Chapter 20

SWR with Multiband and Non-resonant Antennas

Sec 20.1 Introduction

In Chapter 9, I departed from the study of impedance matching from the viewpoint of wave reflections, and began an in-depth examination of matching directly from the viewpoint of impedance. During that examination I covered several pertinent subject areas, all of which have a direct bearing on matching antenna terminal impedance to the transceiver.

I began with the assumption that the conventional setup included a transceiver, an SWR indicator, and a feed line running directly to the antenna. Subsequent discussion showed that flexibility in operating bandwidth is vastly improved when the matching capability of the pi-network tank circuit in the final amplifier is extended by the addition of an external matching unit — the antenna tuner, or transmatch.

Sec 20.2 Multi-band Dipoles

So far I have discussed only simple dipoles fed with coaxial transmission line. With the exception of 15-meter third-harmonic operation on a 40-meter dipole, the simple coax-fed dipole is limited to single-band operation, because the excessive antenna to feed-line mismatch precludes its use on even-harmonic frequencies related to the fundamental frequency for which it is designed. However, the simple dipole can be modified in different ways to extend its performance to multi-band operation. Let us now examine those different ways.

Sec 20.2.1 Trap Dipoles

One method of achieving multi-band operation from a dipole is to insert frequency-selective traps in the antenna. Traps allow operation at the lowest fundamental frequency for which the total electrical length of the dipole is λ/2, but which selectively disconnects dipole portions extending beyond traps designed to present a high impedance in series with the dipole at frequencies higher than the fundamental. Hence, the effective electrical length of the dipole is automatically shortened to λ/2 on the higher-frequency bands, so that it maintains an acceptable match to a coaxial feed line.

But unfortunately, there is an undesirable penalty to be paid when using the trap method of multi-band operation. The penalty is that the operational bandwidth on all the bands on which the trap dipole operates is far narrower than that of separate simple dipoles cut to λ/2 for each band. In other words, the SWR rises much more rapidly with a trap dipole than with the simple dipole, as the operating frequency is moved away from the resonant frequency of λ/2 section currently in use. Evidence of this sharp rise in SWR is shown in Figs 20-1 to 20-3, and in Tables 20-1 to 20-5, from which data the Figs were plotted. These show antenna-termi-

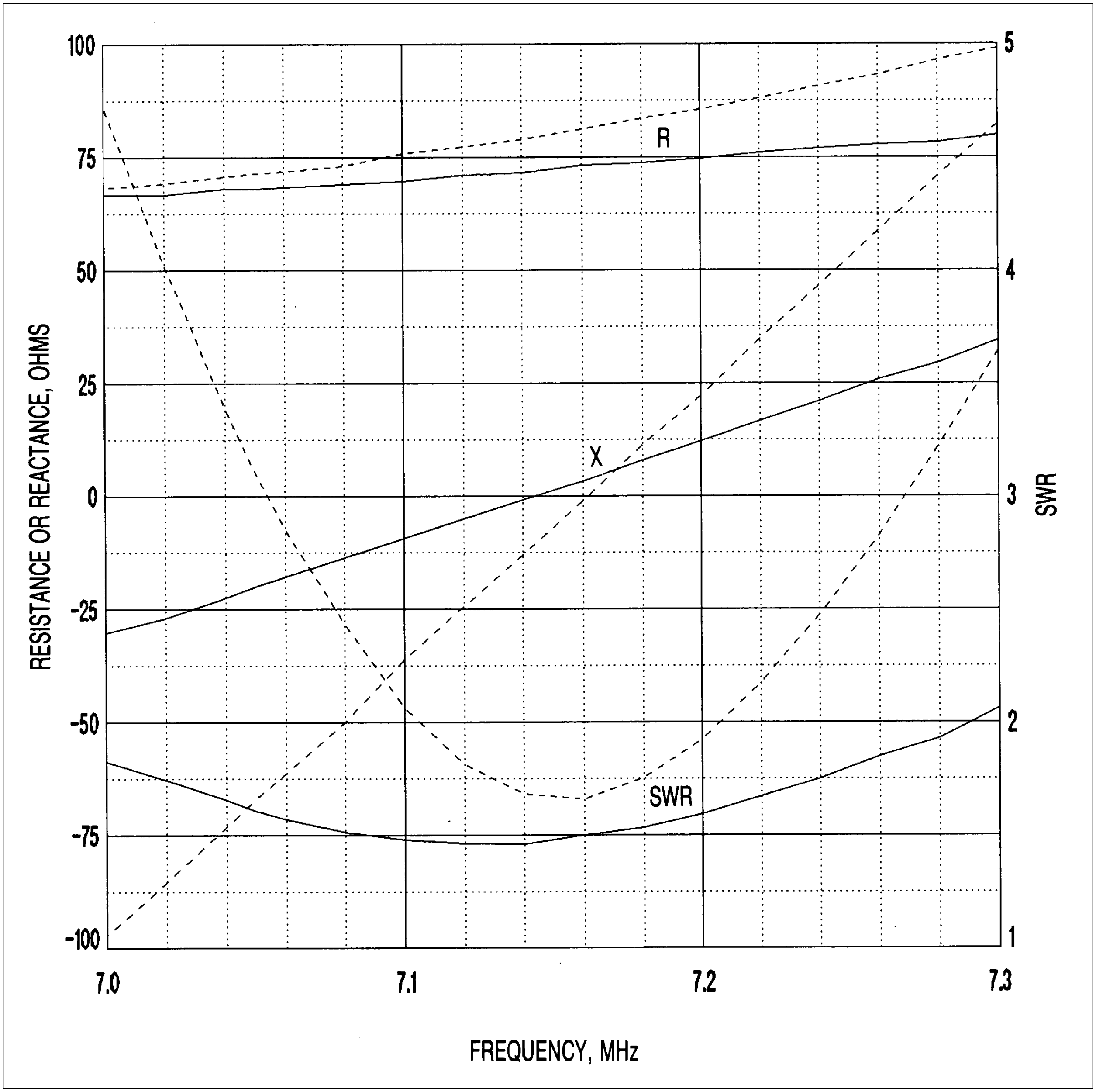

Fig 20-1 — Measured feed-point resistance R, reactance X, and SWR versus frequency of 40-meter dipoles at a height of 40 feet. The solid lines show data for a 66-ft, 2-in. radiator with no traps (data from Table 20-1). The broken lines show data for the same antenna but with 40-meter traps and 21-ft 5-in. extensions added at each end to make the antenna usable on 80 meters (data from Table 20-2). ***(Computer-generated plot courtesy of Rick Maxwell, WB4GNR)***

nal resistance, reactance, and SWR data measured with professional, precision laboratory equipment including a General Radio 1606-A RF bridge. The tables also include the corresponding reflection coefficient data, appearing in columns ρ_{IN} and ρ_L. A more detailed explanation of trap operation may be found in *Ref 71, p 7-8.*

Sec 20.2.2 Stagger-Tuned Dipoles

There is a second method of obtaining multi-band dipole operation that does not have the undesirable bandwidth limitation of the trap dipole. This method uses multiple dipoles fed in parallel from the

Table 20-1 — Measured Antenna Impedance Data Transformed Through Calibrated Feed Line

Measurement data: Z40 (no traps); see Fig 20-1. 66-ft 2-in. 40-meter dipole, height 40 ft, resonant frequency 7.1439 MHz, calibrated RG-214 plus W2DU HF balun, RF bridge General Radio 1606-A, receiver Kenwood TS-530S, signal generator Boonton 250A RX meter.
Feed line calibration:
Line length in degrees/MHz, PHI = 23.7
Line attenuation in dB/√MHz , A = 0.082
Line impedance, Z_C = 49 ohms

Freq	R_{IN}	X_{IN}	ρ_{IN}	SWR_{IN}	ρ_L	SWR_L	R_L	X_L
7.000	83.00	–14.500	0.2783	1.77	0.2926	1.827	66.67	–30.19
7.020	80.00	–12.536	0.2580	1.70	0.2712	1.744	66.61	–26.96
7.040	77.50	–8.376	0.2343	1.61	0.2463	1.654	67.96	–22.38
7.050	75.80	–6.667	0.2210	1.57	0.2323	1.605	68.01	–19.98
7.060	74.50	–4.958	0.2102	1.53	0.2210	1.567	68.27	–17.77
7.080	72.50	–1.624	0.1939	1.48	0.2038	1.512	69.04	–13.60
7.100	71.00	0.999	0.1835	1.45	0.1930	1.478	69.6	–10.15
7.120	69.50	5.281	0.1785	1.43	0.1877	1.462	70.95	–5.09
7.140	68.00	8.473	0.1773	1.43	0.1865	1.459	71.45	– .81
7.145	68.00	9.517	0.1810	1.44	0.1904	1.470	72.04	0.31
7.150	68.00	10.499	0.1848	1.45	0.1944	1.483	72.59	1.38
7.155	68.00	11.321	0.1882	1.46	0.1979	1.493	73.05	2.31
7.160	67.70	12.011	0.1894	1.47	0.1993	1.498	73.12	3.29
7.180	66.50	15.390	0.2000	1.50	0.2104	1.533	73.62	7.88
7.200	66.00	18.750	0.2172	1.55	0.2285	1.592	74.63	12.20
7.220	65.80	22.299	0.2387	1.63	0.2512	1.671	75.88	16.70
7.240	65.70	25.553	0.2598	1.70	0.2733	1.752	76.90	20.94
7.250	65.50	27.586	0.2729	1.75	0.2872	1.806	77.35	23.64
7.260	65.50	29.201	0.2838	1.79	0.2987	1.852	77.79	25.78
7.280	65.50	31.868	0.3019	1.87	0.3177	1.931	78.26	29.43
7.300	66.10	35.890	0.3297	1.98	0.3470	2.063	79.83	34.52

same feed line, and is called stagger tuning. The length of each separate dipole is $\lambda/2$ for each band. Hence, each dipole presents a good impedance match to the feed line on the band for which it is intended and a poor match on all the others. It is an effective system because none of the dipoles takes power from the feed line except the one that is $\lambda/2$ at the operating frequency, and thus it is the only one matched to the feed line at that frequency.

As an example, consider a two-dipole arrangement with one dipole cut to $\lambda/2$ on 80 meters and the other cut for 40 meters. With this arrangement, $\lambda/2$ dipole bandwidth is obtained on both 80 and 40, and in addition, the 40-meter dipole is also a center-fed $3\lambda/2$ radiator on 15 meters, which also presents a good match to coaxial feed lines. Here is how the frequency selection occurs. On 80 meters, the 80-meter dipole behaves in the conventional manner, but the 40-meter dipole is inactive because its terminal impedance at 80 meters is approximately $14 - j1300$ ohms. This impedance results in a mismatch of well over 2400:1 on 50-ohm line, assuring its inactivity. On 40 meters, the 40-meter dipole also behaves in the conventional manner, but the 80-meter dipole presents a terminal impedance of approximately 5000 ohms to the feed line at 40 meters, for a mismatch of 100:1. Consequently, this mismatch is also sufficiently

Table 20-2 — Measured Antenna Impedance Data Transformed Through Calibrated Feed Line

Measurement data: Z40 with 40-meter traps; see Fig 20-1. 66-ft 2-in. 40-meter dipole, height 40 ft, KW-40 traps (res. 7.150 and 7.160 MHz), 21-ft 5-in. extensions, calibrated RG-214 plus W2DU balun, RF bridge General Radio 1606-A, receiver Kenwood TS-530S, signal generator Boonton 250A RX meter.

Feed line calibration:
Line length in degrees/MHz, PHI = 23.7
Line attenuation in dB/√MHZ, A = 0.082
Line impedance, Z_C = 49 ohms

Freq	R_{IN}	X_{IN}	ρ_{IN}	SWR_{IN}	ρ_L	SWR_L	R_L	X_L
7.000	180.00	–68.714	0.6187	4.25	0.6504	4.721	68.18	–97.11
7.020	153.00	–61.396	0.5720	3.67	0.6014	4.017	69.11	–85.27
7.040	132.00	–50.710	0.5175	3.14	0.5440	3.386	70.64	–73.16
7.050	123.00	–45.10	0.4874	2.90	0.5124	3.102	71.27	–66.92
7.060	111.60	–39.518	0.4476	2.62	0.4706	2.778	70.37	–58.89
7.080	103.00	–29.520	0.3975	2.32	0.4179	2.436	72.96	–49.52
7.100	93.20	–16.620	0.3298	1.98	0.3469	2.062	75.73	–36.27
7.120	85.50	–6.461	0.2753	1.76	0.2895	1.815	77.22	–24.25
7.140	80.00	2.661	0.2411	1.64	0.2536	1.680	78.85	–13.09
7.145	79.00	5.178	0.2376	1.62	0.2499	1.666	79.60	–10.16
7.150	78.00	7.203	0.2349	1.61	0.2471	1.656	80.02	–7.59
7.155	77.00	9.790	0.2347	1.61	0.2469	1.656	80.73	–4.45
7.160	75.70	12.430	0.2350	1.61	0.2472	1.657	81.16	–1.00
7.180	72.40	22.006	0.2604	1.70	0.2739	1.754	83.63	11.39
7.200	70.00	28.333	0.2883	1.81	0.3033	1.871	84.43	20.53
7.220	68.30	38.920	0.3515	2.08	0.3698	2.174	88.00	34.81
7.240	67.50	47.238	0.4035	2.35	0.4246	2.476	90.71	46.58
7.250	67.20	51.448	0.4294	2.51	0.4518	2.649	92.01	52.69
7.260	67.00	55.510	0.4538	2.66	0.4775	2.827	93.20	58.66
7.280	67.50	63.874	0.5005	3.00	0.5267	3.225	96.52	70.74
7.300	68.00	71.781	0.5409	3.36	0.5693	3.643	98.94	82.48

severe to result in an inactive 80-meter dipole on 40 meters, especially since the 40-meter dipole is taking practically all the power from the line because of its good match. On 15 meters, the mismatch of the 80-meter dipole is in the same ballpark as it is on 40 meters, assuring inactivity on this band.

In practice, I have found that a good match results on 80, 40, and 15 meters when 80- and 40-meter dipoles are prepared for λ/2 operation using the standard length formula

$$\text{len}_{\text{FEET}} = \frac{468}{\text{f MHz}} \qquad \text{(Eq 20-1)}$$

When a 20-meter dipole is added to the 80- and 40-meter dipoles, there is a slight degradation in the impedance match of the 40-meter dipole on 15 meters. This results from a reactance component in the 20-meter dipole impedance when operating on 15 meters. There should be no serious problem in adding a 10-meter dipole, except that it may require a little trimming to obtain a satisfactory match at a particular frequency in the band. The bandwidth of each dipole is practically identical with that of a single-fed dipole, and hence, the stagger tuning arrangement provides a multi-band antenna sys-

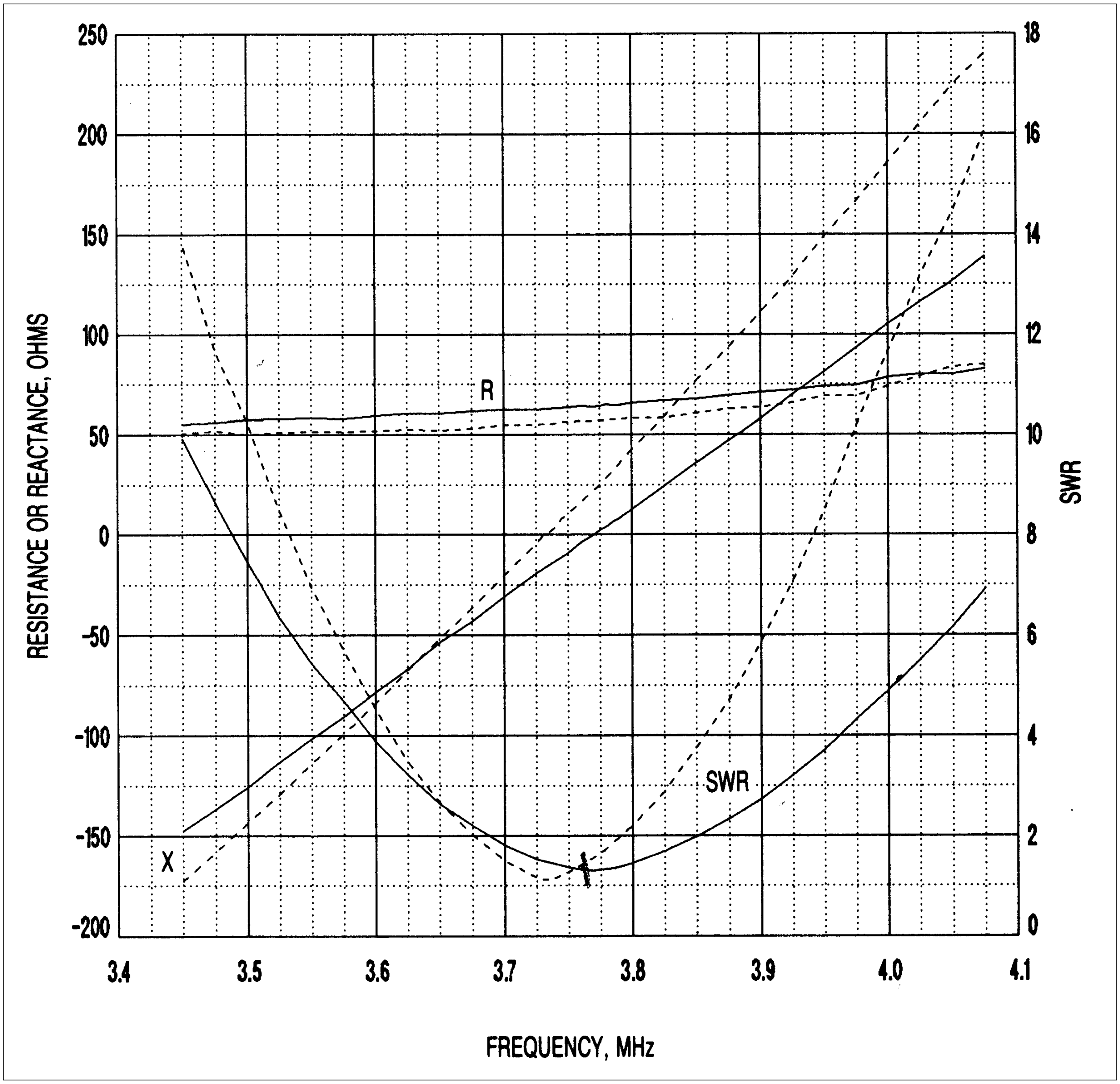

Fig 20-2—Measured feed-point resistance R, reactance X, and SWR versus frequency of 80-meter dipoles at a height of 40 feet. The solid lines show data for a 125-ft radiator with no traps (data from Table 20-3). The broken lines show data for a 109-ft radiator with traps (data from Table 20-4). (This is the 40-meter antenna of Fig 20-1 with traps and extensions added to make the antenna usable on 80 meters.) Computer-generated plot courtesy of Rick Maxwell, WB4GNR)

tem far more satisfactory than a trap dipole. Each dipole in the parallel-fed combination may be supported from different directions if different directions of radiation are desired. Otherwise the shorter dipoles may simply be suspended from the longer ones. Additional information on multi-band dipoles in the parallel configuration may be found in *Ref 71, p 7-3.*

With the trap dipole, the conventional pi-network tank circuit is unable to provide an acceptable match to the input impedance of the feed line except perhaps for a few kilohertz on either side of the resonant frequency of the trap. Hence, an antenna tuner is necessary if any wider frequency excursion is to be enjoyed. All solid-state rigs that have no internal an-

Table 20-3 — Measured Antenna Impedance Data Transformed Through Calibrated Feed Line

Measurement data: Z80 (no traps); see Figs 20-2 and 20-3. 125-ft 80-meter dipole, height 40 ft, calibrated RG-214 plus W2DU HF balun, RF bridge General Radio 1606-A, receiver Kenwood TS-530S, signal generator Boonton 250A RX meter.

Feed line calibration:
Line length in degrees/MHz, PHI = 23.7
Line attenuation in dB/√MHZ, A = 0.082
Line impedance, Z_C = 49 ohms

Freq	R_{IN}	X_{IN}	ρ_{IN}	SWR_{IN}	ρ_L	SWR_L	R_L	X_L
3.450	5.90	6.957	0.7889	8.47	0.8171	9.933	55.22	–147.31
3.475	6.70	8.201	0.7653	7.52	0.7927	8.649	56.21	–136.31
3.500	7.70	9.429	0.7370	6.60	0.7635	7.457	57.75	–125.48
3.525	9.00	10.922	0.7026	5.72	0.7279	6.350	58.16	–112.97
3.550	10.50	12.394	0.6655	4.98	0.6896	5.443	58.40	–101.44
3.575	12.25	13.902	0.6256	4.34	0.6483	4.687	58.15	– 90.45
3.600	14.80	15.139	0.5704	3.66	0.5912	3.892	59.37	–78.39
3.625	17.90	16.000	0.5084	3.07	0.5271	3.229	60.58	–66.58
3.650	22.00	16.575	0.4345	2.54	0.4505	2.640	60.62	–53.76
3.675	26.00	15.782	0.3640	2.14	0.3774	2.212	61.86	–42.99
3.700	30.90	13.568	0.2791	1.77	0.2894	1.815	62.32	–30.65
3.725	35.00	9.799	0.2021	1.51	0.2096	1.530	62.64	–19.44
3.750	37.20	4.853	0.1478	1.35	0.1533	1.362	63.60	–9.32
3.760	37.50	1.862	0.1346	1.31	0.1397	1.325	64.36	–3.88
3.770	37.80	–0.040	0.1290	1.30	0.1339	1.309	64.14	–0.33
3.775	37.60	–1.457	0.1327	1.31	0.1376	1.319	64.46	2.26
3.780	37.20	–2.566	0.1400	1.33	0.1453	1.340	64.98	4.39
3.785	37.20	–3.699	0.1433	1.33	0.1487	1.349	64.63	6.49
3.790	36.90	–4.749	0.1511	1.36	0.1567	1.372	64.70	8.54
3.800	35.60	–6.711	0.1766	1.43	0.1832	1.449	65.74	12.93
3.825	32.00	–10.850	0.2468	1.66	0.2561	1.688	67.15	24.37
3.850	28.00	–13.507	0.3194	1.94	0.3314	1.992	67.87	35.86
3.875	23.95	–14.452	0.3889	2.27	0.4036	2.353	69.44	47.23
3.900	20.60	–14.359	0.4478	2.62	0.4648	2.737	71.15	57.90
3.925	17.50	–13.885	0.5067	3.05	0.5260	3.220	72.28	69.85
3.950	15.10	–12.911	0.5548	3.49	0.5760	3.717	74.00	81.09
3.975	12.95	–11.950	0.6020	4.02	0.6251	4.334	74.42	93.31
4.000	11.40	–10.375	0.6365	4.50	0.6610	4.899	78.61	105.24
4.025	10.15	–9.242	0.6670	5.01	0.6928	5.510	80.00	116.23
4.050	9.10	–8.272	0.6943	5.54	0.7212	6.175	79.96	126.62
4.075	8.16	–6.994	0.7195	6.13	0.7475	6.920	82.50	139.11

tenna tuner require an external tuner in any case, except over very narrow frequency ranges away from dipole resonance where the input impedance of the feed line happens to be close to 50 ohms. And even in the case of the simple single dipole, there are some frequencies that will be out of range of pi-network tank circuits when using coaxial feed lines. This is especially true of the 80-meter band. If operation over the entire 80-meter band is desired when using coaxial feed line, the minimum band-edge SWR occurs when the dipole is cut to a length which resonates at 3.750 MHz, the center of the band. This length is usually 125

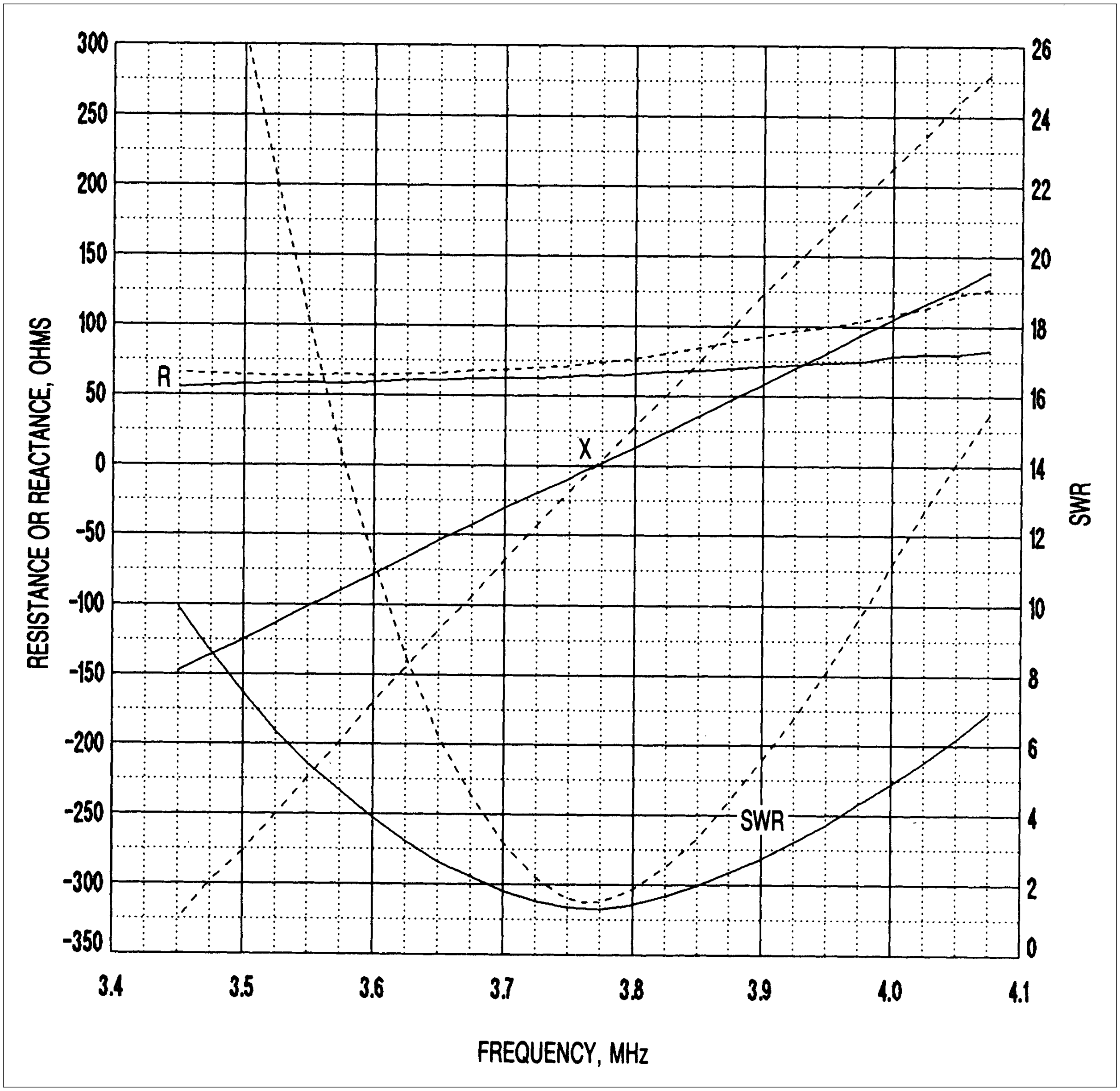

Fig 20-3—Measured feed-point resistance R, reactance X, and SWR versus frequency of 80-meter dipoles at a height of 40 feet. The solid lines show data for a 125-ft radiator with no traps (data from Table 20-3), the same as the solid-line curves in Fig 20-2. The broken lines show data for the same antenna with 80-meter traps and 42-ft extensions added at each end to make the antenna usable on 160 meters (data from Table 20-5). (Computer-generated plot courtesy of Rick Maxwell, WB4GNR)

feet. With this length, the SWR is around 6.5:1 at 3.5 MHz, and 5:1 at 4.0 MHz. Consequently, an external antenna tuner is necessary for operation out to the band edges. The point I'm making is that an antenna tuner is an indispensable part of any amateur station that operates in the HF bands. Anyone operating without one is operating with limited flexibility.

Sec 20.2.3 Random-Length Dipoles

Now I'm coming to the crucial topic concerning multi-band operation at HF. I hope I've convinced you of the necessity for an antenna tuner, so why not use it to

Table 20-4 — Measured Antenna Impedance Data Transformed Through Calibrated Feed Line

Measurement data: Z80 with 40-meter traps; see Fig 20-2. 66-ft 2-in. 40-meter dipole, height 40 ft, KW-40 traps (res. 7.150 and 7.160 MHz), 24-ft 3-in. extensions, calibrated RG-214 plus W2DU balun, RF bridge General Radio 1606-A, receiver Kenwood TS-530S, signal generator Boonton 250A RX meter.

Feed line calibration:
Line length in degrees/MHz, PHI = 23.7
Line attenuation in dB/√MHZ, A = 0.082
Line impedance Z_C = 49 ohms

Freq	R_{IN}	X_{IN}	ρ_{IN}	SWR_{IN}	ρ_L	SWR_L	R_L	X_L
3.450	4.45	5.507	0.8354	1.15	0.8652	13.840	51.11	–172.70
3.475	5.15	6.907	0.8132	9.71	0.8423	11.683	52.11	–157.90
3.500	5.81	8.571	0.7937	8.70	0.8223	10.252	50.20	–143.30
3.525	6.92	10.213	0.7617	7.39	0.7892	8.489	51.22	–128.76
3.550	8.40	12.113	0.7222	6.20	0.7484	6.948	51.59	–113.43
3.575	10.25	14.098	0.6770	5.19	0.7017	5.704	51.66	–99.06
3.600	13.00	16.250	0.6162	4.21	0.6387	4.536	51.91	–83.68
3.625	17.20	18.207	0.5337	3.29	0.5532	3.477	52.67	–67.38
3.650	22.80	19.589	0.4396	2.57	0.4557	2.674	52.56	–51.84
3.675	30.10	18.640	0.3266	1.97	0.3387	2.024	53.28	–36.53
3.700	37.90	12.973	0.1943	1.48	0.2015	1.505	54.99	–20.50
3.725	43.40	3.222	0.0699	1.15	0.0725	1.156	54.95	–4.63
3.730	43.50	0.268	0.0595	1.13	0.0617	1.132	55.40	–0.74
3.735	43.90	–1.071	0.0561	1.12	0.0582	1.124	54.95	1.07
3.740	43.20	–3.209	0.0718	1.15	0.0745	1.161	55.74	3.95
3.745	42.20	–6.008	0.0993	1.22	0.1030	1.230	56.41	7.97
3.750	41.50	–7.733	0.1186	1.27	0.1230	1.281	56.63	10.60
3.775	35.80	–15.364	0.2350	1.61	0.2438	1.645	57.26	25.32
3.800	27.60	–19.211	0.3641	2.15	0.3778	2.214	58.23	42.60
3.825	21.20	–19.739	0.4675	2.76	0.4851	2.885	58.26	58.56
3.850	15.90	–17.922	0.5591	3.54	0.5802	3.764	60.67	76.79
3.875	12.50	–15.871	0.6266	4.36	0.6504	4.720	62.69	93.92
3.900	10.00	–13.974	0.6833	5.31	0.7092	5.878	63.47	111.27
3.925	8.30	–11.975	0.7247	6.27	0.7524	7.077	66.00	128.79
3.950	6.95	–10.000	0.7605	7.35	0.7896	8.504	69.33	148.59
3.975	5.90	–8.554	0.7908	8.56	0.8212	10.184	69.10	166.25
4.000	5.40	–9.250	0.8077	9.40	0.8388	11.407	53.98	158.40
4.025	4.80	–8.944	0.8269	10.55	0.8588	13.163	46.67	160.29
4.050	4.35	–4.198	0.8380	11.35	0.8705	14.442	83.76	223.92
4.075	4.00	–3.190	0.8496	12.30	0.8827	16.044	85.07	239.80

the fullest advantage and achieve multiband HF operation with the simplest, yet most effective and efficient antenna? I'm speaking of a random-length dipole fed with either open-wire line or ladder line. By random length, I mean any length at least λ/4 long at the lowest frequency of operation.

A center-fed λ/4 dipole radiates with an effectiveness of approximately 95% relative to a λ/4 dipole, and has a terminal impedance of approximately 14 – *j*1300 ohms. This terminal impedance yields an SWR of 244:1 on 600-ohm line, 300:1 on 450-ohm line, and 424:1 on 300-ohm line. As would be expected, the tun-

Table 20-5 — Measured Antenna Impedance Data Transformed Through Calibrated Feed Line

Measurement data: Z80 with 80-meter traps; see Fig 20-3. 125-ft 80-meter dipole, height 40 ft, KW-80C traps (res. 3.770 MHz), 42-ft extensions, calibrated RG-214 plus W2DU HF balun, RF bridge General Radio 1606-A, receiver Kenwood TS-530S, signal generator Boonton 250A RX meter.

Feed line calibration:

Line length in degrees/MHz, PHI = 23.7
Line attenuation in dB/√MHZ, A = 0.082
Line impedance, Z_C = 49 ohms

Freq	R_{IN}	X_{IN}	ρ_{IN}	SWR_{IN}	ρ_L	SWR_L	R_L	X_L
3.450	2.25	0.000	0.9122	21.78	0.9448	35.202	65.33	–325.75
3.475	2.50	1.094	0.9030	19.61	0.9353	29.915	65.11	–298.18
3.500	2.72	2.143	0.8950	18.05	0.9272	26.468	63.88	–276.56
3.525	3.10	3.404	0.8815	15.88	0.9133	22.081	63.65	–250.10
3.550	3.60	4.789	0.8643	13.74	0.8956	18.163	63.48	–224.14
3.575	4.35	6.294	0.8394	11.45	0.8699	14.371	64.88	–198.23
3.600	5.39	8.194	0.8067	9.35	0.8362	11.207	63.96	–170.03
3.625	6.90	10.069	0.7621	7.41	0.7900	8.524	65.36	–144.92
3.650	9.30	12.329	0.6976	5.61	0.7232	6.226	65.72	–117.68
3.675	12.60	14.150	0.6179	4.23	0.6407	4.566	67.39	–94.12
3.700	18.00	15.405	0.5035	3.03	0.5222	3.185	68.36	–68.17
3.725	25.40	13.691	0.3607	2.13	0.3740	2.195	70.05	–42.31
3.745	30.90	9.212	0.2525	1.68	0.2619	1.710	70.76	–23.41
3.750	31.90	7.387	0.2293	1.60	0.2378	1.624	71.33	–18.43
3.755	32.60	5.459	0.2114	1.54	0.2192	1.562	71.95	–13.61
3.760	33.20	3.723	0.1973	1.49	0.2046	1.515	72.03	–9.32
3.765	33.10	1.594	0.1946	1.48	0.2019	1.506	73.29	–4.49
3.775	33.00	–2.172	0.1968	1.49	0.2042	1.513	73.66	4.47
3.800	28.30	–9.921	0.2945	1.84	0.3056	1.880	76.45	28.10
3.825	22.00	–12.811	0.4142	2.41	0.4298	2.508	80.31	50.86
3.850	16.70	–12.987	0.5198	3.17	0.5394	3.343	84.02	74.38
3.875	12.75	–12.258	0.6078	4.10	0.6309	4.418	85.04	98.59
3.900	10.10	–10.205	0.6706	5.07	0.6960	5.580	93.16	123.32
3.925	8.40	–8.764	0.7153	6.03	0.7426	6.770	96.80	145.05
3.950	7.10	–7.418	0.7519	7.06	0.7807	8.120	99.61	167.06
3.975	6.10	–6.038	0.7816	8.16	0.8116	9.614	103.88	190.45
4.000	5.35	–4.750	0.8048	9.25	0.8358	11.178	108.65	213.97
4.025	4.80	–3.603	0.8224	10.26	0.8542	12.717	113.20	236.13
4.050	4.41	–2.395	0.8352	11.14	0.8676	14.103	122.57	260.19
4.075	4.10	–1.472	0.8457	11.96	0.8786	15.469	126.78	279.33

ing of the antenna tuner is quite sharp with these values of SWR. However, with the low-loss characteristics of lines of these impedances, the results are good. This is what I use for 160-meter operation — an 80-meter λ/2 dipole, which is λ/4 on 160 meters, and fed with 300-ohm line. It works very well. I find it more satisfactory than the traditional method of tying the two wires of the parallel feed line together for a single-conductor feed to the resulting flattop. Tying the two wires together results in as single wire. A single wire that center-feeds both dipole halves feeds the halves in a phase relationship that causes current to flow in opposite directions in each dipole half. This opposite current flow results in no radiation from the flattop — the flattop is now only a capacitive-loading top hat, and *it is only the feed line that radiates as an antenna!*

I'm not suggesting that everyone use a dipole as short as λ/4, but I do recommend a length of about 3λ/8, halfway between λ/4 and λ/2, if you can't erect a full λ/2 on 80-meters. For general use, this antenna results in a little higher effectiveness than the λ/4 dipole, and it does not have such sharp tuning in the antenna tuner. A 3λ/8 dipole has an effectiveness greater than 98% relative to a λ/2 dipole, and has a terminal impedance of approximately $34 - j400$ ohms. This impedance yields an SWR of 25.5:1 on 600-ohm line, 23.7:1 on 450-ohm line, and 24.6:1 n 300-ohm line, all very reasonable values for open wire or ladder line. A 3λ/8 dipole at 3.5 MHz is approximately 100 feet long, which means that a random length from 90 to 100 feet will make an excellent radiator on all the HF amateur bands, 80 through 10 meters, including the WARC-79 bands. The length of a 3λ/8dipole may be found using the formula

$$\text{len}_{\text{FEET}} = \frac{351}{f_{\text{MHz}}} \qquad \text{(Eq 20-2)}$$

If you don't have room for even 90 feet of straight wire for operation on 80 meters, a 10- to 15-foot portion of each end may be dropped vertically from each end support. There will be no significant change in radiation pattern on 80 and 40 meters. However, there will be a minor change in polarization in the radiation at higher frequencies, but the effect on propagation will be negligible. Although I work 160 meters with a 125-foot dipole, tuning of the antenna tuner would be less critical on 160 meters with a 200-foot dipole, and admittedly, the feed-line loss would be somewhat lower. However, the loss from feed-line attenuation is quite low, even at the high values of SWR. Your attention is invited to the loss versus SWR graph in Fig 6-1 to see just how little loss is incurred with open-wire feeders. The point I'm stressing here is that when using an antenna tuner with open-wire or ladder-line feeders, the dipole length is not critical, because the tuner provides the impedance match throughout the entire antenna system, whatever the dipole length may be.

Sec 20.2.4 The G5R V Antenna

With this background on random-length dipoles behind us, it seems appropriate to make a critical examination of a particular 102-foot dipole that is enjoying a great deal of popularity — Louis Varney's G5RV dipole. In spite of its popularity, its operation is not well understood among many amateurs, so I'll shed a little light on the G5RV. First of all, the reason for the 102-foot length for the G5RV is no secret, but it is not well known. Being unaware of certain antenna principles, many amateurs have come to believe that there is some sort of magic in the 102-foot length, and that their all-band success with this antenna is dependent on this specific length. Nothing could be further from the truth, because, except for 20 meters (as I'll soon explain), any random length of at least 3λ/8 at the lowest operating frequency will perform equally well.

What is the significance of the 102-foot length? Unbeknown to many amateurs who use it, Varney designed the antenna to be a resonant 3λ/2 radiator on 20 meters — that length is 102 feet. He had two specific reasons for selecting 3λ/2 on 20 — he wanted a four-lobe radiation pattern and a low feed-point impedance. The 3λ/2 was a clever choice, because this length yields a four-lobe pattern, in addition to a low feed-point impedance that can be matched to a 50-ohm line with a line transfomer without requiring an antenna tuner. As Varney also intended, this 102-foot length results in a strictly random length on all bands except 20, so except for the 20-meter considerations I've just described, there is no magic whatever to this length. The last comment in the previous paragraph should be taken seriously. It should be noted that the 102-foot length of the G5RV is almost exactly the length I recommended above for a random-length antenna, 3λ/8 at the lowest frequency of operation, because 100 feet is the length required for 3λ/8 at 3.5 MHz.

On 20 meters, the input impedance of the 3λ/2 G5RV radiator is low because the feed point is at the center of the central λ/2 portion. Hence, the impedance (the resonant resistance) is only moderately higher than if the outer λ/2 sections were eliminated, leaving a single λ/2 dipole. At the frequency of mid-band resonance, the free-space feed-point impedance is approximately 100 + *j*0 ohms, which reduces to around 90 + *j*0 ohms at a convenient height above ground. This results in a mismatch of about 1.8:1 relative to 50 ohms. Varney's choice of the 34-foot line-transformer matching section, λ/2 on 20 meters, was to make a 1:1 impedance- transformer that repeats the 90 + *j*0 antenna impedance at its input terminals. Thus, with a suitable choke balun to make a transition from a balanced to an unbalanced line, the low 1.8:1 mismatch makes connecting to a 50-ohm line feasible without requiring an antenna tuner. The SWR on a λ/2 matching section of 300-ohm line is around 3.3:1, while on a 450-ohm line it is about 5:1. Keep in mind that these considerations apply only to 20-meter operation. On all other bands, the G5RV antenna terminal impedance is much higher and reactive, resulting in a higher SWR and making the use of an antenna tuner imperative. Incidentally, the length of a 3λ/2 radiator may be found using the long-wire antenna formula

$$\text{len}_{\text{FEET}} = \frac{492(\text{n} - 0.05)}{\text{f MHz}} \qquad \text{(Eq 20-3)}$$

where n = the number of half wavelengths in the radiator

It is unfortunate that many amateurs believe that the balun should be omitted. These people have been misled, because failure to include a balun between the balanced open wire and the unbalanced coax results in RF radiation in the shack from current flow on the outer surface of the coax shield.

In addition to the misunderstanding concerning the "magical" 102-foot length of the G5RV, there are also other areas of confusion focused on this antenna, some concerning the role of the feed line. There are some who believe that a particular combination of open-wire and coaxial feed line yields a perfect 1:1 match on all bands without a tuner. As stated above, this is true only on 20 meters. Others believe that because the 102-foot dipole length is shorter than λ/2 on 80 meters, a certain length of the feed line is a folded-up portion of the antenna to make up for the difference in length, and that the folded-up portion radiates along with the antenna. Still others believe certain lengths of feed line are to be avoided to prevent "antenna current" from flowing on the feed line because of line resonance. Patently untrue! I wish I knew how these myths originate.

My own involvement with the G5RV antenna dates back to the early '70s when I began lecturing on SWR and reflections on transmission lines. My lectures promoted the use of antenna tuners with open-wire feed line on random-length antennas as the best way to achieve all-band operation. I also promoted the concept that the correct length of feed line is that which is required to reach from the antenna terminals to the tuner, because, regardless of the length of the feed line, both the feed line and the antenna are made resonant by the conjugate matching action of the tuner. Hence, there is no reason to avoid certain lengths to prevent line resonance, because the tuner makes them resonant anyway.

I first heard of the G5RV when someone in my audience described his 102-foot antenna with open-wire and coax feed line. He claimed it gave him a 1:1 SWR on all bands without a tuner. I told him he must have a lossy coax to get 1:1, because I knew a 1:1 would be impossible with such an arrangement without some exceptionally high resistive loss somewhere in the antenna system. After hearing several more identical claims in later lecture sessions, I analyzed the antenna on all bands, observing it to be the $3\lambda/2$ that it is on 20 meters, but a random length on all other bands, so I felt confident in rebutting the ridiculous "1:1 on all bands without a tuner" claims. Incidentally, Varney published an update of the G5RV in *The ARRL Antenna Compendium, Volume 1 (Ref 112)*, in which he presented the same specifications for the antenna that I described above, which confirms my earlier observation that his antenna is $3\lambda/2$ on 20 meters, and a *random length on all other bands.*

Let's now examine the other myths and confusion concerning the G5RV that I mentioned earlier. First, we'll consider the feed-line combination believed to yield a 1:1 match on all bands. It has been written that the combination of 33 feet of open-wire line, plus 68 feet of 50-ohm coaxial line will yield such a match. Don't you believe it! A determination of the G5RV antenna-terminal impedance on all bands shows that there is no length of open-wire line of any characteristic impedance Z_C that will transform the antenna impedance Z_A to an impedance that is even close to presenting a match to 50- or 75-ohm coax, except on 20 meters. However, when fairly long lengths of coax follow a length of open wire, the high SWR appearing at the junction of the open wire and the coax will be reduced significantly at the input of the coax because of the attenuation loss in the coax, especially at the higher frequencies. The longer the coax, the lower the input SWR, but remember that this method of lowering the SWR is costly in terms of lost power. Because an antenna tuner is necessary anyway, except on 20 meters, it makes no sense to use any coax at all. Coax performs no useful function in the feed system, and it consumes power unnecessarily because of the high SWR. A more sensible method is to run the open-wire line all the way to the tuner and eliminate the coax entirely.

Second, let's consider the length of feed line believed to be a folded-up portion of the antenna that radiates. Radiation occurs when the electromagnetic field developed by current flow on a conductor is not canceled by an opposing field developed by an equal current flowing in the opposite direction. Hence, radiation occurs as a result of current flowing on an antenna. However, antenna current ceases being antenna current at the antenna terminals, because once it enters the transmission line, the current becomes transmission-line current, with the current in the two conductors flowing in opposite directions. There is no radiation from any portion of the line, because the fields developed by the currents flowing in opposite directions in the two conductors oppose and cancel each other throughout the entire length of the line. Therefore, no portion of the feed line becomes part of the antenna.

Sec 20.3 Antenna Currents on Feed Lines

We know there are times when the feed line does radiate in spite of the statement in the previous paragraph, so let's now examine this concept a little further to determine what conditions must exist to cause the feed line to radiate. Antenna currents and radiation can occur on a two-wire balanced line, but only when the currents in the two wires are unequal. Neither a resonant line nor a resonant combination of line and antenna length will cause the currents to be unequal. Nor will high SWR cause unequal currents or feed-line radiation. Never forget that whatever the length of the feed line (or the antenna), the antenna and feed-line combination is always made resonant by the conjugate matching action of the antenna tuner.

I'll now explain how antenna currents are developed, and it will become clear why feed-line length is not a factor in causing feed-line radiation. As stated earlier, equal transmission-line currents in the two wires of the line flow in opposite directions (push-pull). This mode of current flow is called the *differential mode.* The electromagnetic fields developed by these two currents are thus 180° out of phase, and oppose each other. Because the separation between the wires is small in terms of a wavelength, the two opposing fields cancel each other, preventing radiation from the feed line. No antenna currents are generated. On the other hand, if the transmission-line currents in the two wires are unequal, their corresponding fields are also unequal, and thus do not completely cancel each other; hence, an antenna current is developed and radiation results. In this case the current resulting from the *difference* between the currents flowing in the two wires flows in the same direction on both wires. The unidirectional current flowing in this case is called the *common-mode* current.

The two main causes of transmission-line current imbalance that result in common-mode currents are (1) asymmetrical positioning of the feed line relative to the antenna, and (2) the antenna itself is unbalanced, either by unequal lengths relative to the feed point (as in the twin-lead off-center fed, misnamed "Windom" antenna), or one portion of the antenna is closer to surrounding objects such as a metal roof. If the feed line is positioned symmetrically relative to the antenna, each half of the antenna induces an equal but opposite current flow on the feed line. This is because each half of the antenna is of opposite polarity. The result is zero induced current, regardless of line length.

If the feed line is *not* positioned symmetrically, the currents induced from each half of the antenna are unequal. The result is an induced current on the feed line, traveling in the same direction on both wires as common-mode current. When the induced common-mode current joins the differential-mode transmission-line currents, the net current is increased in one wire and decreased in the other. The resulting difference in current now flowing in each wire, the common-mode current, constitutes the antenna current, which does cause the feed line to radiate. Therefore I repeat, if the currents in the two wires of the feed line are equal, antenna current and radiation will be zero, regardless of the length or resonant condition of the feed line. Antenna current flowing on a coaxial (unbalanced) feed line resulting from not using a balun is another subject, and is treated in depth in Chapter 21.

Although it is not pertinent to the G5RV, a strange example of asymmetrical feed-line positioning exists in the misnamed “Windom” antenna. This is a dipole antenna fed off-center with twin lead at the point where a true Windom would be fed with a single-wire feeder. This antenna is not a Windom, and the feed current paths are not the same. In this pseudo Windom, the go and return currents flow on the two wires of the twin lead. In the true Windom, the return path for the feeder current is in the ground-reflected image of the single-wire feeder. And yes, the Windom feeder does radiate, but not for the same reason the pseudo-Windom feeder radiates. The off-center twin-lead feeder of the pseudo-Windom radiates because it carries a common-mode antenna current in addition to the differential-mode transmission-line currents, because the currents induced in it from the asymmetrical dipole portions are unequal. There is a legitimate reason for moving the twin-lead feeder away from the center of the antenna, however, as discussed in Sec 21.10. In addition, for ease in matching a λ/2 dipole to a low-impedance line, a feed point 1/3 of its length from one end exhibits low-impedance current loops on the even harmonics of the fundamental frequency, while the center of the dipole exhibits low-impedance current loops on the odd harmonics.

Sec 20.4 Standing Waves and Feed-Line Radiation

It goes without saying that practically every amateur takes SWR measurements on his feed line to determine the condition of his antenna system. However, unless the SWR is 1:1, the results of the measurements are often misinterpreted, and the standing wave innocently becomes the culprit in an unfortunate scenario that leads to all sorts of needless effort to get the SWR down to 1:1. Many believe that standing waves produced by an impedance mismatch between the feed line and the antenna result in an energy field surrounding the feed line, causing it to radiate as an antenna. Is this true? No! This is not the case at all, so I’ll explain.

A voltage standing wave is simply a variation in the line voltage appearing *between the feed-line conductors* at different positions along the line. And a current standing wave is a corresponding variation in line current flowing through the conductors. Both voltage and current standing waves are illustrated in Fig 9-3. The variations in voltage and current that develop the standing wave result from the interaction between the forward and reflected waves of voltage and current, as explained in Chapter 9. But first let’s consider the conditions prevailing on a matched, open-wire line with no standing waves. Here, there is no variation in either the line voltage or line current as we move in position along the line. And we know from the discussion in the previous section that there is no radiation from the line, because the opposing fields produced by the oppositely flowing currents in the two conductors of the line cancel each other. In other words, there are actually two energy fields surrounding the feed line (open wire, not coax), but they cancel each other because they are of opposite polarity, resulting in no radiation.

Now consider the conditions prevailing on a mismatched line with standing waves. As stated above, we now have a variation in line voltage and current as we move in position along the line—at some points the current is higher and at other points it is lower. The crucial point is that no matter whether the current is higher at one point and lower at another, the current is equal and opposite in both conductors at any given point along the line. Therefore, the fields produced by the currents in the two conductors are also *equal and of opposite* polarity everywhere along the line, and cancel in exactly the same manner as in the line with no standing waves. Hence, there is no radiation from the line, standing waves or not.

So far I have been discussing open-wire lines, where there is nothing to contain the electromagnetic fields produced by the line currents. However, there is an additional reason why there is no radiation from *coaxial* lines because of standing waves. This is because the fields produced by the currents flowing through the conductors of coaxial lines are entirely confined within the coaxial shield surrounding the line. Hence, standing waves on transmission lines do not cause radiation from either open-wire or coaxial transmission lines.

Sec 20.5 The Extended Double Zepp and the 5λ/8 Vertical

There is another dipole type of antenna that is becoming popular with amateurs for its increased gain, called the extended double Zepp, or EDZ for short. It is a collinear dipole, although it can't rightfully be called a dipole because each half of its length is greater than λ/2 (each half is actually 0.64 λ). This means it has a reversal of current flow in each antenna half, and therefore has more than two "poles." Hence, the EDZ rightfully belongs in the realm of the long wire. The EDZ is described in *The ARRL Antenna Book (Ref 71, p 8-34)*, which shows the current distribution on the radiator and feed line, as well as the radiation pattern.

The reason for my mentioning the EDZ here is that it has a long history relative to AM broadcasting that is not well known, and I believe you will find it very interesting. In the early 1920s, antennas used in AM broadcasting were in their infancy. Many simply used a configuration similar to those used in long-wave, or LF transmission. These antennas generally comprised a top-loaded vertical wire supported by two towers, one at each end of the top-loading wires. The vertical wire was usually much shorter than λ/4, and the radiation pattern in elevation was the same as the typical λ/4 vertical. However, the pattern was not uniform in all azimuth directions because of field distortion caused by the supporting towers. There is no radiation from the horizontal top-loading wires, because the currents in each opposing wire are flowing in opposite directions. The horizonal wires simply add capacitance to ground, electrically lengthening the short vertical portion. Consequently, the only radiation is from the vertical wire.

In 1923, Stuart Ballantine of the Harvard University Physics Department made an important discovery, which he published in 1924 *(Ref 115)*. He discovered that there is an optimum height for a vertical radiator that produces the maximum radiation in the horizontal, broadside direction. That height is 0.64 λ. The increase in radiation in the horizontal direction is 3.03 dB relative to a λ/4 vertical radiator. This increase in horizontal radiation arises from a corresponding decrease in the vertical components of the radiation in the major lobe. In other words, the fat half-doughnut pattern of the λ/4 vertical radiator is squashed down into a thinner doughnut, but one having a greater diameter. However, because this 0.64-λ is greater than λ/2, the current in the radiator reverses direction at a point λ/2 from the top, 0.14 λ above the ground. The reversal in current at this point produces a separate radiation field from the bottom 0.14-λ portion, that is 180° out of phase relative to the field producing the major lobe of radiation. Consequently, this separate out-of-phase field produces a minor lobe of radiation at a high angle, with a deep null between the major and minor lobes.

I have performed a computer analysis of the 0.64-λ vertical radiator; a pattern integration yields 0.6346 λ (228.45°.) as the true optimum height, furnishing a gain of 8.1898 dBi, or 3.029 dB over the λ/4 vertical. The maximum field in the minor lobe, which occurs at 58° in elevation, is 9.13 dB below that of the major lobe. The null between the major and minor lobes occurs in elevation at 35°. You may recognize by now that this vertical radiator is also the well-known 5λ/8 vertical.

Getting back to Ballantine, his discovery formed the basis for the evolution of the vertical tower becoming the radiator in AM broadcasting, replacing the top-loaded vertical wire supported by two towers. There were two principal advantages in using the tower as the radiator. First, the cost for one tower is less than for two. And the second very important advantage was that the single tower eliminated the radiation-pattern distortion caused by the two towers supporting the vertical radiator in the earlier arrangement. In addition, Ballantine's 1923 prediction of increased radiation in the horizontal direction was proved correct when single-tower radiators were erected at his predicted height. However, one unforeseen problem crept in — the radiation from the higher angle minor lobe returned to ground from the ionosphere at night and caused severe fading several miles from the antenna. At the distance where the minor-lobe signal from the ionosphere was the same strength as that of the direct ground wave from the major lobe, wave interference occurred between the two signals, causing the fading. The solution to the problem was the small reduction of the tower height to 0.528 λ (190°), which nearly eliminated the minor lobe, while reducing the radiation level by only 1.03 dB. Thus, the fading problem was solved. As a result, many of the AM broadcast stations throughout the world are still using 190° towers.

One other factor that resulted in increased radiation in the horizontal direction was the use of a more efficient ground-radial system that emanated from the experiments of my colleagues, RCA's Brown, Lewis (W2EBS), and Epstein in 1937 *(see Ref 20)*. The system they developed is still in use today. If you are interested in more detail concerning the evolution of the vertical radiator and the ground-radial systems in present use, I recommend reading *Radio Antenna Engineering* by the late Edmund A. Laport, also of RCA *(Ref 57)*. Also see Chapters 1 and 5. In addition, Brown's analysis of the ground currents surrounding the base of the vertical antenna also makes interesting reading *(Ref 111)*.

Let's now return to the EDZ. What is the connection between the EDZ and the vertical radiator used in AM broadcasting? Simply its length. We must remember that the ground-reflected image of the vertical radiator supplies the missing half of the dipole. Consequently, a dipole having a half-length of 0.64 λ (0.6346 λ if we nit pick) yields the maximum possible radiation in the broadside direction from a single radiator, 3.03 dB greater than that of a λ/2 dipole. With further increases in length, the broadside radiation diminishes rapidly, and becomes zero when the half-length is 360°. At 360°, the radiation pattern forms two separate, equal lobes resembling a four-leaf clover when viewed on both sides of a pattern representing the radiation.

As stated earlier, the radiation pattern of the EDZ appears on page 8-34 of *The ARRL Antenna Book (Ref 71)*, and for comparison, the pattern of the λ/2 dipole appears there on page 3-11. The difference in the widths of the lobes is remarkable. However, despite the 3 dBd gain obtained in the broadside direction from the EDZ, the narrower main lobe of the EDZ may work against you at angles away from broadside. Keep in mind that long-distance propagation at HF is via reflection from the ionosphere, so also remember to consider the takeoff angle from the antenna to the ionosphere for the station you're contacting. At angles away from broadside, a dipole may be radiating more energy at the higher wave angles than the EDZ.

I would be remiss if I neglected to discuss the terminal impedance of the EDZ, so for those who are thinking of feeding it directly with coax, guess again! From interpolating thin-wire antenna impedance data from King (*Ref 37*), the terminal impedance of a radiator with a half-length of 0.64-λ is 126.18 – *j*658.2 ohms. On a 50-ohm transmission line, the normalized terminal impedance is 2.5236 – *j*13.164, yielding an SWR of 71.57:1. [These impedances were interpolated from King's text book before Roy Lewallen's (W7EL) ELNEC and EZNEC were available.] However, on a more realistic approach, here are the values for three higher impedance transmission lines. On 300-ohm line the normalized impedance is 0.4206 – *j*2.194, SWR 14.17:1; on 450-ohm line the normalized impedance is 0.2804 – *j*1.4631, SWR 11.39:1; on 600-ohm line the normalized impedance is 0.2103 – *j*1.0907, SWR 10.59:1. These values of SWR are reasonable for the transmission lines involved, and the balanced output of your antenna tuner should be able to handle these mismatches very well! Just as an exercise, you might want to try calculating these SWR values using the hand-held calculator program listed in Appendix 4 of Chapter 23. I should warn you though, that program is in reverse Polish notation for Hewlett-Packard calculators. Sorry I couldn't include programs for the scientific-notation units.

I mentioned earlier that the 0.64-λ vertical is the same as the 5λ/8 vertical used in many VHF and UHF mobile applications. It is interesting to observe the ease in which this antenna can be matched to a 50-ohm transmission line. The terminal impedance of a vertical radiator over ground, or a ground plane, is half the impedance of the complete dipole having the same half-lengths. Therefore, half of the EDZ terminal impedance of 126.18 – *j*658.2 ohms is 63.09 – *j*329.1 ohms for the 5λ/8 vertical. However, this capacitive reactance of 329.1 ohms was determined for a thin radiator, while the whips used in our mobile applications are not *thin* for lengths and diameters we use at VHF or UHF. So the actual reactance at these frequencies will be considerably less than 300 ohms.

Common practice is to simply insert an inductor having a reactance equal to the capacitive reactance of the antenna in series with the antenna, thus canceling the antenna reactance, and leaving only the 63-ohm resistance component of the antenna terminal impedance to be fed with the 50-ohm line. The result is an SWR of only 1.26:1, which hardly needs any improvement. An alternative method of feeding the 5λ/8 vertical is to connect the inductor between the antenna and ground, and connect the center conductor of the feed line to one of the turns of the inductor. By trimming the length of the antenna and selecting the correct turn to tap onto the coil, an SWR of 1:1 can be achieved. With all of this said about the 5λ/8 antenna, perhaps you are now considering a change to a 5λ/8 vertical from λ/4. If so, there is a paper by Donald Reynolds, K7DBA that is worth studying (*Ref 119*).