CHAPTER 6

The Feed Line and The antenna

The feed line is the necessary link between the antenna and the transmitter/receiver. It may seem odd that I cover feed lines and antenna matching before discussing any type of antenna. I want to make it clear that antenna matching and feeding has no influence on the characteristics or the performance of the antenna itself (unless the matching system and/or feed lines also radiate). Antenna matching is generic, which means that any matching system can, in theory, be used with any antenna. Antenna matching must therefore be treated as a separate subject.

The following topics are covered:

- Coaxial lines; open-wire lines
- Loss mechanisms
- Real need for low SWR
- Quarter-wave transformers
- L networks
- Stub matching
- Wide-band transformers
- 75-Ω feed lines in 50-Ω systems
- Baluns
- Connectors

Before we discuss antennas from a theoretical point of view and describe practical antenna installations, let us analyze what matching the antenna to the feed line really means and how we can do it.

1. PURPOSE OF THE FEED LINE

The feed line transports RF from a source to a load. The most common example is from a transmitter to an antenna. When terminated in a resistor having the same value as its own characteristic impedance, a transmission line operates under ideal circumstances. The line will be *flat*—meaning that there are no standing waves on the line. The value of the impedance will be the same in each point of the line. If the feed line were lossless, the magnitude of the voltage and the current would also be the same along the line. The only thing that would change is the phase angle and that would be directly proportional to the line length. All practical feed lines have losses, however, and the values of current and voltage decrease along the line.

In the real world the feed line will rarely if ever be terminated in a load giving a 1:1 SWR. Since the line is most frequently terminated in a load with a complex impedance, in addition to acting as a transport vehicle for RF, the feed line also acts as a transformer. The impedance (also the voltage and current) will be different at each point along a mismatched line.

Besides transporting energy from the source to the load, feed lines are also used to feed the elements of an antenna array, whereby the characteristics of the feed lines (with SWR) are used to supply current at each element with the required relative magnitude and phase angle. This application is covered in detail in Chapter 11, Vertical Arrays and Chapter 7 (Receiving antennas).

2. FEED LINES WITH SWR

The typical characteristics of a line with SWR are:

- The impedance in every point of the line is different; the line acts as an impedance transformer. (While the impedances in a lossless line repeat themselves every half wavelength, the impedances in a real-world lossy line do not repeat exactly.)
- The voltage and the current at every point on the feed line are different.
- The losses of the line are higher than for a flat line.
- The phase shift in current and voltage is not linearly proportional to the line length. (Line length in degrees does not equal phase shift in degrees, except in very special cases such as for 90º long lines.)

Most transmitters, amplifiers and transceivers are designed to work into a nominal impedance of 50 Ω. Although they will provide a match to a range of impedances that are not too far from the 50-Ω value (eg, within the 2:1 SWR circle on the Smith Chart), it is generally a proof of good engineering and workmanship that an antenna on its design frequency, shows a 1:1 SWR on the feed line. This means that the feedpoint impedance of the antenna must be *matched* to the characteristic impedance of the line at the design frequency. The SWR bandwidth of the antenna will be determined in the first place by the Q factor of the antenna, but the bandwidth will be largest if the antenna has been matched to the feed line (1:1 SWR) at a design frequency within that passband, unless special broadband matching techniques are employed. This means we want a low SWR for reasons of convenience: We don't want to be forced to use an antenna tuner between the transmitter and the feed line in order to obtain a match.

2.1. Conjugate Match

A conjugate match is a situation where all the available power is coupled from the transmitter into the line. In a conjugate match with lossless line, the impedance seen looking towards the load ($a + jb$) at a point in the transmission line is the complex conjugate of that seen looking towards the source ($a - jb$). A conjugate match is automatically achieved when we adjust the transmitter for maximum power transfer into the line. In transmitters or amplifiers using vacuum tubes, this is done by properly adjusting the common pi or pi-L network. Modern transceivers with fixed-impedance solid-state amplifiers do not have this flexibility, and an external antenna tuner will be required in most cases if the SWR is higher than 1.5:1 or 2:1. Many present-day transceivers have built-in antenna tuners that automatically take care of this situation.

But this is not the main reason for low SWR. The above reason is one of "convenience." The real reason is one of losses or attenuation. A feed line is usually made of two conductors with an insulating material in between. Open-wire feeders and coaxial feed lines are the two most commonly used types of feed lines.

2.2. Coaxial Cable

Coaxial feed lines are by far the most popular type of feed lines in amateur use, for one specific reason: Due to their coaxial (unbalanced) structure, all magnetic fields caused by RF current in the feed line are kept inside the coaxial structure. This means that a coaxial feed line is totally *inert* from the outside, when terminated in an unbalanced load (whether it has SWR or not). An unbalanced load is a load where one of the terminals is grounded. This means you can bury the coax, affix it to the wall, under the carpet, tape it to a steel post or to the tower without in any way upsetting the electrical properties of the feed line. Sharp bending of coax should be avoided, however, to prevent impedance irregularities and permanent displacement of the center conductor caused by cable dielectric heating and induced stresses. A minimum bending radius of five times the cable outside diameter is a good rule of thumb for coaxial cables with a braided shield.

Like anything exposed to the elements, coaxial cables deteriorate with age. Under the influence of heat and ultraviolet light, some of the components of the outer sheath of the coaxial cable can decompose and migrate down through the copper braid into the dielectric material, causing degradation of the cable. Ordinary PVC jackets used on older coaxial cables (RG-8, RG-11) showed migration of the plasticizer into the polyethylene dielectric. Newer types of cable (RG-8A, RG-11A, RG-213 and so on) use non-contaminating sheaths that greatly extend the life of the cable.

Also, coaxial cables love to drink water! Make sure the end connections and the connectors are well sealed. Because of the structure of the braided shield, the interstices between the inner conductor insulation and the outer sheath will literally suck up liters (quarts) of water, even if only a pin hole is present. Once water has penetrated cable with a woven copper shield, it is ruined. Here is one of the big advantages of the larger coaxial cables using expanded polyethylene and a corrugated solid copper outer conductor: Since the polyethylene sticks (bonds) to the copper, water penetration is impossible even if the outer jacket is damaged.

You should check the attenuation of your feed lines at regular intervals. You can easily do this by opening the feed line at the far end. Then feed some power into the line through an accurate SWR meter (such as a Bird wattmeter), and measure the SWR at the input end of the line. A lossless line will show infinite SWR (Ref 1321).

The loss in the cable at the frequency you do the measurement is given by:

$$\text{Loss (dB)} = \log \left[\frac{\text{SWR} + 1}{\text{SWR - 1}} \right] \qquad \text{(Eq 1)}$$

The attenuation can also be computed using the graph in **Fig 6-1**. It is difficult to do this test at low frequencies because the low attenuation is such that accurate measurements are difficult. For best measurement accuracy the loss of the cable to be measured should be on the order of 2 to 4 dB (SWR between 2:1 and 4:1). The test frequency can be chosen accordingly. Use a professional type SWR meter such as a Bird wattmeter. Many cheaper SWR meters are inadequate.

It is obvious that this measurement can also be done using done of the popular Antenna Analyzers (eg, MFJ, Autek or AEA). Dave Hachadorian, K6LL, described a variant of the above method: "Plug your antenna into the feed line in the shack and tune it to a frequency where it shows a peak SWR. At this frequency, the antenna, whatever it is, will be a good approximation of an open or short circuit. The frequency will probably NOT be in the ham bands. Start at 30 MHz and work down." The same formula as above and the graph in Fig 6-1 apply to this technique too.

The advantage of K6LL's method is that you can actually

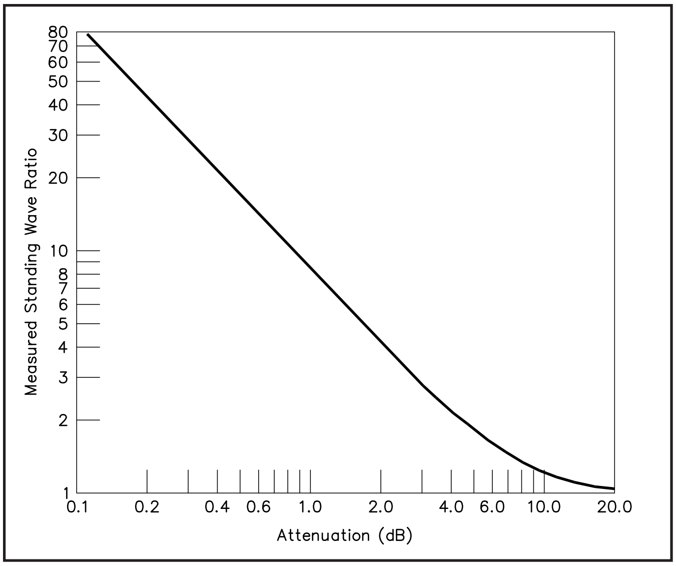
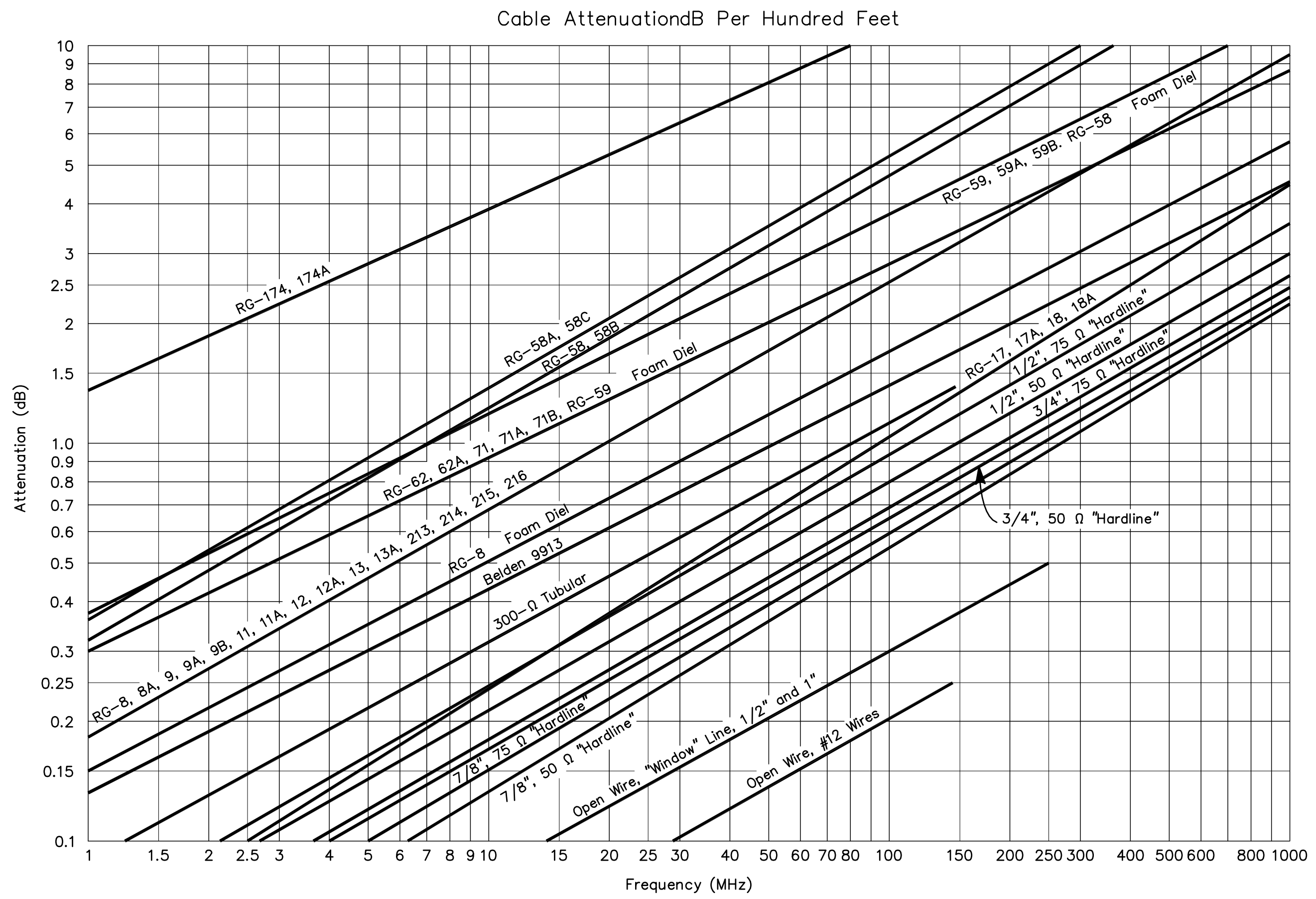
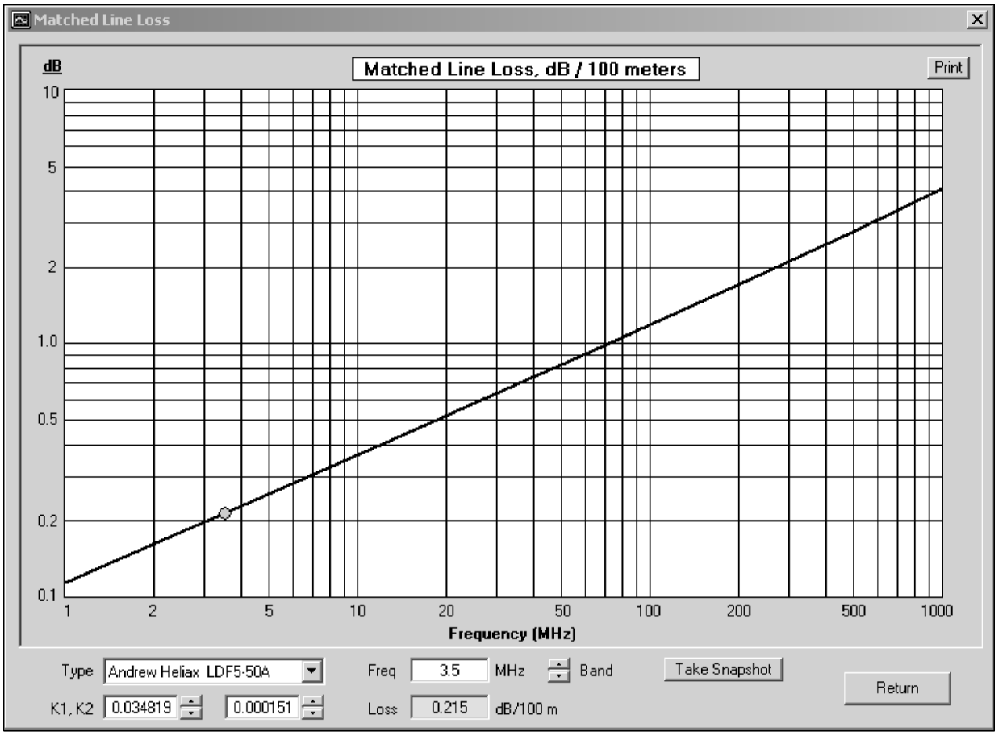


Fig 6-1—Cable loss as a function of SWR measured at the input end of an open or short-circuited feed line. For best accuracy, the SWR should be in the 1:1 to 4:1 range.



(A)



Type Andrew Heliax LDF5-50A

K1, K2 0.034819 0.000151

Freq 3.5 MHz Band

Loss 0.215 dB/100 m

(B)

Fig 6-2—At A, nominal attenuation characteristics in dB per 100 feet (30.48 meters) for commonly used transmission lines. (*Courtesy of* The ARRL Antenna Book.) At B, attenuation vs frequency chart generated with AC6LA's *TLDetails* software for Andrews LDF5-50A Heliax. (Note that the attenuation shown here is per 100 meters.)

do the measurement without having to disconnect the feed line at the antenna. Using one of the popular SWR analyzers, you should make sure that the SWR measured at this worst frequency is at least 15:1 (equivalent to a line loss of 0.6 dB). K6LL points out that the impedance of most non-resonant antennas is several thousand ohms (SWR > 40). If the presence of an antenna does degrade the measurement at all, it will be in a direction to make the feed line loss appear higher than it really is. If you have any concerns about whether this method is making your feed line appear too lossy, you will have to disconnect the antenna. At that time you can do the measurement at any frequency.

2.3. Open-Wire Transmission Line

Even when properly terminated in a balanced load, an open-wire feeder will exhibit a strong RF field in the immediate vicinity of the feedline (try a neon bulb close to an open-wire feeder with RF on it!). This means you cannot "fool around" with open-wire feeders as you can with coax. During installation all necessary precautions should be taken to preserve the balance of the line: The line should be kept away from conductive materials. In one word, generally it's a nuisance to work with open-wire feeders!

But apart from this mechanical problem, open-wire feeders outperform coaxial feed lines in all respects on HF (VHF/UHF can be another matter).

2.4. The Loss Mechanism

The intrinsic losses of a feed line (coaxial or open-wire) are caused by two mechanisms:

- Conductor losses (losses in the copper conductors).
- Dielectric losses (losses in the dielectric material).

Dry air is an excellent insulator. From that point of view, an open-wire line is unbeatable. Coaxial feed lines generally use polyethylene as a dielectric, or polyethylene mixed with air (cellular PE or foam PE). Cables with foam or cellular PE have lower losses than cables with solid PE. They have the disadvantage of potentially having less mechanical (impact and pressure) resistance. Cell-flex cables using a solid copper or aluminum outer conductor are the top-of-the line coaxial feed lines used in amateur applications. Sometimes Teflon is used as dielectric material. This material is mechanically very stable and electrically very superior, but very expensive. Teflon-insulated coaxial cables are often used in baluns. (See Section 7.)

Coaxial cables generally come in two impedances: 50 Ω and 75 Ω. For a given cable outer diameter, 75-Ω cable will show the lowest losses. That's why 75 Ω is always used in systems where losses are of primary importance, such as CATV. If power handling is the major concern, a much lower impedance is optimum (35 Ω). The standard of 50 Ω has been created as a good compromise between power handling and attenuation.

Fig 6-2 shows typical matched-line attenuation characteristics for many common transmission lines. Note how the open-wire line outperforms even its biggest coaxial brother by a large margin. But these attenuation figures are only the "nominal" attenuation figures for lines operating with a 1:1 SWR.

TLDetails (see Section 2.4 and Fig 6-2A) is a freeware software program by Dan, AC6LA (**www.qsl.net/ac6la/tldetails.html**) that can generate beautiful attenuation vs frequency charts for any type of transmission line. *TLDetails* includes characteristics for 49 built-in line types, and you can specify your own. For information concerning the K1 and K2 loss coefficients see **www.qsl.net/ac6la/bestfit.html**.

TLW (Transmission Line for Windows), by N6BV, is available from the ARRL as part of the CD that comes with the 20th Edition of *The ARRL Antenna Book*. *TLW* is a full-featured transmission line analysis program with beautiful graphic capabilities. It includes a design section for an antenna matcher (tuner), using four possible networks: high and low-pass L-networks, low-pass Pi networks and high-pass T-networks. The database contains transmission line characteristics of over 30 current types of lines, and the user can, in addition, enter the specs of his own line.

Frank Donovan, W3LPL, put together **Table 6-1**, which lists most of the commonly used coaxial cable types in the US. The table was made in two versions, one giving the classic atenuation/100 foot. The second list gives the cable length for 1 dB of attenuation.

When there are standing waves on a feed line, the voltage and the current will be different at every point on the line. Current and voltage will change periodically along the line and can reach very high values at certain points. The feed line uses dielectric (insulating) and conductor (mostly copper) materials with certain physical properties and limitations. The very high currents at peaks along the line are responsible for extra conductivity-related losses. The voltages associated with the voltage peaks will be responsible for increased dielectric losses. These are the mechanisms that make a line with a high SWR have more losses than the same line when matched. **Fig 6-3** shows additional losses caused by SWR. By the way, the losses of the line are the reason why the SWR we measure at the input end of the feed line (in the shack) is always lower than the SWR at the load.

An extreme example is that of a very long cable, having

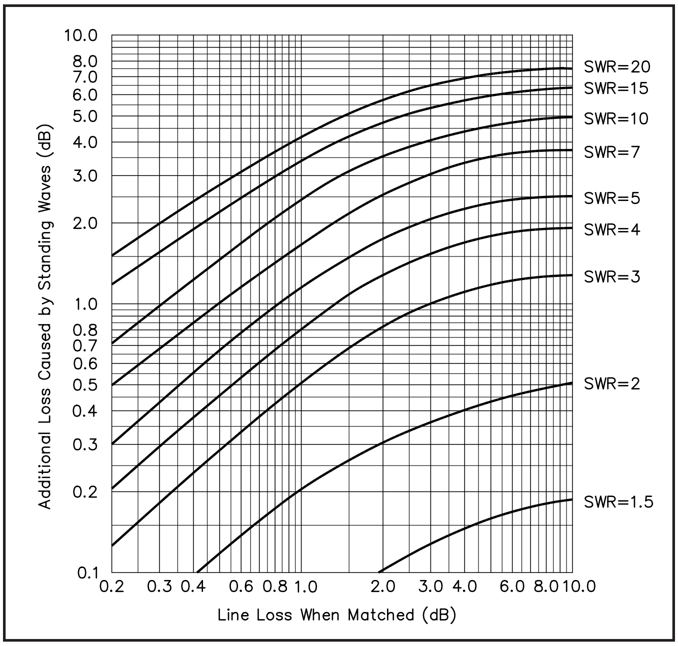


Fig 6-3—This graph shows how much additional loss occurs for a given SWR on a line with a known (nominal) flat-line attenuation. (*Courtesy of* The ARRL Antenna Book.)

Table 6-1

Cable Attenuation (dB per 100 feet)

MHz	1.8	3.5	7.0	14.0	21.0	28.0	50.0	144	440	1296
LDF7-50A	0.03	0.04	0.06	0.08	0.10	0.12	0.16	0.27	0.5	0.9
FHJ-7	0.03	0.05	0.07	0.10	0.12	0.15	0.20	0.37	0.8	1.7
LDF5-50A	0.04	0.06	0.09	0.14	0.17	0.19	0.26	0.45	0.8	1.5
FXA78-50J	0.06	0.08	0.13	0.17	0.23	0.27	0.39	0.77	1.4	2.8
$^{3}/_{4}$" CATV	0.06	0.08	0.13	0.17	0.23	0.26	0.38	0.62	1.7	3.0
LDF4-50A	0.09	0.13	0.17	0.25	0.31	0.36	0.48	0.84	1.4	2.5
RG-17	0.10	0.13	0.18	0.27	0.34	0.40	0.50	1.3	2.5	5.0
SLA12-50J	0.11	0.15	0.20	0.28	0.35	0.42	0.56	1.0	1.9	3.0
FXA12-50J	0.12	0.16	0.22	0.33	0.40	0.47	0.65	1.2	2.1	4.0
FXA38-50J	0.16	0.23	0.31	0.45	0.53	0.64	0.85	1.5	2.7	4.9
9913	0.16	0.23	0.31	0.45	0.53	0.64	0.92	1.6	2.7	5.0
RG-217	0.19	0.27	0.36	0.51	0.61	0.73	1.1	2.0	4.0	7.0
RG-213	0.25	0.37	0.55	0.75	1.0	1.2	1.6	2.8	5.1	10.0
RG-8X	0.49	0.68	1.0	1.4	1.7	1.9	2.5	4.5	8.4	17.8

Cable Attenuation (Feet per dB)

MHz	1.8	3.5	7.0	14.0	21.0	28.0	50.0	144	440	1296
LDF7-50A	3333	2500	1666	1250	1000	833	625	370	200	110
FHJ-7	2775	2080	1390	1040	833	667	520	310	165	92
LDF5-50A	2500	1666	1111	714	588	526	385	222	125	67
FXA78-50J	1666	1250	769	588	435	370	256	130	71	36
$^{3}/_{4}$" CATV	1666	1250	769	588	435	385	275	161	59	33
LDF4-50A	1111	769	588	400	323	266	208	119	71	40
RG-17	1000	769	556	370	294	250	200	77	40	20
SLA12-50J	909	667	500	355	285	235	175	100	53	34
FXA12-50J	834	625	455	300	250	210	150	83	48	25
FXA38-50J	625	435	320	220	190	155	115	67	37	20
9913	625	435	320	220	190	155	110	62	37	20
RG-217	525	370	275	195	160	135	90	50	25	14
RG-213	400	270	180	130	100	83	62	36	20	10
RG-8X	204	147	100	71	59	53	40	22	12	6

LDF7-50A is Andrew 1$^{5}/_{8}$" 50 Ω foam dielectric Heliax
LDF4-50A is Andrew $^{1}/_{2}$" 50 Ω foam dielectric Heliax
LDF5-50A is Andrew $^{7}/_{8}$" 50 Ω foam dielectric Heliax
FHJ-7 is an older version of Andrew 1$^{5}/_{8}$" 50 Ω foam dielectric Heliax
FXA78-50J is Cablewave $^{7}/_{8}$" 50 Ω aluminum jacketed foam dielectric hardline
FXA12-50J is Cablewave $^{1}/_{2}$" 50 Ω aluminum jacketed foam dielectric hardline
SLA12-50J is Cablewave $^{1}/_{2}$" 50 Ω aluminum jacketed air dielectric hardline
FXA38-50J is Cablewave $^{3}/_{8}$" 50 Ω aluminum jacketed foam dielectric hardline

a loss of at least 20 dB, where you can either short or open the end and in both cases measure a 1:1 SWR at the input. Such a cable is a perfect dummy load!

For a transmission line to operate successfully under high SWR, we need a low-loss feed line with good dielectric properties and high current-handling capabilities. The feeder with such properties is the open-wire line. Air makes an excellent dielectric, and the conductivity can be made as good as required by using heavy gauge conductors. Good-quality open-wire feeders have always proved to be excellent as feed-line transformers. Elwell, N4UH, has described the use and construction of homemade, low-loss open-wire transmission lines for long-distance transmission (Ref 1320). In many cases, the open-wire feeders are used under high SWR conditions (where the feeders do not introduce large additional losses) and are terminated in an antenna tuner. On the low bands the extra losses caused by SWR are usually negligible (Ref. 1319, 322), even for coaxial cables.

2.5. The Universal Transmission-Line Program

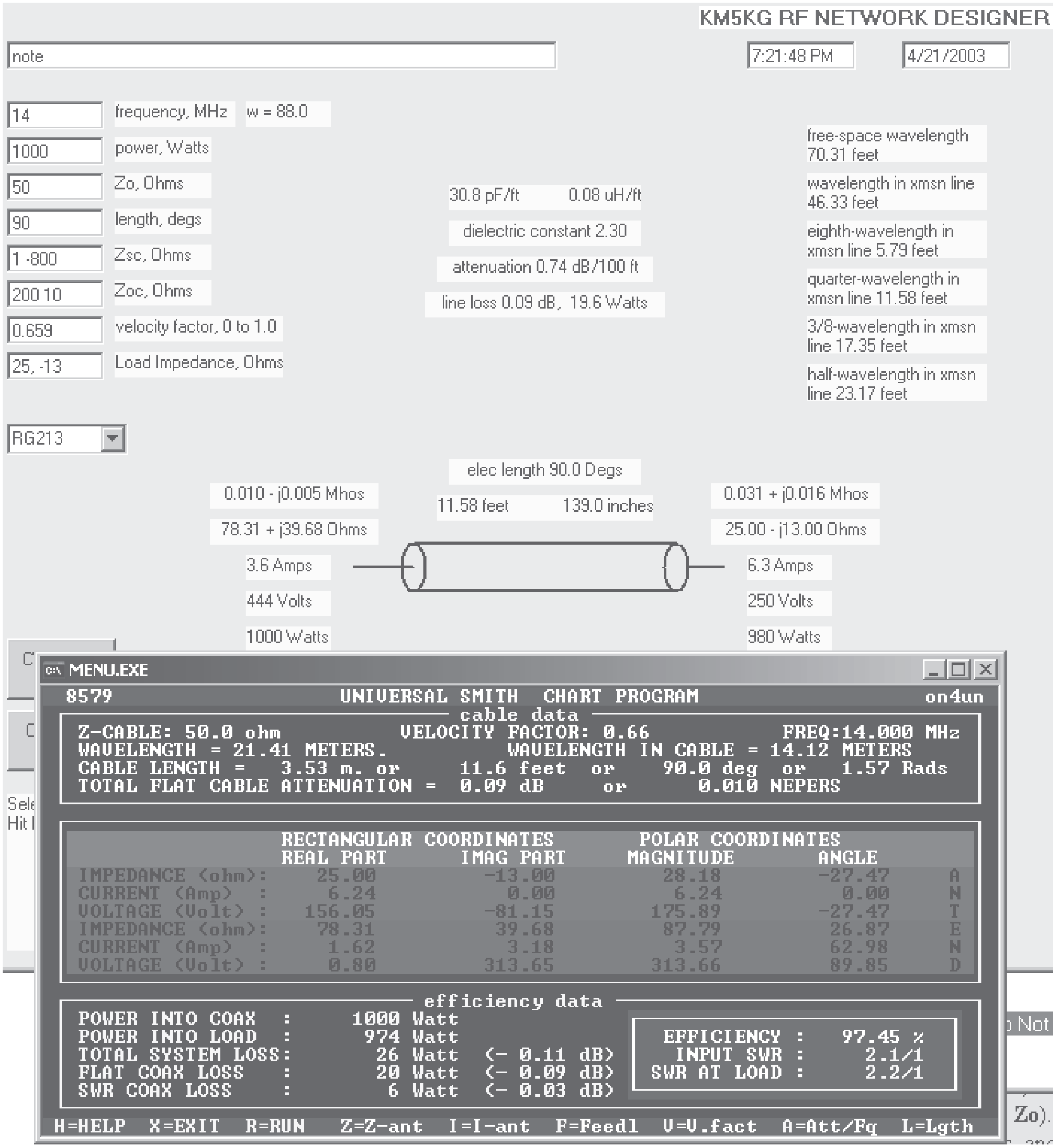
The COAX TRANSFOMER/SMITH CHART computer program, which is part of the NEW LOW-BAND SOFTWARE, is a good tool for evaluating the behavior of feed lines. Let us analyze the case of a 50-meter long RG-213 coax, feeding an impedance of 36.6 Ω (without a matching network). The frequency is 3.5 MHz.

Fig 6-4 shows a screen print obtained from the COAX TRANSFOMER/SMITH CHART module (using the program WITH cable losses). All the operating parameters are listed on the screen: impedance, voltage and current at both ends of the line, as well as the attenuation data split into nominal coax losses (0.61 dB) and losses due to SWR (0.03 dB). We also see the real powers involved. In our case we need to put 1734 W into the 100-meter long RG-213 cable to obtain 1500 W at the load, which represents a total efficiency of 86%. Note also the difference in SWR at the load

(1.4:1) and at the feed line end (1.3:1). For higher frequencies, longer cables or higher SWR values, this software module is a real eye-opener.

TLDetails (Transmission Line Details) mentioned above in Section 2.4 is a small standalone Windows program by AC6LA (**www.qsl.net/ac6la/tldetails.html**) that does exactly what my program does, and more. Dan wrote in an E-mail to me: "*When I was first playing with the transmission line equation several years ago, I remember comparing my results to several examples shown in your LOW BAND DXing book. I considered my code to be debugged when my results matched yours!*"

Another interesting software tool by AC6LA is *XLZIZL* (**www.qsl.net/ac6la/xlzizl.html**). This is an Excel application that analyzes the components of an antenna feed system, including transmission lines, stubs, baluns and tuners. Calculations include impedance transforms, SWR and reflection coefficient, power loss, voltage and current standing waves, stress on tuner components, network attenuation (S21), and return loss (S11). Analysis results are available in spreadsheet



KM5KG RF NETWORK DESIGNER

note

7:21:48 PM

4/21/2003

14 frequency, MHz w = 88.0

1000 power, Watts

50 Zo, Ohms

90 length, degs

1 -800 Zsc, Ohms

200 10 Zoc, Ohms

0.659 velocity factor, 0 to 1.0

25, -13 Load Impedance, Ohms

RG213

30.8 pF/ft 0.08 uH/ft

dielectric constant 2.30

attenuation 0.74 dB/100 ft

line loss 0.09 dB, 19.6 Watts

free-space wavelength 70.31 feet

wavelength in xmsn line 46.33 feet

eighth-wavelength in xmsn line 5.79 feet

quarter-wavelength in xmsn line 11.58 feet

3/8-wavelength in xmsn line 17.35 feet

half-wavelength in xmsn line 23.17 feet

elec length 90.0 Degs

11.58 feet 139.0 inches

0.010 - j0.005 Mhos

78.31 + j39.68 Ohms

3.6 Amps

444 Volts

1000 Watts

0.031 + j0.016 Mhos

25.00 - j13.00 Ohms

6.3 Amps

250 Volts

980 Watts

MENU.EXE

```
 8579                   UNIVERSAL SMITH  CHART PROGRAM                  on4un
 ┌───────────────────────────── cable data ─────────────────────────────────┐
 │ Z-CABLE: 50.0 ohm          VELOCITY FACTOR: 0.66          FREQ:14.000 MHz │
 │ WAVELENGTH = 21.41 METERS.          WAVELENGTH IN CABLE = 14.12 METERS    │
 │ CABLE LENGTH =   3.53 m. or     11.6 feet  or     90.0 deg  or   1.57 Rads│
 │ TOTAL FLAT CABLE ATTENUATION =  0.09 dB     or       0.010 NEPERS         │
 └──────────────────────────────────────────────────────────────────────────┘

                    RECTANGULAR COORDINATES       POLAR COORDINATES
                    REAL PART       IMAG PART      MAGNITUDE       ANGLE
  IMPEDANCE (ohm):    25.00          -13.00          28.18         -27.47     A
  CURRENT (Amp)  :     6.24            0.00           6.24           0.00     N
  VOLTAGE (Volt) :   156.05          -81.15         175.89         -27.47     T
  IMPEDANCE (ohm):    78.31           39.68          87.79          26.87     E
  CURRENT (Amp)  :     1.62            3.18           3.57          62.98     N
  VOLTAGE (Volt) :     0.80          313.65         313.66          89.85     D

 ┌────────────────────────── efficiency data ───────────────────────────────┐
 │ POWER INTO COAX   :      1000 Watt                                         │
 │ POWER INTO LOAD   :       974 Watt           EFFICIENCY :    97.45 %       │
 │ TOTAL SYSTEM LOSS:         26 Watt  (- 0.11 dB)  INPUT SWR :    2.1/1      │
 │ FLAT COAX LOSS    :        20 Watt  (- 0.09 dB) SWR AT LOAD :    2.2/1      │
 │ SWR COAX LOSS     :         6 Watt  (- 0.03 dB)                             │
 └──────────────────────────────────────────────────────────────────────────┘
 H=HELP  X=EXIT  R=RUN   Z=Z-ant  I=I-ant  F=Feedl  V=V.fact  A=Att/Fq  L=Lgth
```

Fig 6-4—An overlay of two transmission-line programs. At the top, the *KM5KG RF NETWORK DESIGNER* program shows that how a load impedance of 25 – *j* 13 Ω is transformed through a 90°-long 50-Ω feed line (having a loss of 0.74 dB/100 feet at 14 MHz). At the bottom is shown ON4UN's UNIVERSAL SMITH CHART, a module of the NEW LOW BAND SOFTWARE. See text for details. Both programs calculate the impedance at the end of this (lossy) line as 78.31 + *j* 39.68 Ω.

format and in five different chart formats, including Smith charts.

You can also use the *Transmission Line Transformer* or the *Transmission Line Model* module from Grant Bingeman's (KM5KG) software *Professional RF Network Designer* (see Chapter 4). Fig 6-4B shows the screen result of Bingeman's program and the same using the author's program, both yielding exactly the same results.

2.6. Which Size of Coaxial Cable?

RG-213 will easily handle powers up to 2 kW on the low bands, even with moderate SWR. Is there any point in using "heavier" coax? 100 meters of RG213, when perfectly matched (SWR of 1:1) gives a loss of approx 2 dB/100 meters on 7 MHz, 1.2 dB/100 meters on 1.5 MHz and 0.8 dB/100 meters on 1.8 MHz. What's 0.8 dB? Do you have to worry about 0.8 dB? The answer is: You need not to worry about 0.8 dB. But you should worry about 0.8 dB here, 0.5 dB there and again 0.3 dB somewhere else. It's the sum of all these fractions of dB you need to worry about!

I use $^7/_8$-inch hardline on all my antennas, even on 160 meters (loss is approximately 0.25 dB /100 meters at 1.8 MHz). If your run is 100 meters long, you "gain" 0.55 dB over the same length of RG-213, which is a gain of 13% in power.

An additional reason for using hardline is that it is practically indestructible. With a solid copper shield, water ingress is impossible, and the black PE sheath used on these types of cables is perfectly UV resistant for lifetime! In addition this cable can often be obtained for less money than new RG-213 from Cell phone companies renewing their sites.

2.7. Conclusions

Coaxial lines are generally used when the SWR is less than 3:1. Higher SWR values can result in excessive losses when long runs are involved, and also in reduced power-handling capability. Many popular low-band antennas have feed-point impedances that are reasonably low, and can result in an acceptable match to either a 50-Ω or a 75-Ω coaxial cable.

In some cases we will intentionally use feed lines with high SWR as part of a matching system (eg, stub matching) or as a part of a feed system for a multi-element phased array. It is good engineering practice to use a feed line with the lowest possible attenuation—This employs the concept of cost versus performance, called in the USA getting the most "bang for the buck." We would like that cable to operate at a 1:1 SWR at the design frequency of our antenna system.

3. THE ANTENNA AS A LOAD

A very small antenna can radiate the power supplied to it almost as efficiently as much larger ones (see Chapter 9 on vertical antennas), but small antennas have two disadvantages. Since their radiation resistance is very low, antenna efficiency will be lower than it would be if the radiation resistance were much higher. Further, if short antennas use loading, the losses of the loading devices have to be taken into account when calculating antenna efficiency. On the other hand, if the short antenna (dipole or monopole) is not loaded, the feed-point impedance will exhibit a large capacitive reactance in addition to the resistive component.

You could install some sort of remote tuner at the antenna feed point to match the complex antenna impedance to the feed-line impedance. Then the matched feed line will no longer act as a transformer itself. Matching done with such a remote tuner results in a certain sacrifice in efficiency, especially for extreme impedance ratios. Transforming a very short vertical with a feed-point impedance of, say, $0.5 - j\,3000\ \Omega$ to a $50 + j\,0\ \Omega$ transmission line is a very difficult task, one that can't be done without a great deal of loss.

You can also supply power to an antenna point without inserting a tuner at the antenna's feed point. In this case the feed line itself acts as a transformer. In the above example of $0.5 - j\,3000\ \Omega$, an extremely high SWR would be present on the feed line. The losses in the transmission line itself will be determined by the quality of the materials used to make the feed line. In pre-WW II days, when coaxial cables were still unknown, everybody used 600 Ω open-wire lines, and nobody knew (or cared) about SWR. The transmission line is fed with a low-loss antenna tuner in the shack. What is a quality antenna tuner? The same qualifications for feed lines apply here: One that can transform the impedances involved, at the required power levels and with minimal losses.

Many modern unbalanced to unbalanced antenna tuners use a toroidal transformer/balun to achieve a relatively high-impedance balanced output. This principle is cost effective, but has its limitations where extreme transformations are required. The "old" tuners (for example, Johnson Matchboxes) are well suited for matching a wide range of impedances. Unfortunately these Matchboxes are no longer available commercially and are not designed to cover 160 meters.

4. A MATCHING NETWORK AT THE ANTENNA

Let's analyze a few of the most commonly used matching systems.

4.1. Quarter-Wave Matching Sections

For a given design frequency you can transform impedance A to impedance B by inserting a quarter-wave long coaxial cable between A and B having a characteristic impedance equal to the square root of the product A × B.

$$Z_{\lambda/4} = \sqrt{A \times B} \qquad \text{(Eq 2)}$$

Example:

Assume we have a short vertical antenna that we wish to feed with 75-Ω coax. We have determined that the radiation resistance of the vertical is 23 Ω, and the resistance from earth losses is 10 Ω (making the feed-point resistance 33 Ω). We can use a $^1/_4$-wave section of line to provide a match, as shown in **Fig 6-5**. The impedance of this line is determined to be

$$\sqrt{33 \times 75} = 50\ \Omega.$$

Coaxial cables can also be paralleled to obtain half the nominal impedance. A coaxial feed line of 35 Ω can be made by using two parallel 70-Ω cables. Time Microwave (**www.timesmicrowave.com/**) offers a 35-Ω coaxial line (RG-83), which may be somewhat hard to find. This cable can, of course, be replaced with two paralleled 75-Ω coaxes.

You can parallel coaxial cable of different impedances to obtain odd impedances, which may be required for specific matching or feeding purposes. See **Table 6-2**. Make sure you use cable of exactly the same electrical length! Don't fool yourself—just because you parallel three identical cables the attenuation will not be one-third the attenuation of one cable. There is no change: Currents are now divided by the three cables, so all remains the same. Three cables in parallel will increase the power handling capability though.

One way to adjust $^{1}/_{4}$- or $^{1}/_{2}$-wavelength cables exactly for a given frequency is shown in **Fig 6-6**. Connect the transmitter through a good SWR meter (ON4UN uses a Bird Model 43) to a 50-Ω dummy load. Insert a coaxial-T connector at the output of the SWR bridge. Connect the length of coax to be adjusted at this point and use the reading of the SWR bridge to indicate where the length is resonant. Quarter-wave lines should be short-circuited at the far end, and half-wave lines left open. At the resonant frequency, a cable of the proper length represents an infinite impedance (assuming lossless cable) to the T-junction. At the resonant frequency, the SWR will not change when the quarter-wave shorted line (or half-wave open line) is connected in parallel with the dummy load. At slightly different frequencies, the line will present small

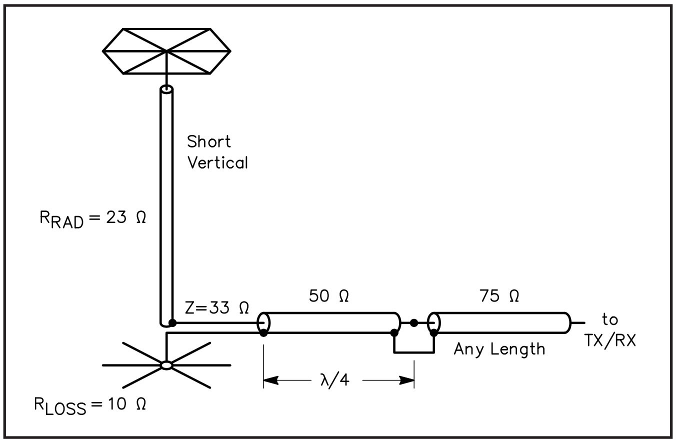


Fig 6-5—Example of a quarter-wave transformer, used to match a short vertical antenna (R_{rad} = 23 Ω, R_{ground} = 10 Ω, Z_{feed} = 33 Ω) to a 75-Ω feed line. In this case a perfect match can be obtained with a 50-Ω quarter-wave section.

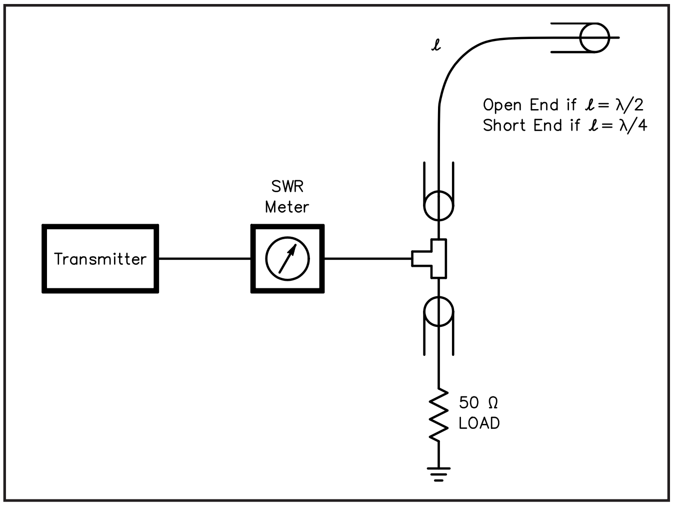


Fig 6-6—Very precise trimming of $^{1}/_{4}$ λ and $^{1}/_{2}$ λ lines can be done by connecting the line under test in parallel with a 50-Ω dummy load and watching the SWR meter while the feed line length or the transmit frequency is changed. See text for details.

Table 6-2
Net characteristic impedance resulting from paralleling different coaxial cables.

Cables in Parallel	*Net Impedance*
75 Ω + 75 Ω	37.5 Ω
75 Ω + 50 Ω	30 Ω
50 Ω + 50 Ω	25 Ω
75 Ω + 75 W + 50 Ω	21.5 Ω
75 Ω + 50 W + 50 Ω	18.8 Ω
50 Ω + 50 W + 50 Ω	16.7 Ω

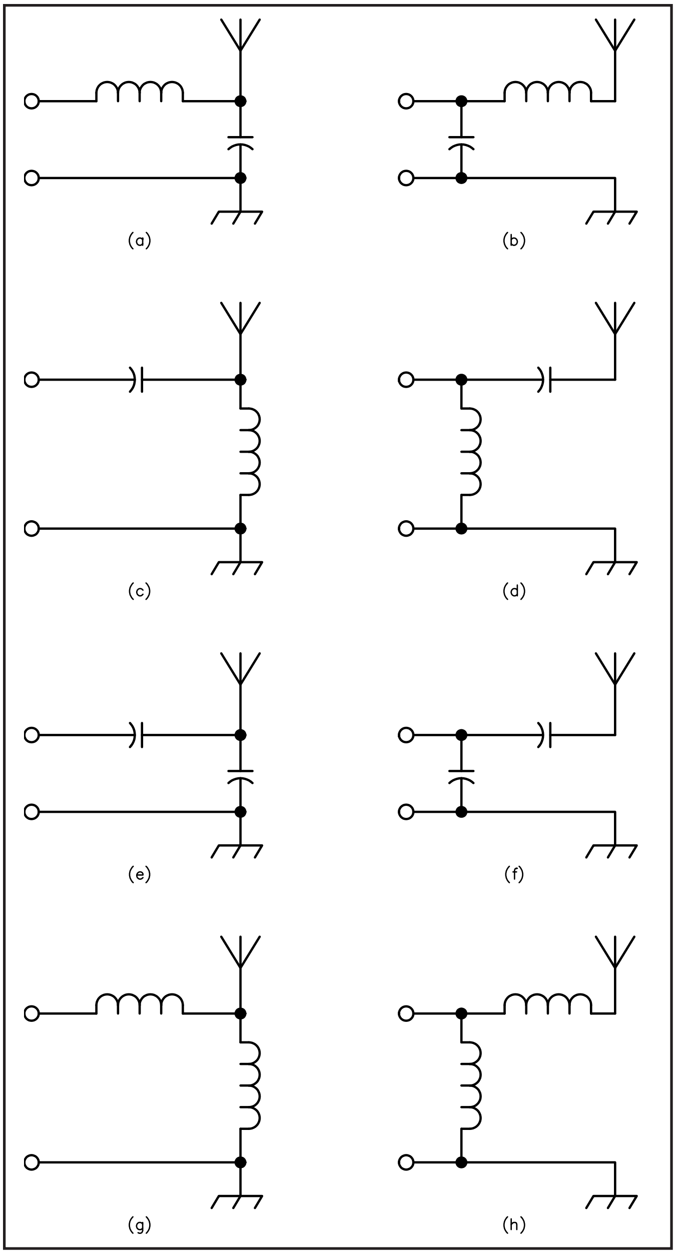


Fig 6-7—Eight possible L-network configurations. (After W. N. Caron, *ARRL Impedance Matching*.)

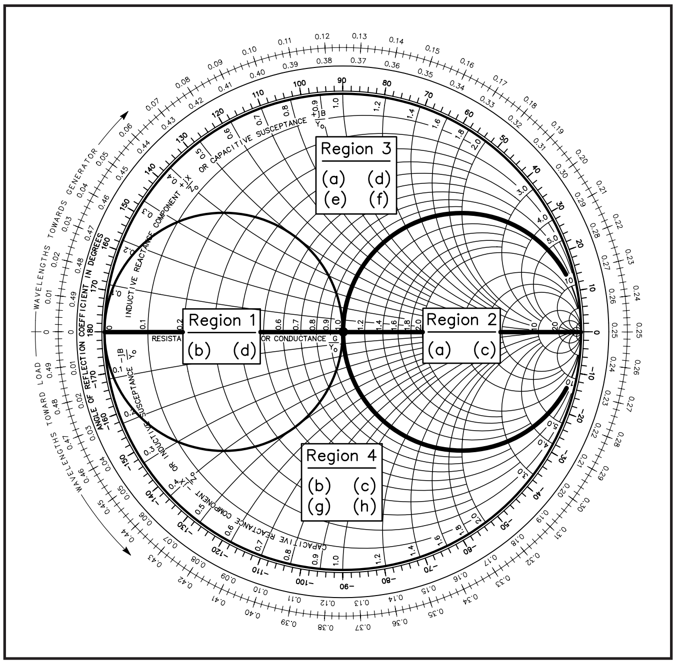


Fig 6-8—The Smith Chart subdivided in four regions, in each of which two or four L-network solutions are possible. The graphic solution methods are illustrated in Fig 6-9. (After W. N. Caron, *ARRL Impedance Matching*.)

values of inductance or capacitance across the dummy load, and these will influence the SWR reading accordingly. I have found this method very accurate, and the lengths can be trimmed precisely, to within a few kHz. Alternative methods are described in Chapter 11, Section 3.3.8.3.

Odd lengths, other than $^1/_4$- or $^1/_2$ wavelength, can also be trimmed this way. First calculate the required length difference between a quarter (or half) wavelength on the desired frequency and the actual length of the line on the desired frequency. For example, if you need a 73º length of feed line on 3.8 MHz, that cable would be 90º long on (3.8 × 90º/73º) = 4.685 MHz. The cable can now be cut to a quarter wavelength on 4.685 MHz using the method described above.

Some people use a dip oscillator, but this method isn't the most accurate way to cut a 90º length of feed line, and it often accounts for length variations of 2º or 3º (due to the inductance of the link use to couple to the GDO). You can also use a noise bridge and use the line under test to effectively short-circuit the output of the noise bridge to the receiver.

4.2. The L Network

The L network is probably the most commonly used network for matching antennas to coaxial transmission line. In special cases the L network is reduced to a single-element network, being a series or a parallel impedance network (just an L or C in series or in parallel with the load).

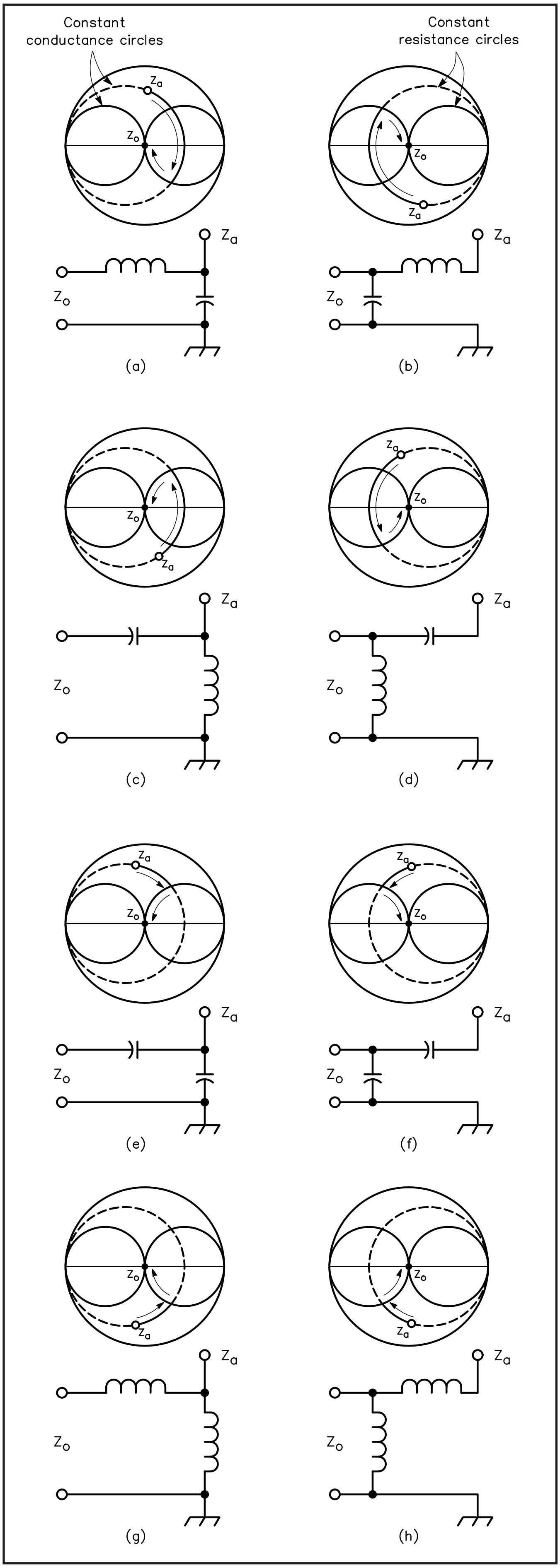


Fig 6-9—Design procedures on the Smith Chart for solution *a* through *h* as explained in Fig 6-8. (After W. N. Caron, *ARRL Impedance Matching*.) If you have a PC you can use the program *ARRL MICROSMITH* to quickly and easily calculate the matching values graphically on screen.

The L network is treated in great detail by W. N. Caron in his excellent book *Antenna Impedance Matching* (an ARRL publication). Caron exclusively used the graphical Smith Chart technique to design antenna-matching networks. The book also contains an excellent general treatment of the Smith Chart and other basics of feed lines, SWR and matching techniques. Graphic solutions of impedance-matching networks have been treated by I. L. McNally, W1NCK (Ref 1446). R. E. Leo, W7LR (Ref 1404) and B. Baird, W7CSD (Ref 1402).

Designing an L network is something you can easily do using a computer program. I have written a computer program (L-NETWORK DESIGN) that will just do that for you. The program is part of the NEW LOW BAND SOFTWARE. So-called shunt-input L networks are used when the resistive part of the output impedance is lower than the required input impedance of the network. The series-input L network is used when the opposite condition exists. In some cases, a series-input L network can also be used when the output resistance is smaller than the input resistance (in this case we have four solutions). All possible alternatives (at least two, but four at the most) will be given by the program.

Other similar computer programs have been described in amateur literature (Ref 1441). The ARRL program *TLW* can design L-networks that take into account component losses.

Fig 6-7 shows the eight possible L-network configurations. **Fig 6-8** shows the four different regions of the Smith Chart and which of the solutions are available in each of the areas. **Fig 6-9** shows the way to design each of the solutions. If you have an IBM or compatible PC, another way to design L networks with an on-screen Smith Chart is with the program *ARRL MICROSMITH* by W. Hayward, W7ZOI. A detailed knowledge of the Smith Chart is not required to use *MICROSMITH.*

The choice of the exact type of L network to be used (low pass, high pass) will be up to the user, but in many cases, component values will determine which choice is more practical. In other instances, performance may be the most important consideration: Low-pass networks will give some additional harmonic suppression of the radiated signal, while

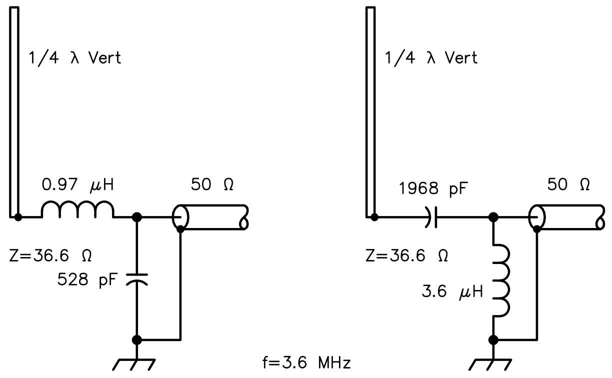
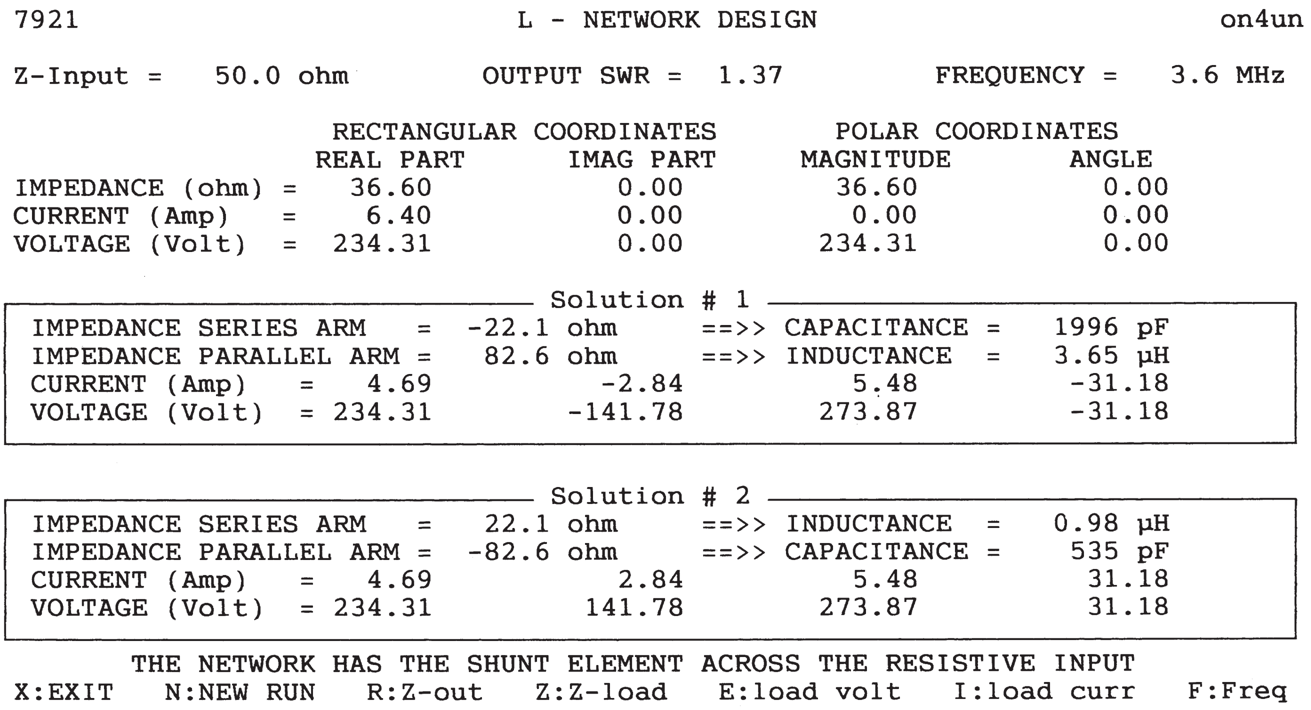


Fig 6-10—Design of an L-network to match a resonant quarter-wave vertical with a feed-point impedance of 36.6 Ω to a 50-Ω line. Note that in practice we must add the ground resistance to the radiation resistance to obtain the feed-point impedance. Therefore, in most cases the impedance of a quarter-wave vertical will be fairly close to 50 Ω.



```
7921                           L - NETWORK DESIGN                            on4un

Z-Input =   50.0 ohm         OUTPUT SWR =  1.37          FREQUENCY =   3.6 MHz

                   RECTANGULAR COORDINATES        POLAR COORDINATES
                  REAL PART      IMAG PART     MAGNITUDE        ANGLE
IMPEDANCE (ohm) =   36.60           0.00          36.60           0.00
CURRENT (Amp)   =    6.40           0.00           0.00           0.00
VOLTAGE (Volt)  =  234.31           0.00         234.31           0.00

 ------------------------------------ Solution # 1 -------------------------------
| IMPEDANCE SERIES ARM    =  -22.1 ohm     ==>> CAPACITANCE =   1996 pF          |
| IMPEDANCE PARALLEL ARM =   82.6 ohm     ==>> INDUCTANCE  =   3.65 µH          |
| CURRENT (Amp)    =   4.69            -2.84          5.48          -31.18       |
| VOLTAGE (Volt)  = 234.31          -141.78        273.87          -31.18       |
 ---------------------------------------------------------------------------------

 ------------------------------------ Solution # 2 -------------------------------
| IMPEDANCE SERIES ARM    =   22.1 ohm     ==>> INDUCTANCE  =   0.98 µH          |
| IMPEDANCE PARALLEL ARM =  -82.6 ohm     ==>> CAPACITANCE =    535 pF          |
| CURRENT (Amp)    =   4.69             2.84          5.48           31.18       |
| VOLTAGE (Volt)  = 234.31           141.78        273.87           31.18       |
 ---------------------------------------------------------------------------------
       THE NETWORK HAS THE SHUNT ELEMENT ACROSS THE RESISTIVE INPUT
X:EXIT   N:NEW RUN   R:Z-out   Z:Z-load   E:load volt   I:load curr   F:Freq
```

a high-pass filter may help to reduce the strength of strong medium-wave broadcast signals from local stations.

Some solutions provide a direct dc ground path for the antenna through the coil. If dc grounding is required, such as in areas with frequent thunderstorms, this can also be achieved by placing an appropriate RF choke at the base of the antenna (between the driven element and ground).

The L-NETWORK software module from the NEW LOW BAND SOFTWARE also calculates the input and output voltages and currents of the network. These can be used to determine the required component ratings. Capacitor current ratings are especially important when the capacitor is the series element in a network. The voltage rating is most important when the capacitor is the shunt element in the network. Consideration regarding component ratings and the construction of toroidal coils are covered in Section 4.2.1.2.

The user provides to the L-NETWORK software module:

- Design frequency
- Cable impedance
- Load resistance
- Load reactance

Fig 6-10 shows the screen display of a case where we calculate an L network to match (36.6 – *j* 0) Ω to a 50-Ω transmission line. From the prompt line you can easily change any of the inputs. If the outcome of the transformation is a network with one component having a very high reactance (low C value or high L value), then we can try to eliminate this component all together. The SERIES NETWORK or SHUNT NETWORK programs will tell you exactly what value to use, and if the match is not perfect you may want to assess the SWR by switching to the SWR CALCULATION module of the NEW LOW BAND SOFTWARE to do that.

The same values can also be calculated with the L-network Module of Grant Bingeman's *Professional RF Network Designer* or with ARRL's *TLW*.

4.2.1. Component ratings

What kind of capacitors and inductors do we need for building the L networks?

4.2.1.1. Capacitors

The transmitter power as well as the position of the component in the L network will determine the voltage and current ratings that are required for the capacitor.

- If the capacitor is connected in parallel with the 50-Ω transmission line (assuming we have a 1:1 SWR), then the voltage across the capacitor is given by $E = \sqrt{P \times R}$.

  Assume 1500 W and a 50-Ω feed line.

$$E = \sqrt{1500 \times 50} = 274 \text{ V RMS}$$

The peak voltage is $274 \times \sqrt{2} = 387$ V peak.

- If the capacitor is connected between the antenna base and ground, we can follow a similar reasoning. But this time we need to know the absolute value of the antenna impedance. Assume the feed point impedance is 90 + *j* 110 Ω, where $R_r = 90$ Ω. The magnitude of the antenna impedance is:

$$Z_{ant} = \sqrt{90^2 + 110^2} = 142.1\,\Omega$$

The voltage across the antenna feed point is given by:

$$E = I \times Z_{ant} = \sqrt{\frac{P}{R_r}} \times Z_{ant}$$

$$= \sqrt{\frac{1500}{90}} \times 142.2 = 580 \text{ V RMS} = 820 \text{ V peak.}$$

- If the capacitor is the series element in the network, and if the parallel element is connected between the feed line and ground (transmitter side of the network), then the current through the capacitor equals the antenna feed current. Assume a new feed-point impedance of 120 + *j* 190 Ω. The magnitude of the antenna feed-point impedance is:

$$Z = \sqrt{120^2 + 190^2} = 225\,\Omega$$

Again assume 1500 W. The magnitude of the feed current is:

$$I = \sqrt{\frac{P}{Z}} = \sqrt{\frac{1500}{225}} = 2.58 \text{ A}$$

Assume the capacitor has a value of 200 pF and the operating frequency is 3.65 MHz. The impedance of the capacitor is:

$$X_C = \frac{10^6}{2\pi f\,C} = \frac{10^6}{2\pi \times 3.65 \times 200} = 218\,\Omega$$

where f is in MHz and C is in pF. The voltage across capacitor is:

$E = I \times Z = 2.58 \times 218 = 562$ V RMS or 795 V peak

- If the capacitor is the series element in the L network and if the parallel element is connected between the feed point of the antenna and ground, then the current through the capacitor is the current going in the 50-Ω feed line. Assuming we have a 1:1 SWR in a 50-Ω feed line and a power level of 1500 W, the current is given by:

$$I = \sqrt{\frac{P}{Z}} = \sqrt{\frac{1500}{50}} = 5.48 \text{ A}$$

Assume the same 200-pF capacitor as above, whose impedance at 3.65 MHz was calculated to be 218 Ω. The voltage across the capacitor now is:

$E = I \times Z = 5.48 \times 218 = 1194$ V RMS or 1689 V peak

When calculating required voltage ratings we must always calculate the peak value, while for currents we can use the RMS value. This is because the current failure mechanism is a thermal mechanism. In practice we should always use at least a 100% safety factor on these components. For the capacitors across low-impedance points, transmitting type mica capacitors can be used, as well as BC-type variables such as normally used as the loading capacitor in the pi network of a linear amplifier.

Table 6-3
Toroid Cores Suitable for Matching Networks

Supplier	*Code*	*Permeability*	*OD (in.)*	*ID (in.)*	*Height (in.)*	A_L
Amidon	T-40-A2	10	4.00	2.25	1.30	360
Amidon	T-400-2	10	4.00	2.25	0.65	185
Amidon	T-300-2	10	3.05	1.92	0.50	115
Amidon	T-225-A2	10	2.25	1.41	1.00	215

For series capacitors, only transmitting type ceramic capacitors (eg, doorknob capacitors) should be used because of the high RF current. For fine tuning, high-voltage variables or preferably vacuum variables can be used. I normally use parallel-connected transmitting-type ceramics across a low-value vacuum variable (these can usually be obtained at real bargain prices at flea markets).

4.2.1.2. Coils

Up to inductor values of approximately 5 µH, air-wound coils are usually the best choice. A roller inductor comes in very handy when trying out a new network. Once the computed values have been verified by experimentation, the variable inductor can be replaced with a fixed inductor. Large-diameter, heavy-gauge Air Dux coils are well suited for the application.

Above approximately 5 µH, powdered-iron toroidal cores can be used. Ferrite cores are not suitable for this application, since these cores are much less stable and are easily saturated. The larger size powdered-iron toroidal cores, which can be used for such applications, are listed in **Table 6-3**.

The required number of turns for a certain coil can be determined as follows:

$$N = 100 \times \sqrt{\frac{L}{A_L}} \qquad \text{(Eq 2)}$$

where L is the required inductance in µH. The A_L value is taken from Table 6-3. The transmitter power determines the required core size. It is a good idea to choose a core somewhat on the large side for a margin of safety. You may also stack two identical cores to increase power-handling capability, as well as the A_L factor. The power limitations of powdered-iron cores are usually determined by the temperature increase of the core. Use large-gauge enameled copper wire for minimum resistive loss, and wrap the core with glass-cloth electrical tape before winding the inductor. This will prevent arcing at high power levels.

Consider this example: A 14.4-µH coil requires 20 turns on a T-400-A2 core. AWG 4 or AWG 6 wire can be used with equally-spaced turns around the core. This core will easily handle well over 1500 W.

In all cases you must measure the inductance. A_L values can easily vary 10%. It appears that several distributors (such as Amidon) sell cores under the name type number coming from various manufacturers and this accounts for the spread in characteristics.

When measuring the inductance of a toroidal core, it is important to do this on the operating frequency, especially when dealing with ferrite material. The impedance versus frequency ratio is far from linear for this type of material. Be careful when using a digital L-C meter, which usually uses one fixed frequency for all measurements (eg, 1 MHz). Accurate methods of measuring impedances on specific frequencies are covered in Chapter 11 (Arrays).

4.2.1.3. The smoke test

Two things can go wrong with the matching network:

- Capacitors and coils can flash over (short circuit, explode, vaporize, catch fire, burn up, etc) if their voltage rating is too low.
- Capacitors or coils will heat up (and eventually be destroyed after a certain time), if the current through the component is too high or the component's current carrying capability is too low.

In the second case excessive current will heat up either the conductor in a coil or the dielectric in capacitor. One way to find out if there are any losses in the capacitor, resulting from large RF currents, is to measure or feel the temperature of the components in question (not with power applied!) after having stressed them with a solid carrier for a few minutes. This is a valid test for both coils and capacitors in a network. If excessive heating is apparent, consider using heavier-duty components. This procedure also applies to toroidal cores.

4.3. Stub Matching

Stub matching can be used to match resistive or complex impedances to a given transmission-line impedance. The STUB MATCHING software module, a part of the NEW LOW BAND SOFTWARE, allows you to calculate *the position* of the stub on the line and *the length of the stub*, and whether the stub must be open or shorted at the end. This method of matching a (complex) impedance to a line can replace an L network. The approach saves the two L-network components, but necessitates extra cable to make the stub. The stub may also be located at a point along the feed line that is difficult to reach. **Fig 6-11** shows the screen of the computer program where we are matching an impedance of 36.6 Ω to a 50-Ω feed line. Note that between the load and the stub the line is not flat, but once beyond the stub the line is now matched. The computer program gives line position and line length in electrical degrees. To convert this to cable length you must take into account the velocity factor of the feed line being used.

4.3.1. Replacing the stub with a discrete component.

Stub matching is often unattractive on the lower bands because of the lengths of cable required to make the stub. The module STUB MATCHING also displays the equivalent component value of the stub (in either µH or pF). You can replace the stub with an equivalent capacitor or inductor, which is

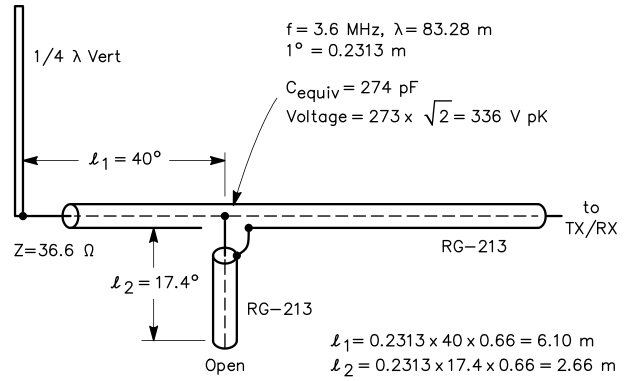
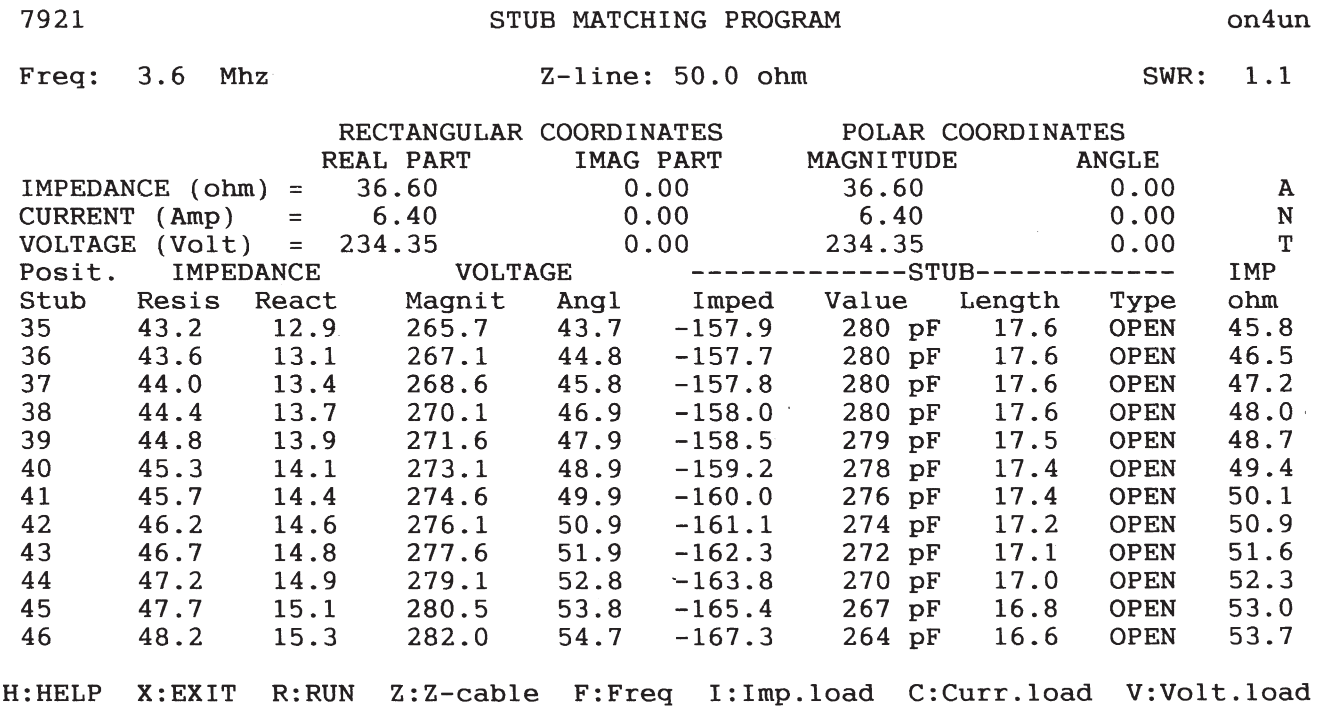


Fig 6-11—A 36.6-Ω resistive load is matched to a 50-Ω feed line using stub matching.



```
7921                       STUB MATCHING PROGRAM                     on4un

Freq:  3.6  Mhz                Z-line: 50.0 ohm                 SWR:  1.1

                       RECTANGULAR COORDINATES      POLAR COORDINATES
                      REAL PART      IMAG PART     MAGNITUDE       ANGLE
IMPEDANCE (ohm) =    36.60             0.00         36.60           0.00      A
CURRENT (Amp)   =     6.40             0.00          6.40           0.00      N
VOLTAGE (Volt)  =   234.35             0.00        234.35           0.00      T
Posit.   IMPEDANCE          VOLTAGE        -------------STUB------------    IMP
Stub    Resis   React     Magnit    Angl     Imped    Value    Length    Type    ohm
35      43.2    12.9      265.7     43.7    -157.9    280 pF    17.6     OPEN    45.8
36      43.6    13.1      267.1     44.8    -157.7    280 pF    17.6     OPEN    46.5
37      44.0    13.4      268.6     45.8    -157.8    280 pF    17.6     OPEN    47.2
38      44.4    13.7      270.1     46.9    -158.0    280 pF    17.6     OPEN    48.0
39      44.8    13.9      271.6     47.9    -158.5    279 pF    17.5     OPEN    48.7
40      45.3    14.1      273.1     48.9    -159.2    278 pF    17.4     OPEN    49.4
41      45.7    14.4      274.6     49.9    -160.0    276 pF    17.4     OPEN    50.1
42      46.2    14.6      276.1     50.9    -161.1    274 pF    17.2     OPEN    50.9
43      46.7    14.8      277.6     51.9    -162.3    272 pF    17.1     OPEN    51.6
44      47.2    14.9      279.1     52.8    -163.8    270 pF    17.0     OPEN    52.3
45      47.7    15.1      280.5     53.8    -165.4    267 pF    16.8     OPEN    53.0
46      48.2    15.3      282.0     54.7    -167.3    264 pF    16.6     OPEN    53.7

H:HELP  X:EXIT  R:RUN  Z:Z-cable  F:Freq  I:Imp.load  C:Curr.load  V:Volt.load
```

then connected in parallel with the feed line at the point where the stub would have been placed. The same program shows the voltage where the stub or discrete element is placed. To determine the voltage requirement for a parallel capacitor, you must know the voltage at the load.

Consider the following example: The load is 50 Ω (resistive), the line impedance is 75 Ω, and the power at the antenna is 1500 W. Therefore, the RMS voltage at the antenna is:

$$E = \sqrt{P \times R} = \sqrt{1500 \times 50} = 274 \text{ V}$$

Running the STUB MATCHING software module, we find that a 75-Ω impedance point is located at a distance of 39° from the load. See **Fig 6-12** for details of this example. The required 75-Ω stub length, open-circuited at the far end, to achieve this resistive impedance is 22.2° (equivalent to 230 pF for a design frequency of 3.6 MHz). The voltage at that point on the line is 334 V RMS (472 V peak). Note that the length of a stub will never be longer than $^1/_4$ wavelength (either open-circuited or short-circuited).

4.3.2. Matching with series-connected discrete components.

In stub matching in a 50-Ω system, we look on a line with SWR for a point where the impedance on the line, together with the impedance of the stub (in parallel) will produce a 50-Ω impedance. A variation consists of looking along the line for a point where the insertion of a series impedance will yield 50 Ω. At that point the impedance will look like 50 + *j* X Ω or 50 – *j* Y Ω. All we need to do is to put a capacitor or inductor in series with the cable at that point. A capacitor will have a reactance of X Ω or an inductor of Y Ω.

Example: Match a 50-Ω load to a 75-Ω line (same example as above). The software module IMPEDANCES, CURRENTS AND VOLTAGES ALONG FEEDLINES from the NEW LOW BAND SOFTWARE lists the impedance along the line in 1° increments, 2 starting at 1° from the load.

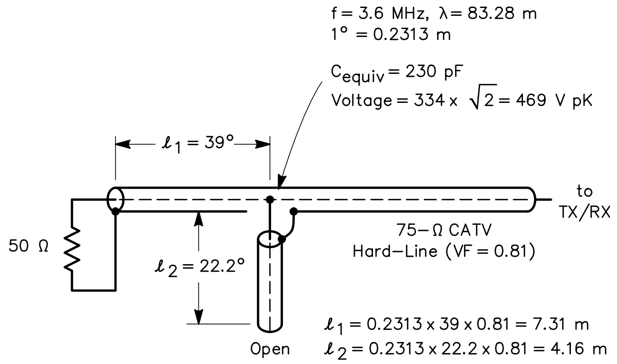
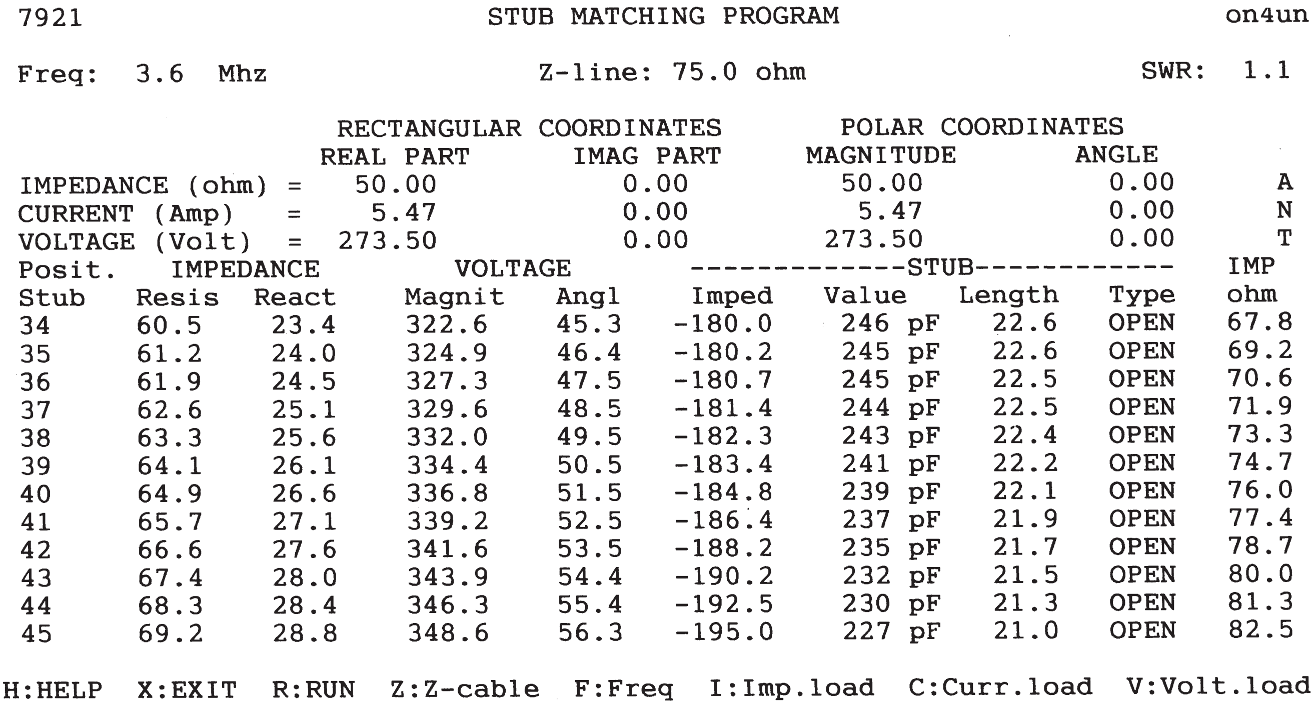


Fig 6-12—Example of how a simple stub can match a 50-Ω load to a 75-Ω transmission line. Note that between the load and the stub the SWR on the line is 1.5:1. Beyond the stub the SWR is 1:1.


```
7921                       STUB MATCHING PROGRAM                        on4un

Freq:  3.6  Mhz                  Z-line: 75.0 ohm                 SWR:  1.1

                    RECTANGULAR COORDINATES       POLAR COORDINATES
                   REAL PART       IMAG PART     MAGNITUDE        ANGLE
IMPEDANCE (ohm) =   50.00            0.00          50.00            0.00       A
CURRENT (Amp)   =    5.47            0.00           5.47            0.00       N
VOLTAGE (Volt)  =  273.50            0.00         273.50            0.00       T
Posit.   IMPEDANCE         VOLTAGE        -------------STUB------------    IMP
Stub     Resis   React    Magnit    Angl    Imped    Value    Length   Type   ohm
34       60.5     23.4    322.6     45.3    -180.0    246 pF    22.6   OPEN   67.8
35       61.2     24.0    324.9     46.4    -180.2    245 pF    22.6   OPEN   69.2
36       61.9     24.5    327.3     47.5    -180.7    245 pF    22.5   OPEN   70.6
37       62.6     25.1    329.6     48.5    -181.4    244 pF    22.5   OPEN   71.9
38       63.3     25.6    332.0     49.5    -182.3    243 pF    22.4   OPEN   73.3
39       64.1     26.1    334.4     50.5    -183.4    241 pF    22.2   OPEN   74.7
40       64.9     26.6    336.8     51.5    -184.8    239 pF    22.1   OPEN   76.0
41       65.7     27.1    339.2     52.5    -186.4    237 pF    21.9   OPEN   77.4
42       66.6     27.6    341.6     53.5    -188.2    235 pF    21.7   OPEN   78.7
43       67.4     28.0    343.9     54.4    -190.2    232 pF    21.5   OPEN   80.0
44       68.3     28.4    346.3     55.4    -192.5    230 pF    21.3   OPEN   81.3
45       69.2     28.8    348.6     56.3    -195.0    227 pF    21.0   OPEN   82.5

H:HELP  X:EXIT  R:RUN  Z:Z-cable  F:Freq  I:Imp.load  C:Curr.load  V:Volt.load
```

Somewhere along the line we will find an impedance where the real part is 75 Ω (see details in **Fig 6-13**). Note the distance from the load. In our example this is 51° from the 50-Ω load. The impedance at that point is $75.2 + j\,30.7$ Ω.

If we want to assess the current through the series element (which is especially important if the series element is a capacitor), we must enter actual values for either current or voltage at the load when running the program. Assuming an antenna power of 1500 W, the current at the antenna is:

$$I = \sqrt{\frac{P}{R}} = \sqrt{\frac{1500}{50}} = 5.47\ \text{A}$$

All we need to do now is connect an impedance of –30.7 Ω (capacitive reactance) in series with the line at that point. Also note that at this point the current is:

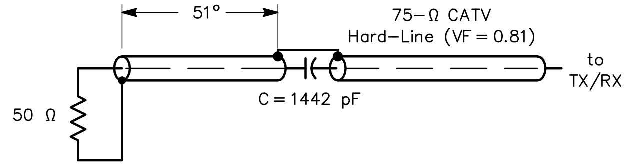
$$I = \sqrt{\frac{1500}{75.2}} = 4.46\ \text{A}$$

The software module SERIES IMPEDANCE NETWORK can be used to calculate the required component value. In this example, the required capacitor has a value of 1442 pF for a frequency of 3.6 MHz (see **Fig 6-14**). The required voltage rating (RMS) is calculated by multiplying the current through the capacitor times the capacitive reactance, which yields a value of E = I × Z = 4.46 × 30.7 = 136.9 V RMS = 193.6 V peak at 1500 W. As outlined above you need to take the peak value into consideration for a capacitor, and apply a safety factor of approximately two. The most important property of this capacitor is its current-handling capability, and we should use a capacitor that is rated approximately 10 A for the job.

In the case of a complex load impedance, the procedure is identical, but instead of entering the resistive load impedance (50 Ω in the above example), we must enter the complex impedance.

4.4. High-Impedance Matching Systems

Unbalanced high-impedance feed points, such as a half-



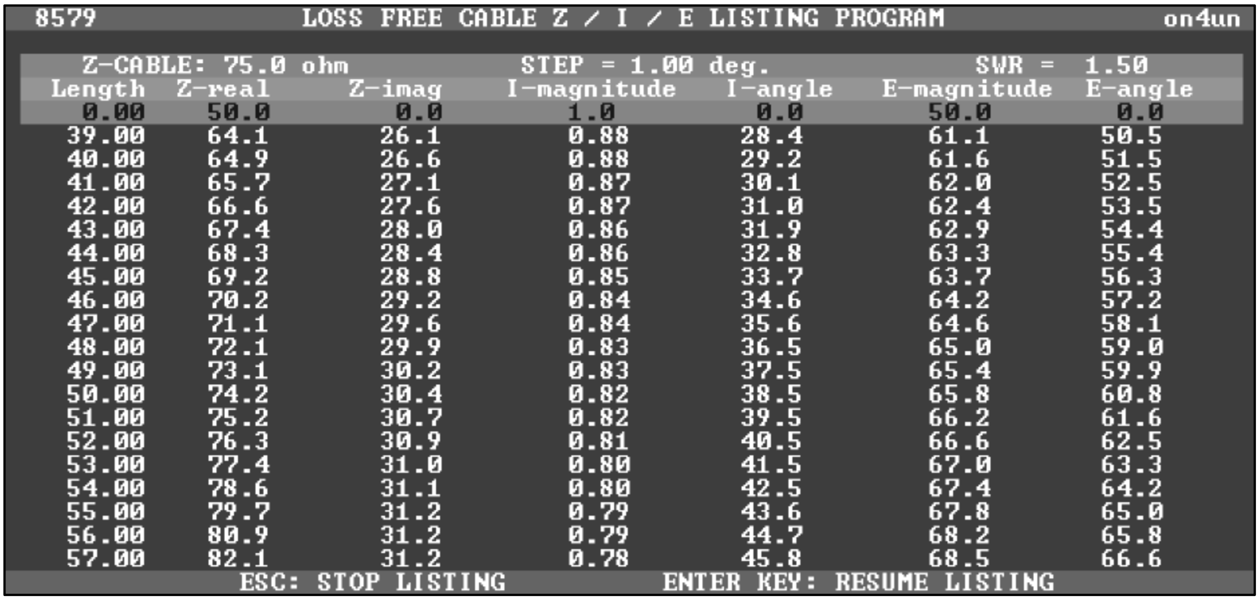
$C = \frac{10^6}{(2 \times \pi \times f \times X_c)} = 1442$ pF

$X_c = 30.7\ \Omega$

$F_d = 3.6,\ \lambda = 83.28$ m, $1° = 0.2313$ m

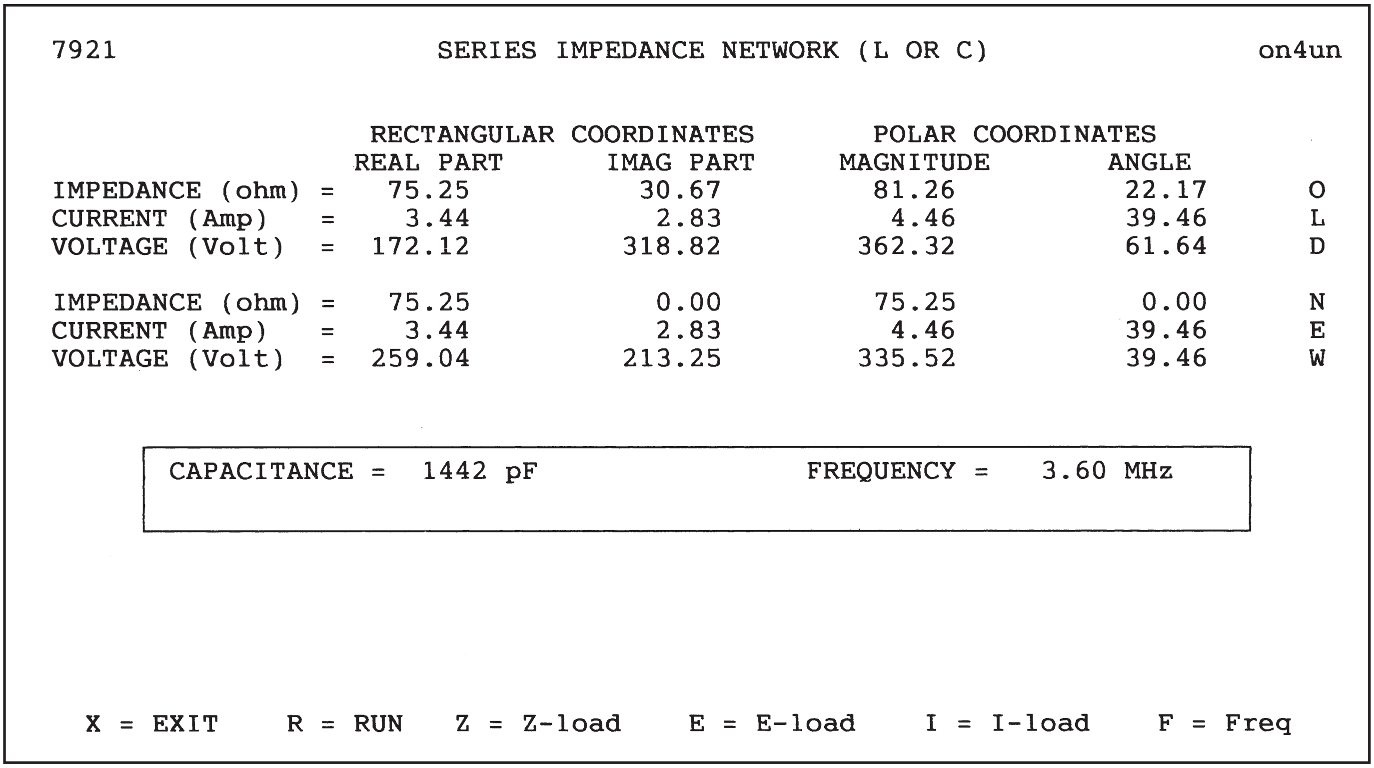
$\ell = 51 \times 0.2313 \times 0.81 = 9.55$ m

Fig 6-13—Example of how a series element can match a 50-Ω load to a 75-Ω transmission line. See text for details.



```
 8579                LOSS FREE CABLE Z / I / E LISTING PROGRAM                 on4un

   Z-CABLE: 75.0 ohm            STEP = 1.00 deg.               SWR =  1.50
  Length  Z-real      Z-imag    I-magnitude    I-angle   E-magnitude   E-angle
    0.00    50.0         0.0        1.0          0.0         50.0         0.0
   39.00    64.1        26.1       0.88         28.4         61.1        50.5
   40.00    64.9        26.6       0.88         29.2         61.6        51.5
   41.00    65.7        27.1       0.87         30.1         62.0        52.5
   42.00    66.6        27.6       0.87         31.0         62.4        53.5
   43.00    67.4        28.0       0.86         31.9         62.9        54.4
   44.00    68.3        28.4       0.86         32.8         63.3        55.4
   45.00    69.2        28.8       0.85         33.7         63.7        56.3
   46.00    70.2        29.2       0.84         34.6         64.2        57.2
   47.00    71.1        29.6       0.84         35.6         64.6        58.1
   48.00    72.1        29.9       0.83         36.5         65.0        59.0
   49.00    73.1        30.2       0.83         37.5         65.4        59.9
   50.00    74.2        30.4       0.82         38.5         65.8        60.8
   51.00    75.2        30.7       0.82         39.5         66.2        61.6
   52.00    76.3        30.9       0.81         40.5         66.6        62.5
   53.00    77.4        31.0       0.80         41.5         67.0        63.3
   54.00    78.6        31.1       0.80         42.5         67.4        64.2
   55.00    79.7        31.2       0.79         43.6         67.8        65.0
   56.00    80.9        31.2       0.79         44.7         68.2        65.8
   57.00    82.1        31.2       0.78         45.8         68.5        66.6
              ESC: STOP LISTING              ENTER KEY: RESUME LISTING
```



```
7921                  SERIES IMPEDANCE NETWORK (L OR C)                on4un


                    RECTANGULAR COORDINATES       POLAR COORDINATES
                   REAL PART       IMAG PART     MAGNITUDE        ANGLE
IMPEDANCE (ohm) =    75.25           30.67          81.26          22.17      O
CURRENT (Amp)   =     3.44            2.83           4.46          39.46      L
VOLTAGE (Volt)  =   172.12          318.82         362.32          61.64      D

IMPEDANCE (ohm) =    75.25            0.00          75.25           0.00      N
CURRENT (Amp)   =     3.44            2.83           4.46          39.46      E
VOLTAGE (Volt)  =   259.04          213.25         335.52          39.46      W


      CAPACITANCE =  1442 pF                 FREQUENCY =   3.60 MHz




  X = EXIT    R = RUN   Z = Z-load    E = E-load    I = I-load    F = Freq
```

Fig 6-14—Calculations of the value of the series element required to tune out the reactance of the load 75.248 + *j* 30.668 Ω. See text for details.

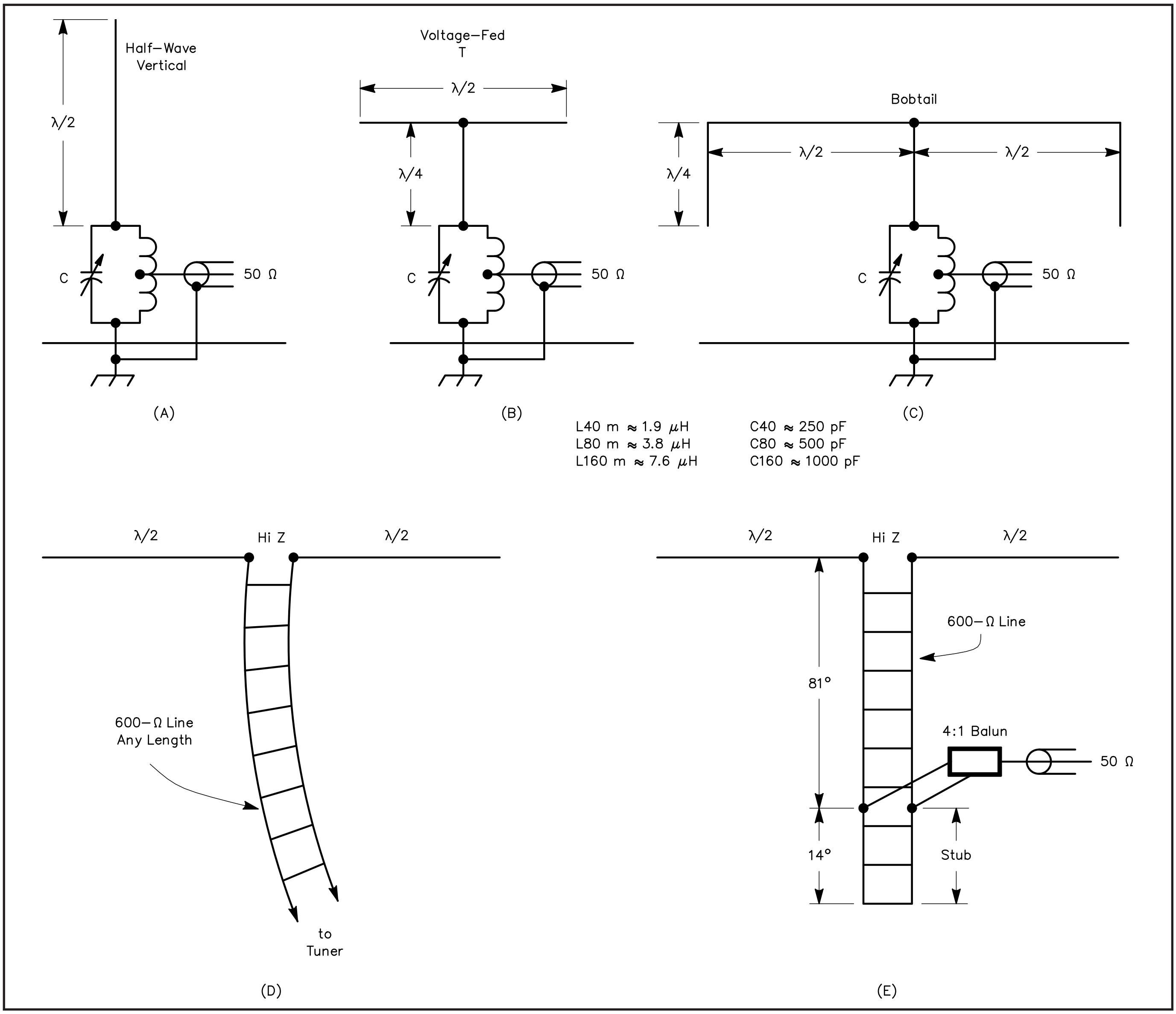


Fig 6-15—Recommended feed methods for high-impedance (2000 to 5000-Ω) feed points. Asymmetrical feed points can be fed via a tuned circuit. The symmetrical feed points can be fed via an open-wire line to a tuner, or via a stub-matching arrangement to a 4:1 (200 to 50-Ω) balun and a 50-Ω feed line.

wave vertical fed against ground, a voltage-fed T-antenna, the Bobtail antenna, etc, can best be fed using a parallel-tuned circuit on which the 50-Ω cable is tapped for the lowest SWR value. See **Fig 6-15**. Symmetrical high-impedance feed points, such as for two half-wave (collinear) dipoles in phase, the bi-square, etc, can be fed directly with a 600-Ω open-wire feeder into a quality antenna tuner (see Fig 6-15D).

Another attractive solution is to use a 600-Ω line and stub matching, as shown in Fig 6-15E. Assume the feed-point impedance is 5000 Ω. Running the STUB MATCHING software module, we find that a 200-Ω impedance point is located at a distance of 81° from the load. The required 600-Ω stub to be connected in parallel at that point is 14° long (X = 154 Ω). The impedance is now a balanced 200 Ω. Using a 4:1 balun, this point can now be connected to a 50-Ω feed line.

Let me sum up some of the advantages and disadvantages of both feed systems.

Tuned open-wire feeders:

- Fewest components, which means the least chance of something going wrong.
- Least likely loss.
- Very flexible (can be tuned from the shack).
- Open-wire lines are mechanically less attractive.

Stub matching plus balun and coax line:

- Coaxial cables are much easier to handle.

4.5. Wideband Transformers

4.5.1. Low-impedance wideband transformers

Broadband transformers exist in two varieties: The classic autotransfomer and the transmission-line transformer. The first is a variant of the Variac, a genuine autotransformer. The second makes use of transmission-line principles. What they have in common is that they are often wound on toroidal cores. It is beyond the scope of this chapter to go into details on this subject. More details can be found in Chapter 7 (Special Receiving Antennas), where such broadband transformers are commonly used to feed receiving antennas such as Beverages. *Transmission Line Transformers* by J. Sevick, W2FMI, is an excellent textbook on the subject of transmission-line transformers. It covers all you might need in the field of wide-band RF transformers.

4.5.2. High-impedance wideband transformer

If the antenna load impedance is both high and almost perfectly resistive (such as for a half wavelength vertical fed at the bottom), you may also use a broadband transformer such as is used in transistor power amplifier output stages. **Fig 6-16** shows the transformer design used by F. Collins, W1FC. Two turns of AWG 12 Teflon-insulated wire are fed through two stacks of 15$^{1}/_{2}$-inch (OD) powdered-iron toroidal cores (Amidon T50-2) as the primary low impedance winding. The secondary consists of 8 turns. The turns ratio is 4:1, the impedance ratio 16:1.

The efficiency of the transformer can be checked by terminating it with a high-power 800 Ω dummy load (or with the antenna, if no suitable load is available), and running full power to the transformer for a couple of minutes. Start with low power. Better safe than sorry. If there are signs of heating in the cores, add more cores to the stack. Such a transformer has the advantage of introducing no phase shift between input and output, and therefore can easily be incorporated into phased arrays.

5. 75-Ω CABLES IN 50-Ω SYSTEMS

Lengths of 75-Ω hardline coaxial cable can often be obtained from local TV cable companies. If very long runs to low-band antennas are involved, the low attenuation of hardline is an attractive asset. If you are concerned with providing a 50-Ω impedance, you need to use a transformer system. Transformers using toroidal cores (so called *ununs*) have been described (Ref 1307, 1517, 1518, 1521, 1522, 1523, 1524, 1525, 1526, 1527, 1528, 1829, 1830).

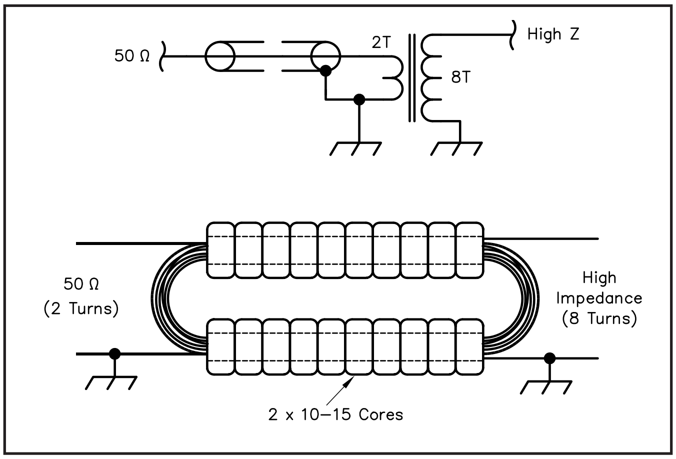


Fig 6-16—A wideband high-power transformer for large transformation ratios, such as for feeding a half-wave vertical at its base (600 to 10,000 Ω), uses two stacks of 10 to 15 half-inch-OD powdered-iron cores (eg, Amidon T502-2). The primary consists of 2 turns and the secondary has 8 turns (for a 50 to 800-Ω ratio). See text for details.

Ununs (Unbalanced to Unbalanced transformers) are really *autotransformers* and have been described for a wide range of impedance ratios. One application is as a matching system for a short, loaded vertical. If the short, loaded vertical is used over a good ground radial system, its impedance will be lower than 50 Ω. Ununs have been described that will match 25 Ω to 50 Ω, or 37.5 Ω to 50 Ω.

Ununs can also be used in array-matching systems to provide proper drive for various elements (see Chapter 7 and 11). Transformer systems can also be made using only coaxial cable, without any discrete components. If 60-Ω coaxial cable is available (as in many European countries), a quarter-wave transformer will readily transform 75 Ω to 50 Ω at the end of the hardline.

Carroll, K1XX, described the non-synchronous matching transformer and compared it to a stub-matching system (Ref 1318). While the toroidal transformer is broadbanded, the stub and non-synchronous transformers are single-band devices.

Compared to quarter-wave transformers, which need coaxial cable having an impedance equal to the geometric mean of the two impedances to be matched, the non-synchronous transformer requires only cables of the same impedances as the values to be matched (see **Fig 6-17**).

On the low bands (and even up to 30 MHz) the losses caused by using 75-Ω hard line in a 50-Ω system (50-Ω

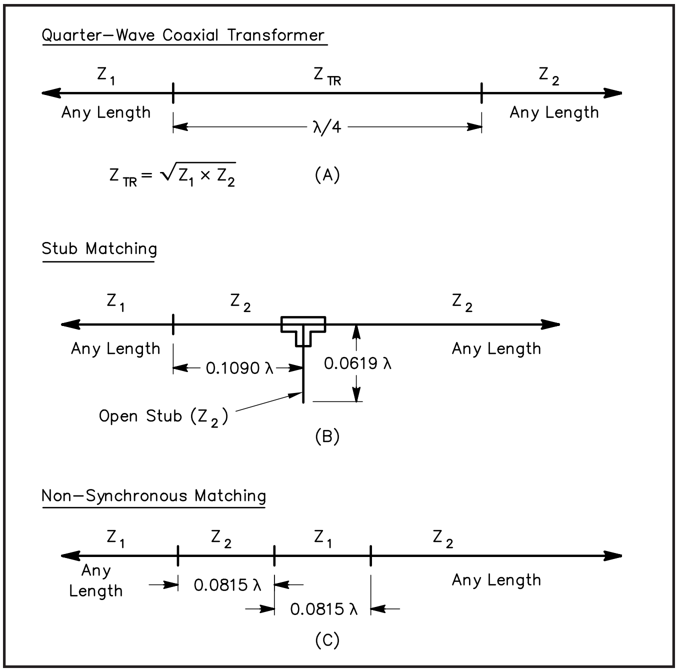


Fig 6-17—Methods of matching 75-Ω cables in 50-Ω systems. The quarter-wave transformer at A requires a cable having an impedance that is the geometric mean of the values being matched. The stub matching system at B and the non-synchronous matching system at C require only cables of the impedances being matched. The stub can be replaced with a capacitor or an inductor. All these matching systems are frequency sensitive.
Z_{TR}—60-Ω line.
Z_1—50-Ω line (or load).
Z_0—75-Ω line.

antenna and 50-Ω transceiver/amplifier) are generally negligible. A real problem is that 75-Ω feed line itself works as a transformer, and even when terminated with a perfect 50-Ω load, will show 100 Ω at the end of the line if the line is an odd multiple of quarter-waves long. This may cause problems for your linear amplifier. There is an easy solution to that problem, which is using $^1/_2$ -λ (of multiples of) lines. If you use a multiband antenna, make sure that the line is a number of half waves on all the frequencies used. For an antenna that works on 80 and 160 meters, make the coaxial line a multiple of half waves on 160 meters. Assuming a 75-Ω hardline with a Velocity Factor of 0.8, then the line should be 0.8 × (300/1.83)/2 = 65.6 meters, or any multiple thereof. You can trim the length by terminating the line with a 50-Ω load, and adjusting the length for minimum SWR on the highest frequency (in the above case, 3.66 MHz). Don't fool yourself though, in this case the SWR on the 75-Ω line is still 1.5:1, but the consequences are minimal so far as additional losses are concerned (because we use a feed line with intrinsic low losses) and are compensated for as far as the transformation effect is concerned, by using $^1/_2$ -λ lengths. To be fully correct the transformation is not a perfect 1:1 transformation with a real line, but close (1:1 is only with a lossless line).

6. THE NEED FOR LOW SWR

In the past many radio amateurs did not understand SWR. Unfortunately, many still don't understand SWR. Reasons for low SWR are often false and SWR is often cited as the single parameter telling us all about the performance of an antenna.

Maxwell, W2DU, published a series of articles on the subject of transmission lines. They are excellent reading material for anyone who has more than just a casual interest in antennas and transmission lines (Refs 1308-1311, 1325-1330 and 1332). These articles have been combined and, with new information added, published as a book, *Reflections II: Transmission Lines and Antennas* (WorldRadio Books). J. Battle, N4OE, wrote a very instructive article "What is your Real Standing Wave Ratio" (Ref 1319), treating in detail the influence of line loss on the SWR (difference between apparent SWR and real SWR).

Everyone has heard comments like: "My antenna really gets out because the SWR does not rise above 1.5:1 at the band edges." Low SWR is no indication at all of good antenna per-formance! It is often the contrary. The "antenna" with the best SWR is a quality dummy load. Antennas using dummy resistors as part of loading devices come next (Ref 663).The TTFD (Tilted Terminated Folded Dipole) and the B&W broadband folded dipole model BWD-18-30 are such examples. You should conclude from this that low SWR is no guarantee of radiation efficiency. The reason that SWR has been wrongly used as an important evaluation criterion for antennas is that it can be easily measured, while important parameters such as efficiency and radiation characteristics are more difficult to measure.

Antennas with lossy loading devices, poor earth systems, high-resistance conductors and the like, will show flat SWR curves. Electrically short antennas should always have narrow bandwidths. If they do not, it means that they are inefficient. In Chapter 5, Section 2.8. I explain further what are valid reasons for a low SWR.

7. THE BALUN

Balun is a term coming from the words *balanced* and *unbalanced*. It is a device we must insert between a symmetrical feed line (such as an open-wire feeder) and an asymmetric load (such as a ground-mounted vertical monopole) or an asymmetric feed line (for example, coax) and a symmetric load (such as a center-fed half-wave dipole). If we feed a balanced feed point with a coaxial feed line, currents will flow on both the outside of the coaxial braid (where we don't want them) and on the inside (where we do want them). Currents on the outside will cause radiation from the line.

Unbalanced loads can be recognized by the fact that one of the terminals is at ground potential. Examples: the base of a monopole vertical (the feed point of any antenna fed against real ground), the feed point of an antenna fed against radials (that's an artificial ground), the terminals of a gamma match or omega match, etc.

Balanced loads are presented by dipoles, sloping dipoles, delta loops fed at a corner, quad loops, collinear antennas, bi-square, cubical quad antennas, split-element Yagis, the feed points of a T match, a delta match, etc.

Many years ago I had an inverted-V dipole on my 25-meter tower and the feed line was just hanging unsupported alongside the tower, swinging nicely in the wind. When I took down the antenna some time later, I noticed that in several places where the coax had touched the tower in the breeze holes were burned through the outer jacket of the RG-213. Further, water had penetrated the coax, rendering it worthless. The phenomena of burning holes illustrates that currents (thus also voltages) are present on the coax if no balun is used. Such currents also create radiated fields, and fields from the feed line upset the field pattern from the antenna.

How much radiation there is from such a feed line depends on several factors, the main one being its length. In most cases the feed-line outer conductor will be (RF) grounded at the station. Assume the feed line is an odd number of quarter-waves long. In that case the impedance of the long wire (which is the outer shield of the feed line) will be very high at the antenna feed point, and hence the currents will be minimal, resulting in low unwanted radiation from it. If, however, the feed line is a number of half-waves long (and the outer shield grounded at the end), then we have a low-impedance point at the antenna end, consequently a large current can flow. In actual practice, unless the feed lines are a multiple of half-waves long, the impedance of the "long-wire" will be reactive, which in parallel with the resistive and low impedance of the real-antenna (at resonance) will result in a relatively small currents flowing on the outer shield of the coaxial feed line. The best answer is "take no chances" and to use a current balun, especially if you use (multiple of) half-wave long feed lines (see also Section 5).

Baluns have been described in abundance in the amateur literature (Refs 1504, 1505, 1502, 1503, 1515, 1519, and 1520 through 1530). In the simplest form a balun consists of a number of turns of coaxial cable wound into a close coil. In order to present enough reactance at the low-band frequencies, a fairly large coil is required.

Another approach was introduced by Maxwell, W2DU. This involves slipping a stack of high-permeability ferrite cores over the outer shield of the coaxial cable at the load terminals. In order to reduce the required ID of the toroids or beads, you can use a short piece of Teflon-insulated coaxial cable such as RG-141, RG-142 or RG-303. These have ODs of approximately 5 mm. A balun covering 1.8 to 30 MHz uses

50 no. 73 beads (Amidon no. FB-73-2401 or Fair-Rite no. 2673002401-0) to cover a length of approximately 30 cm (12 inches) of coaxial cable.

The stack of beads on the outer shield of the coax creates an impedance of one to several kΩ, effectively suppressing any current from flowing down on the feed line. Amidon beads type 43-1024 can be used on RG-213 cable. Ten to thirty will be required, depending on the lowest operating frequency. In general we can state that a choking effect of at least 1 kΩ is required for this *common-mode current arrestor* to be effective. This type of balun transformer is a true transmission line just like the beaded balun. But it can gain a much higher choking action from the transformation of the N turns power.

The two above approaches are called *current* or often *choke* baluns. They are called current-type baluns because even when the balun is terminated in unequal resistances, it will still force equal, opposite-in-phase currents into each resistance.

Current baluns made according to this principle are commercially available from Antennas Etc, PO Box 4215, Andover MA 01810; The Radio Works Inc, Box 6159, Portsmouth VA 23703. The Wireman, Inc, 261 Pittman Road, Landrum SC 29356 (**www.thewireman.com/**). This last supplier also sells a kit consisting of a length of Teflon coax (RG-141 or RG-303) plus 50 ferrite beads to be slipped over the Teflon coax at a very attractive price.

The traditional balun (for example, the well-known W6TC balun) is a *voltage balun*, which produces equal, opposite-phase voltages into the two resistances. With the two resistances we mean the two "halves" of the load, which are "symmetrical" with respect to ground (not necessarily in value!). If the load is perfect in common-mode balance and of a controlled impedance, a voltage-type balun is as good as a choke-type balun. But the choke-type balun is almost always much better in the real world.

The toroidal-core type voltage and current baluns are covered in *Transmission Line Transformers* by J. Sevick, W2FMI. **Fig 6-18** shows construction details for a the W6TC voltage-type balun designed for best performance on 160, 80 and 40 meters, as well as a current-type balun.

I have stated on several occasions that if the reading of an SWR meter changes with its position on the line (small changes in position, not affected by attenuation) this means the SWR meter is not functioning properly. The only other possible reason for a different SWR reading with position on the line is the presence of RF currents on the outside of the coax. For that reason it is common practice in professional SWR-measuring setups to put a number of ferrite cores on the coaxial cable on both sides of the measuring equipment.

We've touched upon three good reasons for using a balun with a symmetrical feed point:

- We don't want to distort the radiation pattern of the antenna.
- We don't want to burn holes in our coax.
- We want our SWR readings to be correct.

Are there good reasons to put a so-called current-balun on a feed-line attached to a asymmetrical feed point? Yes, there are. Assume a vertical antenna using two elevated-radials. The feed point is an asymmetric one, but the ends of the two radials are *not* the real ground, which usually is some distance below it. If we do not connect a current balun at the antenna feed point, antenna-return currents will flow on the outside of the coaxial feed line in addition to flowing in the elevated radials, which is not what we want with elevated radials (see also Chapter 9).

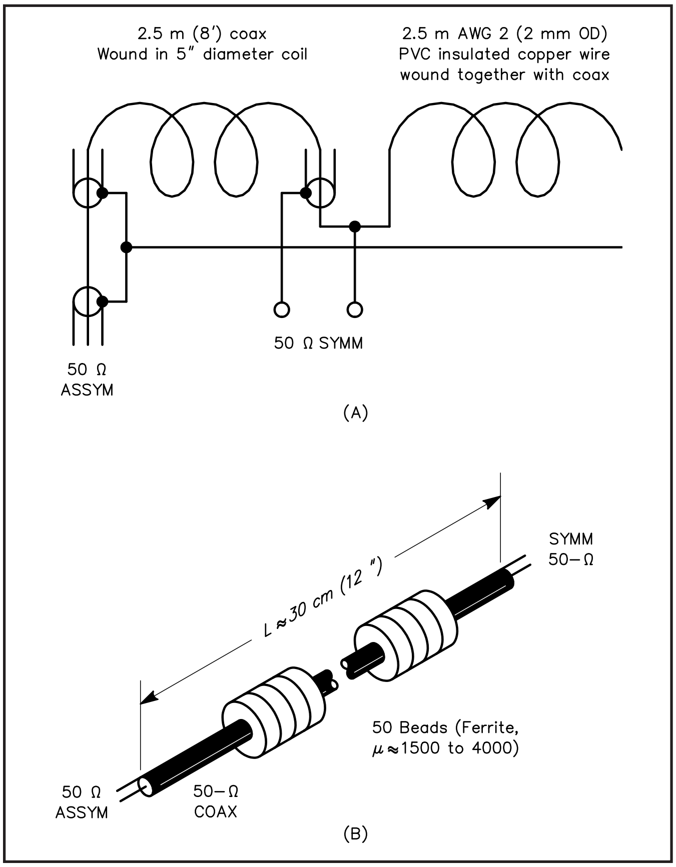


Fig 6-18—At A, details of a W6TC voltage-type balun for 160-40 meters, and at B, a current transformer for 160-10 meters. See text for details.

Is it harmful to put a current balun on all the coaxial antenna feed lines for all your antennas? Not at all. If the feed point is symmetric, there will be no current flowing and the beads will do no harm. As a matter of fact they may help reduce unwanted coupling from antennas into feed lines of other nearby antennas. A good thing is to use an RF-current meter (see Chapter 11) and check currents on the outside of any feed line while transmitting on any nearby (within $^{1}/_{2}$ wavelength) antenna. These current should be zero; if not, they act as parasitically excited elements, which will influence the radiation pattern of your antenna.

How many ferrite beads (toroidal cores) are required on a coaxial cable to make a good current balun? From a choking impedance point of view you need at least 1 kΩ on the lowest operating frequency. The ferrite cores are not lossless, and depending on the mix used, they can be quite lossy. Where no power is involved (such as for solving EMC problems) this is never a problem. The total loss of the RF choke is then made up by the impedance of the inductance in series with the loss resistance. In other words, you have a low Q-coil. Where we use such ferrite cores to choke off potentially high RF currents (this is mostly the case with current baluns on transmitter feed lines), the resistive losses of the ferrites may actually heat those up to the point where they either become totally ineffective (permanently destroyed) or actually crack or explode! This problem can be avoided by using ferrite material that is not very lossy on the transmit frequency. In actual practice you can successfully combine two sorts of ferrite cores in a current choke balun: low resistive (high Q) cores at the "hot side" of the balun and lower-Q beads at the "cold side). In practice the touch-and-feel method is an adequate test method. First run reduced power. If some of the cores get warm at 100 W, chances are you will destroy them with a kW.

8. CONNECTORS

A good coaxial cable connector, such as a PL-259 connector, has a loss of less than 0.01 dB, even at 30 MHz, and typically 0.005 dB or less on the low bands. This means that for 1 KW of power you will have a heat loss of about 1 W per connector. Given the mass of a connector, and the heat-dissipating capacity of the cable, this will produce a hardly noticeable temperature increase. If you feel a connector getting hot (with "reasonable" power) on the low bands, then there is something wrong with that connector. You needn't avoid connectors for their high intrinsic losses, as claimed by some.

But when using connectors make sure they are well installed, and properly waterproofed. Despite what some may claim, N-connectors will easily take 5 kW on the Low bands, and over 2 kW on 30 MHz. N-connectors are intrinsically waterproof and the newer models are extremely easy to assemble (much faster than a PL-259). A PL-259 connector is not a constant-impedance connector, but that is not relevant on the low bands. It is, however, a connector that is difficult to waterproof without external means. I always use a generous amount of medical-grade petroleum jelly (Vaseline) inside the connector to keep moisture out. Some cheaper coax, as well as semi-air-insulated coax, may see the inner conductor retract or protrude after time. Such coaxial cables are best used with PL-259 connectors, where you can mechanically anchor the inner conductor in the connector by soldering. In an N-connector, the retracting inner conductor sometimes will retract the connector pin to the point of breaking the contact.

9. BROADBAND MATCHING

A steep SWR curve is due to the rapid change in reactance in the antenna feed-point impedance as the frequency is moved away from the resonant frequency. There are a few ways to try to broadband an antenna:

- Employ elements in the antenna that counteract the effect of the rapid change in reactance. The so-called "Double Bazooka" dipole is a well-known (and controversial) example. This solution is dealt with in more detail in the chapter on dipoles.
- Instead of using a simple L network, use a multiple-pole matching network that can flatten the SWR curve.

The second solution is covered in great detail in *Antenna Impedance Matching*, by W. N. Caron, published by the ARRL. *ANTMAT* is a computer program described in technical Document 1148 (Sep 1987) of the NOSC (Naval Ocean Systems Center). The document describing the matching methodology as well as the software is called "The Design of Impedance Matching Networks for Broadband Antennas." The computer program assists in designing matching networks to match antennas (such as small whip antennas) over a wide frequency range.