

The Story of the Broadband Dipole

A dipole can be broadbanded by a number of techniques including by matching with resonant sections of transmission feed lines.

The 80-meter amateur band covers a very large fractional bandwidth. I was looking for a way to avoid retuning my 80-meter inverted V on a 140-foot guyed tower, since the ends are out of reach even if they are folded straight down. I found that lumped-element matching networks or the often-referenced Bazooka dipole and other forms of thicker conductors were neither practical nor effective for me at the lower HF bands.¹

In a November 1997 posting on the TowerTalk mail list, I remarked²,

"There's an interesting method of broad banding antennas mentioned in various ARRL publications by Frank Witt, AI1H. It uses the transmission line length you are going to need anyway to match at two frequencies in the band (say 3.52 and 3.80 MHz). It's also mentioned in a text I use teaching a graduate microwave course at Stanford, and I have been wanting to try it."

In particular, I was referring to a September 1993 article³ by Frank Witt, AI1H, that graced the pages of *QST*. Witt uses two cascaded resonant lengths of transmission line, one a multiple of half wavelengths and the other a quarter wavelength, to create a broadband impedance match for a simple wire dipole, as reproduced in Figure 1. Witt says:

"The antenna system described here is simpler than any of its predecessors and has the following features: A 2:1 SWR or better is achieved over all or most of the 80-meter band. Antenna length and appearance are the same as those of a conventional half-wave dipole ... The losses due to broadband matching are acceptable. [and] The dipole antenna itself is not broadband; the system uses a broadband *match*."

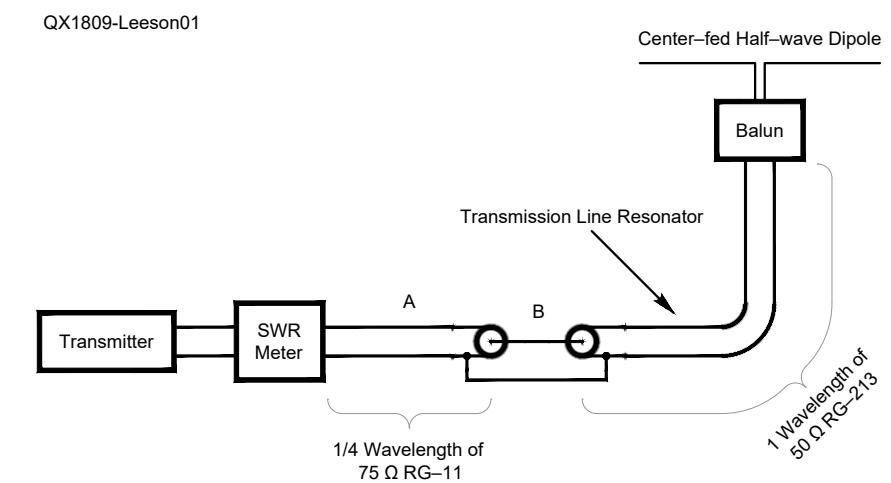


Figure 1 — Broadband feed line match from Witt, AI1H.

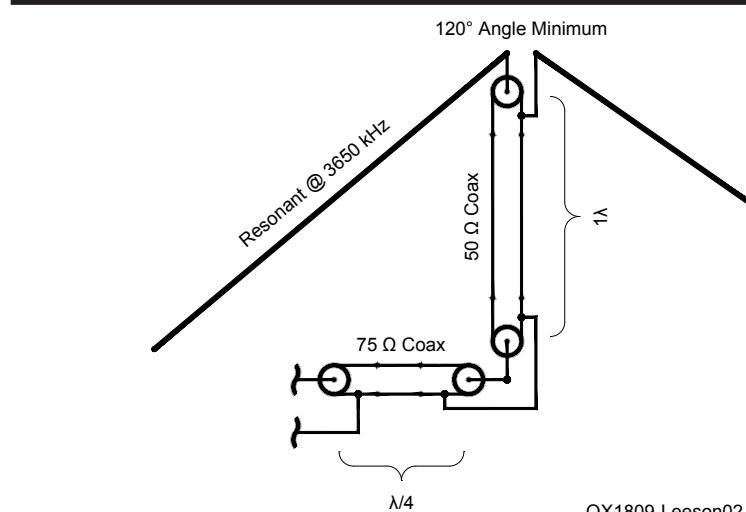
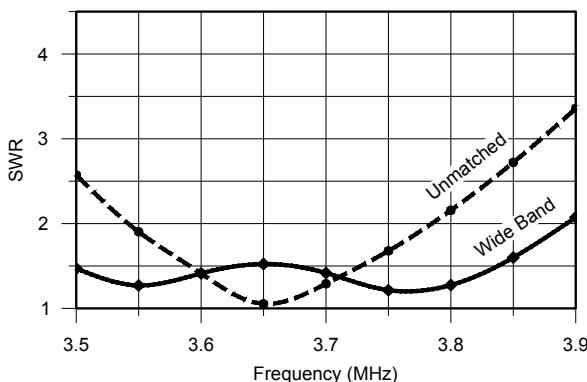
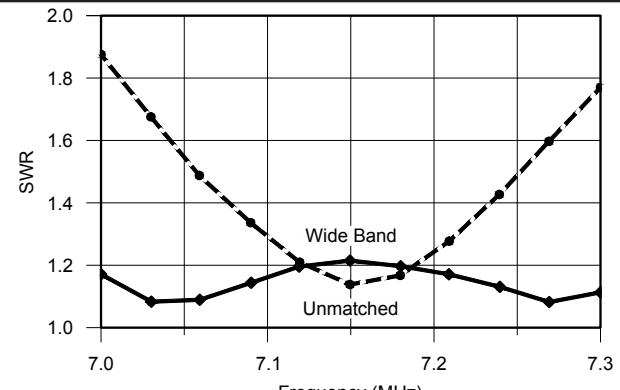


Figure 2 — Inverted V with broadband feed line match.



QX1809-Leeson03a



QX1809-Leeson03b

Figure 3 — Calculated SWR in the (A) 80-m band and (B) 40-m band.

Witt's idea seemed promising, especially after analysis using a spreadsheet and Smith chart software. This simple configuration would not arc or melt at high power, nor tangle or break with wind and ice loading. I found that this general concept was known⁴ as early as the 1940s. If an inverted V is used, the angle must be shallow to keep the radiation resistance higher than the feed line characteristic impedance. Figure 2 is a sketch of the inverted V and feed line matching network from a talk I gave⁵ in October 1998. From my post on TowerTalk:

"Here is a summary of an 80-m inverted V I put up that matches 1:1 at the CW and SSB frequency. The inverted V is designed using AO to resonate at 3.67 MHz (geometric mean of two frequencies of interest), and to have enough height and included angle to have a resistance at resonance of 70-75 ohms. The apex is at 120 ft, and the angle is about 120 degrees. I use the AO optimizer, then knock off 1% length from experience.

Now for the interesting part. I measured a full wavelength of 50-ohm coax using the MFJ-259 antenna scope. Using Belden 8214, it's about 205 feet long, connects to the antenna 1:1 balun and comes down to the ground. Next is connected a 1/4 wavelength of 75-ohm coax.

"At the transmitter end of the 75-ohm quarter wave, the match is perfect (less than 1.1:1) at 3520 and 3800 [kHz]! This should work for a horizontal dipole, or any antenna with impedance in the 75-ohm range.

To see if this was a fluke, I put up a 40 m dipole at 50 feet for Sweepstakes. It uses a half-wave of 50-ohm coax followed by the quarter-wave section of 75-ohm coax, and it matched fine at 7.0 and 7.25 MHz."

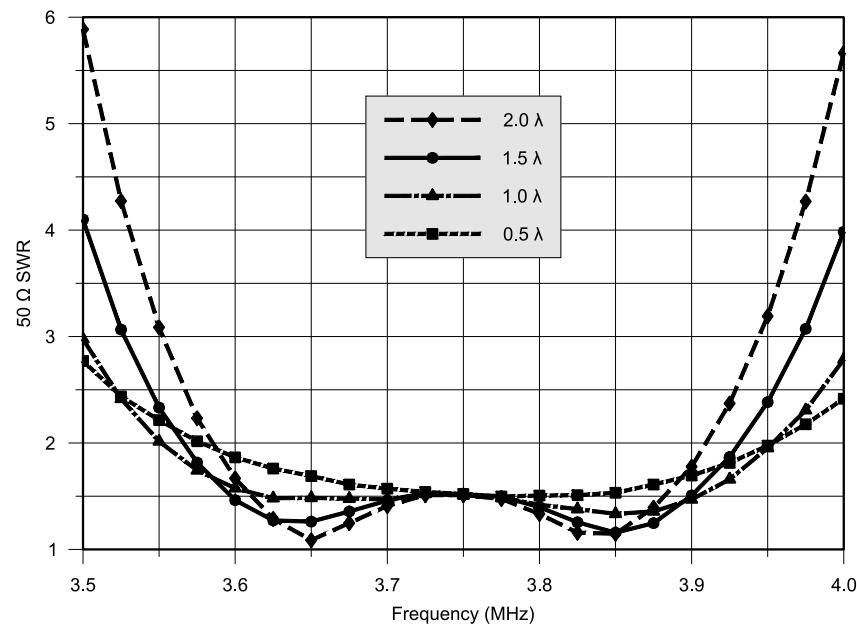
The calculated SWR response for the 80 m antenna is shown in Figure 3A, and the SWR response for the 40 m antenna is shown in Figure 3B, from my 1998 presentation.

L. B. Cebik, W4RNL, posted a confirming comment the following day, in which he provided 80-m calculated results for various configurations, based on dipoles rather than the inverted V.⁶ Cebik later posted a more thorough analysis on his web page.⁷ His principal result, the graph of an analysis of the effect of differing half-wave line-length multiples, is also found in a talk⁸ by Jim George, N3BB, and is reproduced in Figure 4.

This antenna has proven to be a useful addition to the toolkit of station design and

construction. We made use of several such dipoles in our successful contest station⁹ in the Galápagos Islands, HC8N.

In experimenting with a 40-m dipole and this feed system, I found that one could compensate for antenna mistuning by adjusting the length of the 50 Ω transmission line. This is in essence creating a series-section transformer to match an arbitrary impedance.¹⁰ An extended analysis of the transmission-line matching scheme is found in a paper¹¹ by E. J. Shortridge, W4JOQ. However, it is generally easier to adjust the length of the dipole legs themselves, rather than change the transmission line lengths and/or impedances. Once the required multiple



QX1809-Leeson04

Figure 4 — Wide-band match calculated by Cebik, W4RNL.

half-wave $50\ \Omega$ transmission line is in place, an antenna impedance bridge can be used at the feed end on the ground to cut the antenna to resonance at the chosen center frequency.

History of Broadband Matching Alternatives

Broadband impedance matching¹² has drawn particular interest since the development of microwave radar in the Second World War. The classic Fano paper¹³ that defined limits appeared as a thesis in 1948, and was published in 1950. The specific techniques of broadband antenna matching have been explored over the years.¹⁴ The continuing interest in dipole matching bandwidth is evidenced by a recent paper¹⁵ on the subject.

In general, a dipole antenna can be rendered more broadband by increasing its diameter to reduce the reactance variation with frequency — but at the lengths of HF antennas this is not a great improvement even if a wire cage is employed — or by compensating the feed point reactance variation with some form of matching network, preferably one that does not introduce excessive loss. A useful simple model for the driving impedance of a half-wave dipole antenna near resonance is a quarter-wave transmission line loaded by a resistance corresponding to the radiation resistance.¹⁶ The reactance is not zero at an exact half-wave length, and is typically zero at a length slightly less than one half wave. The exact reactance at a half-wave and the length

for zero reactance both depend on the diameter and shape of the dipole. There are more precise lumped-element models in recent literature.¹⁷ Two comprehensive summaries of broadband antenna models and impedance matching are by S. Stearns, K6OIK.¹⁸

The search for a broadband 80-m dipole antenna has a long history, culminating in a series of articles¹⁹ by Frank Witt, AI1H. Beginning with the antennas seen in early radio, a wide range of broadbanding concepts has been explored. Here are some major categories:

- Cage, parallel wire, fan or bow-tie dipoles that have a large equivalent diameter or that approximate conical dipoles²⁰
- “Bazooka” dipoles with coaxial radiating elements²¹
- Multiple dipoles with staggered resonances²²
- Dipoles with a coupled resonator “open-sleeve” element²³

- Dipoles with lumped reactive matching networks²⁴
- Dipoles with coaxial radiating and matching elements²⁵
- Dipoles with resonant feed line matching, as outlined in this article.

Collinear half-wave dipoles have higher feed-point impedance and could provide wider bandwidth. A simpler version is the Extended Double Zepp, but in either case the pattern may be narrower than desired and the extra physical length may be undesirable.²⁶

The “open sleeve” or coupled dipole approach is similar in concept to the technique of using a Yagi director close-coupled to the driven element in the “OWA” Yagi designs that produce a wide SWR curve.²⁷

There are mechanical and reliability problems associated with many of the broadbanding schemes. Cage and multiple dipole configurations have a tendency to become twisted in the wind, are difficult to construct and install, take up more space, and have greater visual impact than a simple dipole. Coaxial radiating elements require sealing from the weather, are heavy to support and are not necessarily strong enough to avoid stretching under load. In addition, some of the published designs don't have sufficient broadband response, while others are broadband mainly because of losses in the matching network.

The advantage of resonant feed-line matching lies in its simplicity and the fact that there are no additional losses at the

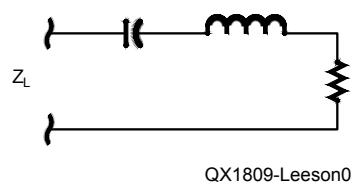
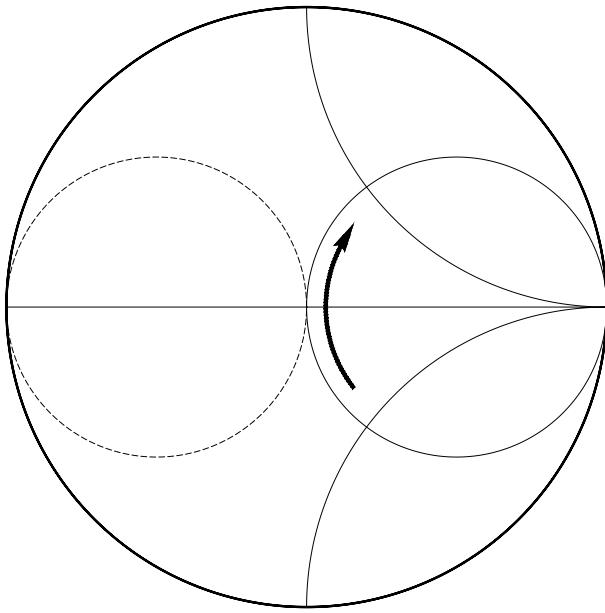
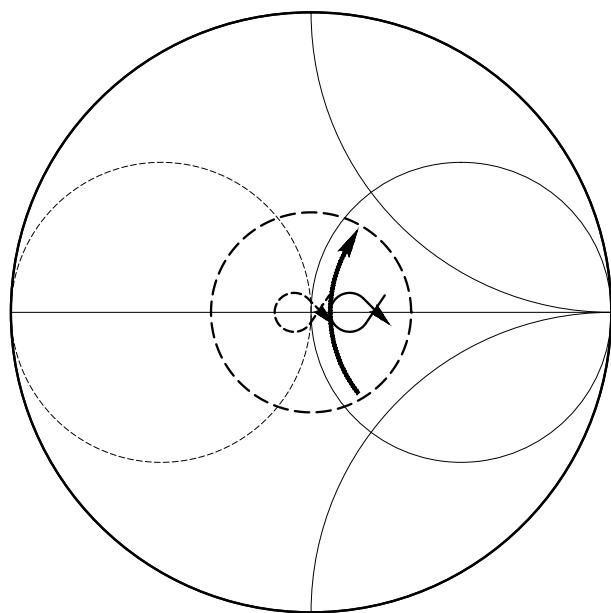


Figure 5 — Dipole equivalent circuit.



QX1809-Leeson06a



QX1809-Leeson06b

Figure 6 — Smith chart shows impedance vs. frequency, (A) on left at antenna terminals, and (B) after multiple half waves.

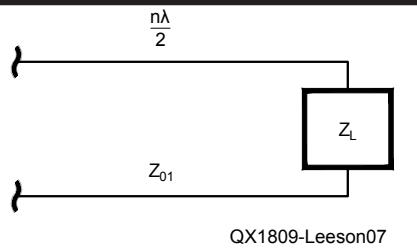


Figure 7 — Multiple half-wave transmission line.

antenna itself. For the specific application in the 80-m amateur band, this approach has proven to be effective and reliable.

Visualizing How This Works

Circuit theory and a Smith chart representation can help to understand how resonant matching of resonant elements works.²⁸ This technique is particularly applicable in the case of a load impedance that has the characteristics of a series *RLC* network. This is typical of antennas, and is shown schematically in Figure 5.

A Smith chart is a polar plot of complex reflection coefficient. The impedance plot of this form of load, in this case for $R > Z_0$, is shown in the Smith chart plot of Figure 6A, with the arrow in the direction of increasing frequency. Placing a parallel resonant circuit across the terminals of the dipole, or feeding it through a single or multiple half-wave line of suitable Z_0 , results in a trace that curls back on itself as frequency varies.

The operation of the matching network is to close up the arc of the impedance plot as shown in the Smith chart of Figure 6B, resulting in a smaller range of SWR. In particular, the feed line of Figure 7 is electrically shorter at the low-frequency end, and longer at the high-frequency end, thus achieving the desired closing of the impedance curve.

A final step is to use a matching network such as an *LC* network, its transmission line equivalent or the series section network to bring the smaller impedance plot to the center of the Smith chart. As sought in filter design and current ultra-wideband antenna work, a trace that curls around the center of the Smith chart represents a broadband low SWR.²⁹

This type of resonant matching is not widely known, but is highly effective in the case of impedances of the form of a loaded series resonant circuit. More than one half-wavelength can be used if the line impedance is not optimum, and a short addition or subtraction can be made from the line length to “center” an impedance plot that is not symmetrical. For the specific impedance plot shown here, we require $Z_01 < R_L$.

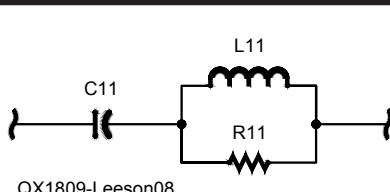


Figure 8 — Dipole equivalent circuit, from Tang, et al.

More detailed descriptions of this matching concept have been available in the technical literature for quite some time.

Dipole Models of Improved Accuracy

Tang, et al.³⁰, present some more accurate equivalent circuits for a dipole near its half-wave resonance. These may possibly be worth exploring, but the simple three-element equivalent circuit, as shown in Figure 8, seems adequate for this application.

In this model, the series capacitance is,

$$C_{11} = \frac{27.82 \times 10^{-12} h}{\{ \ln(2h/a) - 1.693 \}} \quad (1)$$

where h is the half length of the dipole and a is the radius. The inductance is,

$$L_{11} = \frac{1}{\omega_0^2 C_{11}} + C_{11} R_{ao}^2 \quad (2)$$

and the resistance is,

$$R_{11} = \frac{L_{11}}{C_{11} R_{ao}} \quad (3)$$

where ω_0 is the resonant frequency and R_{ao} is the radiation resistance at resonance.

For a 3.65 MHz dipole using #10 AWG wire, the values are, $C_{11} = 61.1 \text{ pF}$, $L_{11} = 31.4 \mu\text{H}$ and $R_{11} = 7.13 \text{ k}\Omega$.

This model can be used with a Smith chart to experiment with various wide-band matching schemes. In general, the amateur bands are sufficiently narrow that the improvement available from a better model is not likely to have much effect, and in any event the Witt broadband transmission-line matching approach provides a very simple and useful antenna.

Dave Leeson, W6NL, was first licensed in 1952. He enjoys the friendship, technology and contesting aspects of ham radio, having been part of winning radiosport efforts from North Africa, the Caribbean, the Galápagos and California. He is the author of the ARRL book Physical Design of Yagi Antennas, and was a designer of the IARU International

Beacon Network. He drove a racecar, retiring in 1979 to return to ham radio after back-to-back national championships. Professionally, he received degrees from Caltech, MIT and Stanford, is the author of widely cited journal papers on oscillator phase noise and nonlinear circuits, and is a Life Fellow of the IEEE. From 1968 to 1993, he was the founding Chairman and CEO of California Microwave, Inc., retiring with a staff of two thousand. Since 1994, he has been a Consulting Professor at Stanford, and is the faculty advisor of the Stanford Amateur Radio Club, W6YX.

Notes

¹F. Witt, AI1H, “Broadband Antenna Matching,” Chap. 9 in R. D. Straw (Ed.), 19th and 20th Ed., *The ARRL Antenna Book*, pp. 9-1 to 9-18.

²D. B. Leeson, W6NL, [TowerTalk] “Wideband 80 and 40 dps,” 26 Nov. 1997, lists.con-testing.com/pipermail/towertalk/1997-November/011030.html.

³F. Witt, AI1H, “A Simple Broadband Dipole For 80 Meters”, *QST*, Sept. 1993, pp. 27-30, 76.

⁴D. B. Leeson, W6NL, Chap. 9, “Impedance Matching” in *Microwave Engineering Notes*, Stanford University, 2005; Montgomery, Dicke and Purcell, *Principles of Microwave Circuits*, MIT Rad Lab Series #8, McGraw-Hill, 1947, pp. 203-6, and P. Rizzi, *Microwave Engineering - Passive Circuits*, Prentice Hall, 1988, pp. 127-132.

⁵D. B. Leeson, W6NL, “Antennas for 1998 Sweepstakes”, NCCC, Oct. 12, 1998; also G. Ordy, “W8WWV - The 80 Meter Inverted Vee (Original), www.seed-solutions.com/gregordy/Amateur%20Radio/Experimentation/Vee80.htm.

⁶L. B. Cebik, W4RNL, [TowerTalk] “Wideband 80 meter dipoles,” 27 Nov. 1997, lists.con-testing.com/pipermail/towertalk/1997-November/011041.html.

⁷L. B. Cebik, W4RNL, “Notes on a wideband 50/75-Ohm coaxial feed system for low HF band dipoles and Vees,” Nov. 29, 1997, www.antentop.org/w4rnl.001/wb.html.

⁸J. George, N3BB, “A Broadband Feed System for an 80 Meter Antenna System”, www.ctdccc.org/n3bb/broadband_antenna/A_Broadband_80_Meter_Antenna_System.ppt.

⁹Contesting in the Galápagos Islands, www.kkn.net/~trey/HC8_10a.pdf.

¹⁰F. Regier, “Impedance Matching with a Series Transmission Line Section”, *Proc. IEEE*, Vol. 59, No. 7, July 1971, pp. 1133-1134; also R. D. Straw (Ed.), *The ARRL Antenna Book*, 19th Ed., “Series Section Transformer”, pp. 26-5 and 28-13.

¹¹E. J. Shortridge, W4JOQ, “Type S Series-Section Broad-banding of 75- to 80-meter Antennas”, docplayer.net/21727218-Type-s-series-section-broad-banding-of-75-to-80-meter-antennas-by-edward-j-shortridge-w4joq.html.

¹²See: www.ieeeghn.org/wiki/index.php/History_of_Broadband_Impedance_Matching.

¹³R. M. Fano, “Theoretical Limitations on the Broadband Matching of Arbitrary Impedances”, *Journal Franklin Inst.*, Vol. 249, No. 2, Feb. 1950, pp. 139-154; see also the same title as *MIT Research Laboratory of Electronics Technical Report No. 41*, Jan. 2, 1948.

- ¹⁴R. C. Hansen, "Fano Limits on Matching Bandwidth", *IEEE Antennas and Propagation Magazine*, Vol. 47, No. 3, June 2005, pp. 89 – 90.
- ¹⁵M. Hirvonen, A. Juhanan, J. Holmberg and J. C.-E. Sten, "Bandwidth Limitations of Dipoles Matched with Non-Foster Impedances," *Proceedings of European Conference on Antennas and Propagation, EUCAP 2007*, Nov. 2007, lib.tkk.fi/Diss/2008/isbn9789513871093/article3.pdf.
- ¹⁶D. B. Leeson, W6NL, Ch. 8 "Self-Impedance of Yagi Elements," in *Physical Design of Yagi Antennas*, ARRL, 1992, pp. 8-1 to 8-30.
- ¹⁷G. Tang, Q. M. Tieng, and M. W. Gunn, "Equivalent Circuit of a Dipole Antenna Using Frequency-Independent Lumped Elements", *IEEE Trans AP*, Vol. 41, No. 1, Jan. 1993, pp. 100-103; also K. Rambabu, M. Ramesh and A.T. Kalghatgi, "Broadband Equivalent Circuit of a Dipole Antenna", *IEE Proc.-Microw. Ant. Prop.*, Vol. 146, No. 6, Dec. 1999, pp. 391-393; also B. Long, B. P. Werner and D. Werner, "A Simple Broadband Dipole Equivalent Circuit Model", *IEEE Antennas and Propagation Society International Symposium*, 2000, Vol. 2, pp. 1046-1049.
- ¹⁸S. Stearns, K6OIK, "Antenna Impedance Models — Old and New", Oct. 2004, www.fars.k6ya.org/docs/antenna-impedance-models.pdf; also S. Stearns, K6OIK, "New Results on Antenna Impedance Models and Matching", Oct. 2007, www.fars.k6ya.org/docs/New-Results-on-Antenna-Impedance-Models-and-Matching.pdf.
- ¹⁹Search 'Frank Witt, AI1H' at www.arrl.org/arrl-periodicals-archive-search, for Witt's articles, also see G. Hall, K1TD, "The Search for a Simple Broadband 80-Meter Dipole," *QST*, Apr. 1983, pp. 22-27.
- ²⁰S. Schelkunoff, "Theory of Antennas of Arbitrary Size and Shape," *Proc. IRE*, Vol. 29, No. 9, Sep. 1941, pp. 493-521; also A. Harbach, WA4DRU, "Broad-Band 80-Meter Antenna", *QST*, Dec. 1980, pp. 36-37; also R. C. Wilson, "Fat Dipoles", *Antenna Compendium*, Vol. 2, pg. 106. ARRL, 1989; Equivalent diameter is calculated by the formula of Y. Mushiake, S. Uda, S. and Y. Mushiake, "Equivalent radii of various cylindrical antennas", Sec. 3.3 in *Yagi-Uda Antenna*, Sasaki, Ltd. 1954, pp. 16-20, see J. Lawson, *Yagi Antenna Design*, ARRL, 1986, pp. 7-12.
- ²¹W. Maxwell, W2DU, "The Broadband Double Bazooka Antenna — How Broad Is It?" Ch. 18 in *Reflections*, 2nd Ed., World Radio Books, 2001; k6mhe.com/files/W2DU_DoubleBazooka.pdf.
- ²²J. Lawson, W2PV, "60/80/75-Meter Broad-Band Inverted--V Antenna", *QST*, Nov. 1970, pp. 17-20, 42; see also M. A. Logan, K4MT, "Stagger-Tuned Dipoles Increase Bandwidth," *Ham Radio*, May 1983, pg. 22.
- ²³R. Severns, N6LF, "A Wideband 80-Meter Dipole", *QST*, July 1995, pp 27-29; rudys.typepad.com/ant/files/antenna_broad-band_dipole.pdf.
- ²⁴F. Witt, AI1H, "Broadband Dipoles—Some New Insights", *QST*, Oct. 1986, pp. 27-37.
- ²⁵F. Witt, AI1H, "The Coaxial Resonator Match and the Broadband Dipole," *QST*, April 1989, pp. 22-27; see also S. Phillips, K6TU, "A Broadband Contest Antenna for 80m", 1vc.typepad.com/ethergeist/2011/01/a-broadband-contest-antenna-for-80m.html.
- ²⁶R. Severns, N6LF, "An Improved Extended Double Zepp", *Antenna Compendium* Vol. 4, ARRL, 1995; rudys.typepad.com/ant/files/antenna_colinear_zepp.pdf.
- ²⁷For a review of OWA concepts by J. Breakall, WA3FET, and N. Miller, NW3Z, see "The Optimized Wideband Antenna (OWA) Yagi", www.naic.edu/~angel/kp4ao/ham/owa.html and L. B. Cebik, W4RNL, "Notes on the OWA Yagi", *QEX*, ARRL, July/Aug. 2002, pp. 22-34; also D. B. Leeson, *Physical Design of Yagi Antennas*, ARRL, 1992.
- ²⁸D. B. Leeson, "Circuit Elements, Transmission Lines, the Smith Chart and S-Parameters", *Stanford University EE344*, Oct. 1997.
- ²⁹See, K. P. Ray, "Design Aspects of Printed Monopole Antennas for Ultra-Wide Band Applications", in J. Becker, et al. (Ed.), "Ultra-Wideband Antennas", *Int'l J. Ant. and Prop.*, 2008, pg. 14; www.hindawi.com/journals/ijap/si/351924/.
- ³⁰T. Tang, Q Tieng and M. Gunn, op cit.