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THE *AAT* (ANALYZE ANTENNA TUNER) PROGRAM

The following article was extracted from the 22nd edition of the ARRL Antenna Book. *The program* AAT *was originally written for the MS-DOS operating system which is no longer supported by recent versions of the Windows operating system. (There are "DOS emulators" which may be able to run* AAT *but the program's functionality is not guaranteed.) The software remains downloadable from* **www.arrl.org/antenna-book-reference**.

As you might expect, the limitations imposed by practical components used in actual antenna tuners depends on the individual component ratings, as well as on the range of impedances presented to the tuner for matching. ARRL has developed a program called *AAT*, standing for "Analyze Antenna Tuner," to map the range over which a particular design can achieve a match without exceeding certain operator-selected limits. *AAT* may be downloaded from.

Let's assume that you want to evaluate a T-network on the ham bands between 1.8 to 29.7 MHz. First, you select suitable variable capacitors for C1 and C2. You decide to try the Johnson 154-16-1, a commonly available surplus or used component rated for a minimum to maximum range from 32 to 241 pF at 4500 V peak. Stray capacitance in the circuit is estimated at 10 pF, making the actual range from 42 to 251 pF, with an unloaded Q of 1000. This value of Q is typical for an air-variable capacitor with wiping contacts. Next, you choose a variable inductor with a maximum inductance of, let's say, 28 μH and an unloaded Q of 200, again typical values for a practical inductor. Set a power-loss limit of 20%, equivalent to a power loss of about 1 dB. Then let *AAT* do its computations.

AAT tests matching capability over a very wide range of load impedances, in octave steps of both resistance and reactance. For example, it starts out with 3.125 – *j* 3200 Ω, and checks whether a match is possible. It then proceeds to 3.125 – *j* 1600 Ω, 3.125 – *j* 800 Ω, etc, down to 3.125 + *j* 0 Ω. Then *AAT* checks matching with positive reactances: 3.125 + *j* 3.125, 3.125 + *j* 6.25, 3.125 + *j* 12.5, etc on up to 3.125 + *j* 3200 Ω. Then it repeats the same process, over the same range of negative and positive reactances, for a series resistance of 6.25 Ω. It continues this process in octave steps of resistance, all the way up to 3200 Ω resistive. A total of 253 impedances are thus checked for each frequency, giving a total of 2277 combinations for nine amateur bands from 1.8 to 29.7 MHz.

If the program determines that the chosen network can match a particular impedance value, while staying within the limits of voltage, component values and power loss imposed by the operator, it stores the lost-power percentage in memory and proceeds to the next impedance. If *AAT* determines that a match is possible, but some parameter is violated (for example, the voltage limit is exceeded), it stores the out-of-specification problem to memory and tries the next impedance.

For the pi-network and the T-network, which have three variable components, the program varies the output capacitor in discrete steps of capacitance. It is possible for *AAT* to miss very critical matching combinations because of the size of the steps necessary to hold execution time down. You can sometimes find such critical matching points manually using the *TLW* program, which uses the same algorithms to determine matching conditions.

Once all impedance points have been tried, *AAT* writes the results to two disk files — one is a summary file (TEENET.SUM, in this example) and the other is a detailed log (TEENET.LOG) of successful matches, and matches that came close except for exceeding a voltage rating. **Figure 1** is a sample printout of part of the summary *AAT* output for the 3.5 MHz band and one for the 29.7 MHz band. (The printouts for 1.8 MHz, and the bands from 7.1 to 24.9 MHz are not shown here.) This is for a T-network whose variable capacitors C1 and C2 (including 10 pF stray) range from 42 to 251 pF, each with a voltage rating of 4500 V. The coil is assumed to go up to 28 μH and has an unloaded Q of 200.

The numbers in the matching map grid represent the power loss percentage for each impedance where a match is indeed possible. Where a "C–" appears, *AAT* is saying that a match can't be made because the minimum capacitance of one or the other variable capacitors is too large. This often happens on the higher frequency bands, but can occur on the lower bands when the power loss is greater than the specified limit and *AAT* continues to try to find a condition where the power loss is lower. It does this until it runs into the minimum-capacitance limit of the input capacitor C1.

Similarly, where a "C+" appears, a match can't be made because the maximum capacitance of one or the other variable capacitors is too small. Where an "L+" is placed in the grid, the match fails because more inductance is needed. Where a "V" is shown, the voltage limit for some component has been exceeded. It may be possible in such a circumstance to reduce the power to eliminate arcing. Where "P" is shown, the power limit has been exceeded, meaning that the loss would be excessive. Where a blank occurs, no combination of matching components resulted in a match.

It should be clear that with this particular set of capacitors, the T-network suffers large losses when the load resistance is less than about 12.5 Ω at 3.5 MHz. For example, for a load impedance of 12.5 – *j* 100 Ω the loss is 16.7%. At 1500 W into the tuner, 250 W would be burned up inside, mainly in the coil. It should also be clear that as the reactance increases, the power loss increases, particularly for capacitive reactance. This occurs because the series capacitive reactance of the load adds to the series reactance of C2, and losses rise accordingly.

For most loads, a larger value for the output capacitor C2 decreases losses. Typically, there is a tradeoff between the range of minimum-to-maximum capacitance and the voltage rating for the variable capacitors that determines the effective impedance-matching range. See **Figure 2**, which assumes that capacitors C1 and C2 have a larger range between minimum to maximum capacitance, but with a lower peak voltage rating. Each tuning capacitor is representative of a Johnson 154-507-1 dual-section capacitor, which has a range from 15 to 196 pF in each section, at a peak voltage rating of 3000 V. The two sections are placed in parallel for the lower frequencies. Again, a stray capacitance of 10 pF is assumed for each variable capacitor.

The result at 3.5 MHz in Figure 2 is a shift of the matching map toward the left. This means that lower values of series load resistance can be matched with lower power loss. However, it also means that the highest value of load resistance, 3200 Ω, now runs into the limitation of the voltage rating of the output capacitor, something that did not happen when the 4500-V capacitors were used in Figure 1.

Now, compare Figure 1 and Figure 2 at 29.7 MHz. The smaller minimum capacitance (25 pF) of the capacitors in Figure 2 allows for a wider range of matching impedance, compared with the circuit of Figure 1, where the minimum capacitance is 42 pF. This circuit can't match loads with resistances greater than 200 Ω.

Note that *AAT* also allows the operator to specify a switchable fixed-value capacitor across the output capacitor C2 to aid in matching low-resistance loads on the lower frequency bands. In Figure 2, a 400 pF fixed capacitor C4 was assumed to be switched across C2 for the 1.8 and 3.5 MHz bands. **Figure 3** shows the schematic for such a T-network antenna tuner.

The power loss in Figure 2 on 3.5 MHz at a load of 6.25 – *j* 3.125 Ω is 7.2%, while in Figure 1 the loss is 19.7%. On the other hand, the voltage rating of one (or both) capacitors is exceeded for a load with a 3200 Ω resistance. By the way, it isn't exceeded by very much: the computed voltage is 3003 V at 1500 W input, just barely exceeding the 3000-V rating for the capacitor. This is, after all, a strictly literal computer program. Turning down the power just a small amount would stop any arcing.

AAT produces similar tables for pi-network and L-network configurations, mapping the matching capabilities for the component combinations chosen. All computations are, of course, only as accurate as the assumed values for unloaded Q_U in the components. The unloaded Q_U of variable inductors can vary quite a bit over the full amateur MF and HF frequency range. Computations produced by *AAT* have been compared to measured results on real antenna tuners and they correlate well when measured values for unloaded inductor Q_U are plugged into *AAT*. Individual antenna tuners may well vary, depending on what sort of stray inductance or capacitance is introduced during construction.

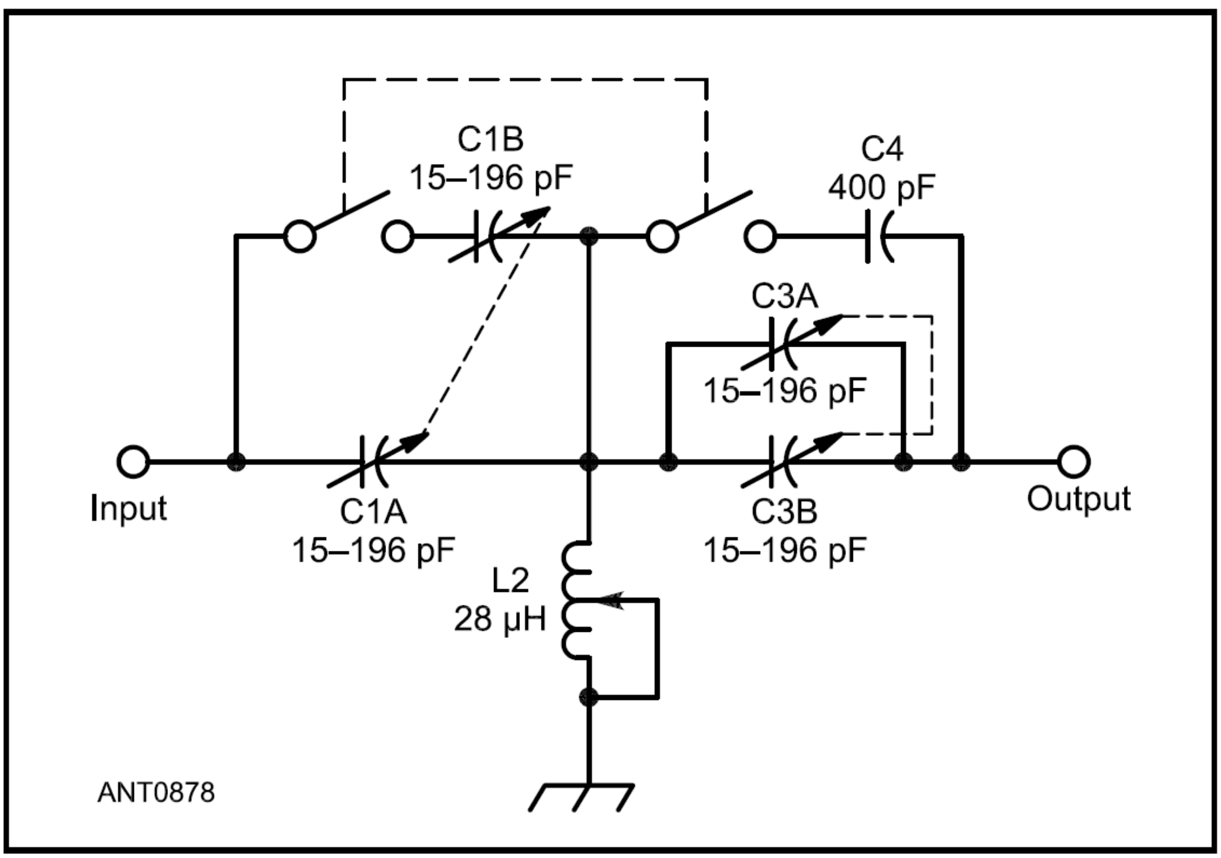

Figure 3 — Schematic for the T-network antenna tuner whose tuning range is shown in Figure 2.

Loss percentage for Tee-network, series cap., shunt inductor, series cap.
Freq: 3.5 MHz, Z0: 50, 1500W, Vmax: 4500 V, Qu: 200 , Qc: 1000
Var. Cap: 42 to 251 pF with switched 160/80 m output cap.: 0 pF

Xa	3.125	6.25	12.5	25	50	100	200	400	800	1600	3200 Ra
- 3200	L+	L+	L+	L+		L+	L+	L+	L+	V	7.2
- 1600	L+	L+	L+	L+		L+	V	V	6.7	5.4	5.6
- 800	L+	L+	C-	C-	V	V	8.1	5.5	4.3	4.2	5.0
- 400	C-	C-	C-	V	12.0	7.6	5.0	3.6	3.2	3.7	4.8
- 200	C-	C-	P	13.3	8.2	5.2	3.5	2.7	2.8	3.5	4.7
- 100	C-	C-	16.7	10.2	6.3	3.9	3.1	2.9	2.6	3.4	4.7
- 50	C-	C-	14.3	8.6	5.2	3.6	3.3	2.9	2.6	3.4	4.7
- 25	C-	C-	13.1	7.8	4.7	3.6	3.1	2.8	2.5	3.4	4.7
- 12.5	C-	C-	12.4	7.4	4.5	3.9	3.5	2.8	2.5	3.4	4.7
- 6.25	C-	C-	12.1	7.2	4.4	3.8	3.5	2.7	2.5	3.4	4.7
-3.125	C-	19.8	11.9	7.1	4.7	3.8	3.5	2.7	2.5	3.4	4.7
0	C-	19.6	11.8	7.0	4.7	3.7	3.4	2.7	2.5	3.4	4.7
3.125	C-	19.3	11.6	6.9	4.6	3.7	3.4	2.7	2.5	3.4	4.7
6.25	C-	19.1	11.4	6.8	4.5	3.7	3.4	2.9	2.5	3.4	4.7
12.5	C-	18.6	11.1	6.6	4.4	4.2	3.3	2.9	2.5	3.4	4.7
25	C-	17.6	10.4	6.2	4.7	4.0	3.2	2.8	2.5	3.4	4.7
50	C-	15.5	9.1	6.1	4.9	3.7	3.4	2.7	2.4	3.3	4.7
100	P	11.0	7.6	6.5	4.9	3.9	3.4	2.9	2.4	3.3	4.7
200	V	V	8.3	7.0	5.3	3.9	3.6	2.8	2.3	3.3	4.7
400	P	V	V	V	V	5.4	3.6	3.5	2.3	3.3	4.6
800	P	P	P	V	V	V	2.3	2.3	2.6	3.4	4.7
1600						L+	2.5	3.6	3.9	4.0	4.9
3200						L+	L+	L+	L+	5.5	5.9

Loss percentage for Tee-network, series cap., shunt inductor, series cap.
Freq: 29.7 MHz, Z0: 50, 1500W, Vmax: 4500 V, Qu: 200 , Qc: 1000
Var. Cap: 42 to 251 pF with switched 160/80 m output cap.: 0 pF

Xa	3.125	6.25	12.5	25	50	100	200	400	800	1600	3200 Ra
- 3200	C-	C-	C-	C-	C-	C-	C-	C-	C-	C-	C-
- 1600	C-	C-	C-	C-	C-	C-	C-	C-	C-	C-	C-
- 800	C-	C-	C-	C-	C-	C-	C-	C-	C-	C-	C-
- 400	C-	C-	C-	C-	C-	C-	C-	C-	C-	C-	C-
- 200	C-	C-	C-	C-	C-	C-	C-	C-	C-	C-	C-
- 100	C-	C-	C-	C-	2.7	1.8	1.6	C-	C-	C-	C-
- 50	C-	C-	C-	2.6	1.6	1.2	1.3	C-	C-	C-	C-
- 25	C-	5.3	2.9	1.7	1.1	1.0	1.2	C-	C-	C-	C-
- 12.5	7.1	3.9	2.1	1.1	0.8	0.9	1.1	C-	C-	C-	C-
- 6.25	6.0	3.2	1.7	1.0	0.6	0.8	1.1	C-	C-	C-	C-
-3.125	5.4	2.8	1.4	1.0	0.6	0.8	1.1	C-	C-	C-	C-
0	4.7	2.5	1.6	1.0	0.6	0.8	1.1	C-	C-	C-	C-
3.125	4.1	2.4	1.7	1.1	0.6	0.7	1.1	C-	C-	C-	C-
6.25	3.4	2.4	1.5	1.0	0.6	0.7	1.1	C-	C-	C-	C-
12.5	3.4	2.9	2.0	1.1	0.6	0.7	1.1	C-	C-	C-	C-
25	4.6	3.2	2.0	1.3	0.6	0.6	1.0	C-	C-	C-	C-
50	5.2	3.9	2.0	1.6	0.7	0.5	1.0	C-	C-	C-	C-
100	8.9	4.8	2.5	C+	0.9	0.5	1.0	C-	C-	C-	C-
200						0.7	1.1	C-	C-	C-	C-
400						C-	C-	C-	C-	C-	C-
800						C-	C-	C-	C-	C-	C-
1600						C-	C-	C-	C-	C-	C-
3200						L+	C-	C-	C-	C-	C-

Figure 1 — Sample printout from the AAT program, showing 3.5 and 29.7-MHz simulations for a T-network antenna tuner using 42-251 pF variable tuning capacitors (including 10 pF of stray), with voltage rating of 4500 V and 28 µH roller inductor. The load varies from 3.125 – j 3200 Ω to 3200 + j 3200 Ω in geometric steps. Symbol "L+" indicates that a match is impossible because more inductance is needed. "C–" indicates that the minimum capacitance is too large. "V" indicates that the voltage rating of a capacitor has been exceeded. "P" indicates that the power rating limit set by the operator to 20% has been exceeded. A blank indicates that matching is not possible at all, probably for a variety of simultaneous reasons.

Loss percentage for Tee-network, series cap., shunt inductor, series cap.
Freq: 3.5 MHz, Z0: 50, 1500W, Vmax: 3000 V, Qu: 200 , Qc: 1000
Var. Cap: 25 to 402 pF with switched 160/80 m output cap.: 400 pF

Xa	3.125	6.25	12.5	25	50	100	200	400	800	1600	3200	Ra
- 3200	L+	L+	L+	L+		L+	L+	L+	L+	V	V	
- 1600	L+	L+	L+	L+		L+	V	V	V	V	V	
- 800	C-	L+	L+	L+	V	V	V	4.9	3.9	4.0	V	
- 400	C-	L+	L+	V	V	6.0	4.0	3.0	2.9	3.6	V	
- 200	C-	L+	V	9.0	5.5	3.5	2.5	2.2	2.6	3.4	V	
- 100	C-	V	9.6	5.7	3.5	2.3	1.8	1.9	2.4	3.4	V	
- 50	19.7	11.7	6.8	4.0	2.6	2.2	1.8	1.8	2.4	3.3	V	
- 25	16.1	9.3	5.4	3.3	2.7	2.3	1.8	1.7	2.4	3.3	V	
- 12.5	14.1	8.1	4.6	3.4	2.9	2.4	1.9	1.7	2.4	3.3	V	
- 6.25	13.1	7.5	4.2	3.5	2.8	2.4	1.9	1.7	2.3	3.3	V	
-3.125	12.6	7.2	4.3	3.3	2.7	2.3	1.8	1.7	2.3	3.3	V	
0	12.1	6.9	4.4	3.6	3.0	2.3	1.8	1.7	2.3	3.3	V	
3.125	11.6	6.5	4.6	3.4	3.0	2.3	2.0	1.7	2.3	3.3	V	
6.25	11.0	6.2	4.4	3.7	2.9	2.6	2.0	1.7	2.3	3.3	V	
12.5	10.0	6.0	4.4	3.5	2.8	2.5	1.9	1.7	2.3	3.3	V	
25	8.5	5.8	4.7	3.6	3.0	2.4	1.9	1.6	2.3	3.3	V	
50	8.6	6.9	4.7	4.2	3.2	2.3	1.8	1.6	2.3	3.3	V	
100	V	V	6.3	4.4	3.2	2.5	1.9	1.5	2.3	3.3	V	
200	V	V	V	V	4.2	2.6	2.0	1.5	2.3	3.3	V	
400	P	V	V	V	V	1.1	1.5	1.7	2.3	3.3	V	
800	P	P	P	V	V	V	2.3	2.6	2.7	3.4	V	
1600	P	P	P	V	V	V	V	V	V	4.1	V	
3200						L+	L+	L+	V	V	V	

Loss percentage for Tee-network, series cap., shunt inductor, series cap.
Freq: 29.7 MHz, Z0: 50, 1500W, Vmax: 3000 V, Qu: 200 , Qc: 1000
Var. Cap: 25 to 402 pF with switched 160/80 m output cap.: 400 pF

Xa	3.125	6.25	12.5	25	50	100	200	400	800	1600	3200	Ra
- 3200	C-	C-	C-	C-		C-	C-	C-	C-	C-	C-	
- 1600	C-	C-	C-	C-	C-	C-	C-	C-	C-	C-	C-	
- 800	C-	C-	C-	C-	C-	C-	C-	C-	C-	C-	C-	
- 400	C-	C-	C-	C-	C-	C-	C-	2.8	C-	C-	C-	
- 200	C-	C-	C-	C-	4.6	2.9	2.2	2.1	2.5	C-	C-	
- 100	C-	C-	C-	4.1	2.5	1.7	1.5	1.8	2.4	C-	C-	
- 50	C-	6.9	3.9	2.3	1.4	1.1	1.3	1.7	2.3	C-	C-	
- 25	7.7	4.3	2.4	1.3	0.9	0.9	1.2	1.6	2.3	C-	C-	
- 12.5	5.4	2.9	1.5	0.8	0.6	0.8	1.1	1.6	2.3	C-	C-	
- 6.25	4.1	2.1	1.3	0.8	0.5	0.7	1.1	1.6	2.3	C-	C-	
-3.125	3.5	1.9	1.4	0.8	0.4	0.7	1.1	1.6	2.3	C-	C-	
0	2.8	1.9	1.4	1.0	0.4	0.7	1.1	1.6	2.3	C-	C-	
3.125	3.2	2.0	1.4	0.9	0.4	0.7	1.1	1.6	2.3	C-	C-	
6.25	3.4	1.9	1.5	1.0	0.4	0.6	1.1	1.6	2.3	C-	C-	
12.5	3.4	2.1	1.4	1.1	0.4	0.6	1.0	1.6	2.3	C-	C-	
25	4.6	2.3	1.5	1.0	0.5	0.6	1.0	1.6	2.3	C-	C-	
50	5.2	3.9	2.0	1.6	0.5	0.5	1.0	1.5	2.3	C-	C-	
100	V	5.6	3.0	1.6	1.0	0.5	0.9	1.5	2.3	C-	C-	
200	V				0.7	0.8	1.1	1.5	2.2	C-	C-	
400						1.2	1.6	1.8	2.3	C-	C-	
800						C-	C-	C-	C-	C-	C-	
1600						C-	C-	C-	C-	C-	C-	
3200						L+	C-	C-	C-	C-	C-	

Figure 2 — Another sample AAT program printout, using a dual-section variable capacitor whose overall tuning range when in parallel varies from 25 to 402 pF, but with a 3000-V rating. The same 28 µH roller is used, but an auxiliary 400 pF fixed capacitor can now be manually switched across the output variable capacitor. Note that the overall matching range has in effect been shifted over to the left from that in Figure 1 for the lower frequency because the maximum output capacitance is higher. The range has been extended on the highest frequency because the minimum capacitance is smaller.