRL has published articles and letters by both men should testify that we are treating each of them fairly. Readers may have seen the on-going series of articles and counter-articles by both Walt and Warren published in *QEX* over the last year or so.

Not true. The articles published **only in *QEX*** does **not** testify that each have been treated fairly, because ***QST*** readers were never given the opportunity to read the correct side of the story—**nothing has been published in *QST* concerning the conjugate match since the erroneous Bruene article appeared in November 1991**.

We are now, however, hearing from *QEX* readers that they are getting fed up with this never-ending controversy — the same kind of messages we received from *QST* readers when that magazine became the forum some years ago for this conjugate-match battle. "Enough already!" is the message that is coming through, loud and clear.

Dean couldn't be more wrong when he refers to a "forum for the conjugate-match battle in *QST"*—there has never been any such battle in *QST*—***QST* has printed nothing on conjugate matching since Bruene's article appeared in 1991**. And the Editors have continuously refused to print, or even acknowledge receiving the responses I submitted to the erroneous material appearing in the Bruene article that instigated the controversy. Dean also refused to even consider my position, already a staple among the League's earlier Technical Department for more than twenty years, stating that League policy prohibited *QST* from publishing controversial material. He totally ignored that **the controversy was initiated by *QST* in publishing Bruene's erroneous material in the November 1991 issue.** This is fair?

And where are the messages supposedly received from *QST* readers? I've never been accorded the courtesy of seeing any of them. When Jerry Hall was involved with my *QST* series of articles and the book *Reflections*, he always sent me a copy of messages received from the *QST* readers concerning my writings.

At Dayton, when Walt asked me directly why I had removed the extensive section on the conjugate match that he had written in earlier *ARRL Handbooks* I told him the following:

1) I am a RF engineer. I have designed and worked with HF and VHF power amplifiers ranging from 250 mW exciters to 250 kW military SSB transmitters.

2) Never, not once, did I consciously use the concept of the "conjugate match" to design and develop any of the above-mentioned transmitters.

Perhaps Dean didn't 'consciously' use the concept of the conjugate match in his design, but **no impedance matching design can occur without involving the principles of conjugate matching**, consciously or not. Such a statement reveals a lack of understanding of the concept of the conjugate match.

3) The output matching networks used in any transmitter I have worked on have been designed using straightforward network equations. The goal was to transform an output load resistance, usually 50 Ω, with a specified level of SWR, to the plate, collector or drain load-line resistance needed to develop the specified output power, at a specified level of Intermodulation Distortion (IMD) and at a specified level of harmonic content. The transmitters also had to be reliable — meaning that the heat dissipation limits for all active and passive devices were kept within safe limits.

I am also an RF engineer. Using straightforward network equations to design output matching networks involves the principles of conjugate matching, whether the designer realizes it or not. Those principles are basic and fundamental to the equations, whether or not they are understood by the designer. Additionally, although IMD may be related to the output power level, there is no relationship between either IMD or heat dissipation and conjugate matching, as Dean implies.

4) I know of no professional (or amateur) design engineer who has ever consciously used the concept of conjugate matching to design a transmitter — and, believe me, over the years I have asked many of them this direct question because of the continuing Maxwell/Bruene battle.

I have also talked to many people at conventions and many have said words to the effect: "I'm not a PhD level mathematician and can't argue the merits of either Maxwell's or Bruene's position. Heck, I can't even understand what they are arguing about."

In my opinion, anyone admitting that he has never consciously used the concept of conjugate matching in designing transmitters to deliver power to a load says a lot about his general knowledge (or lack of) of the subject. And it doesn't take a PhD-level mathematician to understand the principles supporting the impedance matching between a transmitter, or antenna tuner and its load. Every ham at at least the General level should understand those principles as he adjusts his antenna tuner. My *Reflections* writings are mostly 'how it works', and many amateurs and professional engineers have told me that I have accomplished telling them 'how it works' in a very understandable way.

During my career as an electrical engineer with RCA, as one assignment I designed matching networks in printed-circuit stripline to couple four low-wattage transmitters to a complex antenna system operating on four different frequencies simultaneously, and radiating both right- hand and left-hand circular polarization—networks that flew on the World's first eight TIROS weather satellites. My only tools were a slotted line, a slide rule, and a Smith Chart—neither network analyzers, nor desk nor hand calculators had yet been available. It is important to note that the principles of conjugate matching guided me all the way in designing those networks. And they had to be right the first time—there was no

opportunity to 'tune' them once they were launched into space! (There was never a failure in any component I designed or built.) I also developed RF power amplifiers at the kilowatt level, and again I used the principles of conjugate matching to match the amplifiers to their loads.

Readers of *The ARRL Antenna Book* and *The ARRL Handbook* have expressed much the same sentiment over the years. They have, in essence, marveled at the complexity of Walt Maxwell's descriptions of the wave mechanics and the conjugate match, but at the same time many have not found the information to be of much practical value. I told Walt, face-to-face: Our readers have been forced to "take a drink from a fire hose."

I have received hundreds of positive responses to my writings on the conjugate match since 1973, from the *QST* series "*Another Look at Reflections*" and both editions of the book *Reflections*. None of those responses has ever indicated that the information I gave was of no practical value. I consider Dean's statement to that effect to be a continuation of his insulting an arrogant attitude toward me. I don't understand what Dean means when he referred to readers being forced to "take a drink from a fire hose," but it doesn't appear to be complimentary.

As an editor, I have a responsibility to our readers to present information that is not only technically accurate but which is also useful and practical to them. I told Walt that it is my opinion that there are better ways to describe matching networks to Radio Amateurs — and that is the reason why I've removed the concept of conjugate matching.

Removing the description of conjugate matching from the ARRL Handbook for availability to an amateur radio community that works with matching the impedances of their transmitters to their antenna systems is **not being properly responsible to the readers of the Handbook.** Understanding what is happening when adjusting either the pi-network or the antenna tuner is certainly useful and practical, and contrary to Dean's statement above, there is no better way to understand it than with the concept of conjugate matching. Conjugate matching is the basis for all impedance matching operations.

It is not that the basic concept of the conjugate match itself is wrong — it is simply overwhelming and confusing to the average Radio Amateur, and most importantly, it only holds for lossless situations. Others may disagree with this judgment, and I should hope that we can agree to disagree, as gentlemen of good will.

In matters involving scientific truths there is no room for disagreements, unless the disagreement is based on misunderstanding the facts of the matter, as in Edison's case, where his detractors disagreed until he proved them wrong. His detractors simply didn't understand

the scientific truth. It is clearly evident that Dean does not understand the truth in this matter, or he would not disagree. I have explained above the reason for his disagreement.

Furthermore, considering the concept of conjugate matching overwhelming and confusing to the average Radio Amateur is both condescending and untrue. Some questions appearing in the General Class Examination are more advanced than the simple concept of making the real parts of the source and load impedances equal and canceling the reactances in the source and load that occur when tuning the pi-network or antenna tuner. It's unrealistic that a ham wouldn't care to know what's happening electrically when he adjusts his antenna tuner.

Instead of continuing to disagree with the truth, Dean should confront it and admit that a conjugate match exists whenever all the power is being delivered to a load, and that it is not necessary to understand the simple math involved if it overwhelms him.

In his *QST* article of November 1991Bruene invented a 'new'definition for conjugate matching where RF power amplifiers are involved—an **invalid** definition not found in any engineering text. As stated earlier, Bruene asserts that R_L must equal R_S for a conjugate match to exist. This definition is wrong, because R_S is the source resistance appearing at the plate—at the input of the pi-network, and is always much higher than the output resistance appearing at the output terminals of the tank circuit. It is the **output** resistance appearing at the output terminals of the pi-network tank circuit that must equal the load resistance for a conjugate match to exist. Therefore, there is a conjugate match at the output of the network, but NOT at the input. I proved the truth of this concept in my QEX article appearing in the May/Jun issue, and added further proof in Chapter 19A of Reflections 3, which can be downloaded from my web page at www.w2du.com,

Neither Bruene, Dean, nor other ARRL editors will consider the true aspect of the problem, and thus the controversy continues to this day.

The concept of a conjugate match is useful when introducing the basic concepts of wave reflections (and Walt Maxwell does a thorough job in his book on this subject). But when you come down to practical applications of RF power amplifiers and real world, lossy transmission lines and matching networks, it is more useful to analyze things using precise mathematical models, such as transmission-line equations or straightforward network equations.

As I said earlier, the straight-forward network equations involve the principles of conjugate matching, although it appears that Dean doesn't understand that they do. In addition, the concept of a conjugate match is basic in general to practical network circuitry, and not restricted to introducing concepts of wave reflections.

At Dayton, I also re-affirmed to Walt that the reason why ARRL decided not to reprint *Reflections* was a simple economic one. The demand had fallen off greatly towards the end of

the years we sold the book. Simply put, the people who wanted to buy the book had already done so and reprinting it was not a good economic move.

That's what I've been told, but then how is it that reprinting of *Reflections* was not a good economic move when two printings of 5000 copies each sold out, with more people requesting them? The second edition, published by Worldradio, sold out after 3000 copies, and copies are now going for over $100 on eBay, while waiting for the third edition to be released. In addition, here is a quote from a former ARRL staffer (on ARRL stationery):

You mentioned Warren Bruene this morning, and the differences he has had with Walt Maxwell. You may not know that the League has decided to go with Bruene, and will not reprint Walt's book, "Reflections". Walt, unfortunately, has made himself very unpopular at HQ, and has been asked not to write them further. He has achieved 'persona non grata' status.

In closing, let me say that Chapter 19 in *Reflections* 2 explains in great detail why Bruene's claim that a conjugate match cannot exist when the source of power is an RF power amplifier is wrong, proven with data resulting from measurements presented there. In addition, measurements performed since *Reflections* 2 was published yielded data that even further proves Bruene's claim is wrong. As stated above, this additional data appears in Chapter 19A of the forthcoming third edition of Reflections. Both Chapters 19 and 19A are available for downloading from my web page at www.w2du.com. If you still believe that Bruene and Straw are correct in their position concerning the conjugate match, I urge you to review Chapters 19 and 19A (or Chapter 19 in Reflections 3) at your earliest convenience. I'm confident that reviewing them will challenge your thinking.

Before closing I'd like to add that I submitted a copy this response to Dean, to which he responded that he stands by his statements, that I'm still wrong, and that my response was simply an ad hominem attack on his intelligence.

Walter Maxwell, W2DU