

Errata, Clarifications, and Additions to the first printing of
Transmission Line Design Handbook, ©1991–94 B.C. Wadell, All Rights Reserved
 Monday, June 3, 2002

1. Correct (4.5.1.47) p. 203 to read the following:

$$\varepsilon_{eff}(0) = 0.5 (\varepsilon_r + 1.0) + 0.5 (\varepsilon_r - 1.0) \left(1.0 + \frac{10.0}{v}\right)^{-a_e(v)} b_e(\varepsilon_r) \quad (4.5.1.42)$$

The equation given as (4.5.1.42) should be deleted and (3.5.1.2) and (3.5.1.3) should be used instead.

Thanks to Marvin Green.

2. The equations for Q_0 were omitted in section 4.5.1 beginning on p. 199. These are:

$$Q_0 = R_7 \left[1.0 - \frac{1.1241 R_{12}}{R_{16}} e^{(-0.026 f_n^{1.15656} - R_{15})} \right] \quad (4.5.1.3a)$$

$$R_1 = 0.03891 \varepsilon_r^{1.4}$$

$$R_2 = 0.267 u^{7.0}$$

$$R_7 = 1.206 - 0.3144 e^{-R_1} [1.0 - e^{-R_2}]$$

$$R_{10} = 0.00044 \varepsilon_r^{2.136} + 0.0184$$

$$R_{11} = \frac{\left(\frac{f_n}{19.47}\right)^{6.0}}{\left[1.0 + 0.0962 \left(\frac{f_n}{19.47}\right)^{6.0}\right]}$$

$$R_{12} = \frac{1.0}{1.0 + 0.00245 u^2}$$

$$R_{15} = 0.707 R_{10} \left(\frac{f_n}{12.3}\right)^{1.097}$$

$$R_{16} = 1.0 + 0.0503 \varepsilon_r^2 R_{11} \{1.0 - \exp[-(u/15)^6]\}$$

Thanks to Marvin Green.

3. Equation (4.5.1.13) p. 200 is missing a subscript. It should read:

$$Z_{0,e}(f_n) = \frac{Z_{0,e}(0) \{0.9408 [\varepsilon_{eff}(f_n)]^{C_e - 0.9603}\}^{Q_0}}{\{(0.9408 - d_e) [\varepsilon_{eff}(0)]^{C_e - 0.9603}\}^{Q_0}} \quad (4.5.1.13)$$

Thanks to Marvin Green.

4. Several clarifications should be added to section 4.5.1 and an omission must be corrected. $Z_0(f)$ is the frequency-dependent single-strip characteristic impedance. The permittivity $\epsilon_{eff}(f_n)$ is the single-strip frequency-dependent permittivities. The dc values are $Z_0(0)$ and $\epsilon_{eff}(0)$.

$$\epsilon_{eff}(f_n) = (3.5.1.7)$$

$$\epsilon_{eff}(0) = (3.5.1.2) \text{ and } (3.5.1.3)$$

$$Z_0(0) = (3.5.1.1)$$

$$Z_0(f_n) = Z_0(0) (R_{13} / R_{14})^{R_{17}}$$

$$R_{17} = Q_0 (4.5.1.3a)$$

$$R_{13} = 0.9408 \epsilon_{eff}(f_n)^{R_8} - 0.9603$$

$$R_{14} = (0.9408 - R_9) \epsilon_{eff}(0)^{R_8} - 0.9603$$

$$R_8 = 1.0 + 1.275 \{ 1.0 - \exp[-0.004625 R_3 \epsilon_r^{1.674} (f_n / 18.365)^{2.745}] \}$$

$$R_9 = 5.086 R_4 \frac{R_5}{0.3838 + 0.386 R_4} \frac{e^{-R_6}}{1.0 + 1.2992 R_5} \frac{(\epsilon_r - 1.0)^6}{1.0 + 10.0 (\epsilon_r - 1.0)^6}$$

$$R_3 = 4.766 \exp(-3.228 u^{0.641})$$

$$R_4 = 0.016 + (0.0514 \epsilon_r)^{4.524}$$

$$R_5 = (f_n / 28.843)^{12.0}$$

$$R_6 = 22.20 u^{1.92}$$

Thanks to Marvin Green.

5. Equation (4.5.1.21) on page 201 is typeset poorly. For clarity, it is:

$$Q_{12} = 2.121 \frac{(f_n / 20)^{4.91}}{[1.0 + Q_{11} (f_n / 20)^{4.91}]} \exp(-2.87 g) g^{0.902} \quad (4.5.1.21)$$

Thanks to Marvin Green.

6. Page 207 is missing a reference for section 4.5.1:

[7a] Jansen, Rolf, and Martin Kirschning “Arguments and an Accurate Model for the Power-Current Formula of Microstrip Characteristic Impedance,” *Archiv Für Elektronik und Übertragungstechnik*, Band 37, Heft 3/4, 1983, pp. 108–112.

Thanks to Marvin Green.

7. In section 12.3.5, pp. 482–485 a secondary source was referenced for the techniques of combining two-ports. The original development of this technique was carried out by Les Besser which is described in his original papers (add to References page 485):

[0] Besser, Les, “A Fast Computer Routine to Design High Frequency Circuits,” *IEEE International Conference on Communications*, San Francisco, June 8–10, 1970, pp. 24-13–24-16.

[0a] Besser, Les, and R.W. Newcomb, “A Scattering Matrix Program for High Frequency Circuit Analysis,” *Proceedings of the IEEE Conference on Systems, Networks, and Computers*, Mexico, January 1971, pp. 512–515.

Thanks to Les Besser.

8. In equation (4.5.3.43), page 213 the function should be sin() rather than csc(). It should read:

$$E = 0.725 \sin\left(\frac{\pi y}{2.0}\right) \quad (4.5.3.43)$$

Thanks to Doug White.

9. In equation (3.5.1.7) on page 95 the superscript is missing. It should read:

$$P(f) = P_1 P_2 [(0.1844 + P_3 P_4) (10.0 fh)]^{1.5763}$$

The second line of 3.5.1.1 should read:

with ([28], see also [35]):

Thanks to A.J. DeKremer.

10. In equation (3.5.1.3) page 94 “12.o” should read “12.0”.

11. On page 386, in equation (6.3.1.2) d is not defined. It is

$$d = \sqrt{4.0 a^2 + b^2} \quad (6.3.1.3a)$$

Thanks to Bob Stengel.

12. Equation (3.4.1.5), p. 74 should read

$$k_t' = \sqrt{1.0 - k_t^2}$$

Thanks to Paul Levin.

13. On page 133 equations (3.6.3.21)–(3.6.3.30)

$$h_2 > h_1$$

Figures 3.6.3.2 and 3.6.3.3 appear to have $h_1 > h_2$ which is not correct.

Thanks to Donald Ingram.

14. On page 126 and 127, the variable b in (3.6.2.1), (3.6.2.4), (3.6.2.5), (3.6.2.6), and (3.6.2.7) should be replaced with $(b - t)$ to improve accuracy for

$t \ll b$. Equations (3.6.2.1–6) are due to [9]. Equation (3.6.2.2) becomes:

$$b = 2.0 h + t \tag{3.6.2.2}$$

Thanks to Steve Hauptman.

15. The last line on page 23 should read “and we calculate the guide wavelengths of the fundamental and harmonics as (2.3.12).”

16. On page 479 the s -parameter suffixes are scrambled. Equations (12.3.1.4–6) should read:

$$s_{21} = \frac{b_2}{a_1} \Big|_{a_2 = 0} \tag{12.3.1.4}$$

$$s_{22} = \frac{b_2}{a_2} \Big|_{a_1 = 0} \tag{12.3.1.5}$$

$$s_{12} = \frac{b_1}{a_2} \Big|_{a_1 = 0} \tag{12.3.1.6}$$

Thanks to Les Besser.

17. In the software example on page 470 constants CONST1 and CONST2 are undefined. They are defined in the program header with

```
#define CONST1 0.57215665  
#define CONST2 0.63661978
```

Thanks to Robert Lafevre.

18. Figure 5.9.1.3 on page 371 is missing captions. The upper arrow should be labeled microstrip line and the lower is pointing to the ground plane.

19. A new relation for via inductance was presented recently in the literature. Numerical simulation and measurements show good agreement with a relatively simple closed-form equation. The interested reader should refer to:

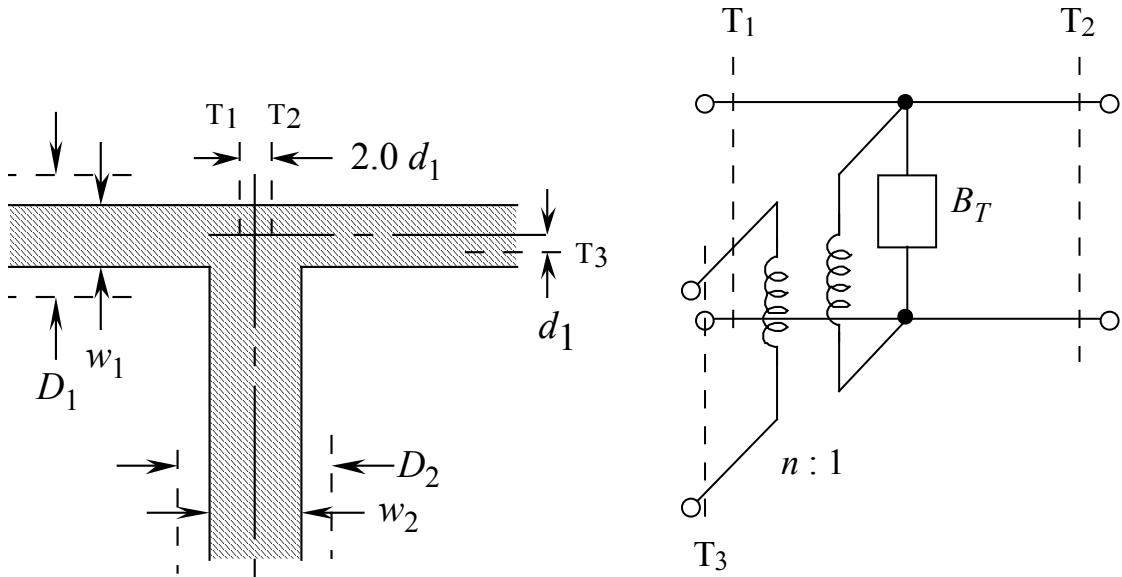
[4a] Goldfarb, Marc E., and Robert A. Pucel, “Modeling Via Hole Grounds in Microstrip,” *IEEE Microwave and Guided Wave Letters*, Vol.1, No. 6, June 1991, pp. 135–137.

20. A number of people have requested information on calculation of complete elliptic integrals. A detailed example is attached as the last page of this document.

21. In the solution to the example on pp. 75–76 the answer should read:

$b = 0.0221 \text{ in.} = 0.0561 \text{ cm}$ $\epsilon_{eff} = 4.45$

22. On page 310, Figure 5.5.10.2 should be



Thanks to Robert Lafevre.

23. On page 126, Equation (3.6.1.1) should read:

$$Z_0 = \frac{h_0}{4.0 \sqrt{\epsilon_r}} \frac{K(k)}{K'(k)} \quad (3.6.1.1)$$

Thanks to Juan Milton Garduño.

24. On page 475, Equation (12.2.4.2a) has a variable z . Replace z with x everywhere.

25. On page 79, Equations (3.4.2.1) and (3.4.2.2) do not define ϵ_1 , and ϵ_2 . The replacement figure and equations below define them:

$$Z_0 = \frac{\eta_0}{(\sqrt{\epsilon_{r1}} + \sqrt{\epsilon_{r2}})} \frac{K(k)}{K'(k)} \quad (\Omega) \quad (3.4.2.1)$$

$$\epsilon_{eff} = \frac{(\sqrt{\epsilon_{r1}} + \sqrt{\epsilon_{r2}})^2}{4.0} \quad (3.4.2.2)$$

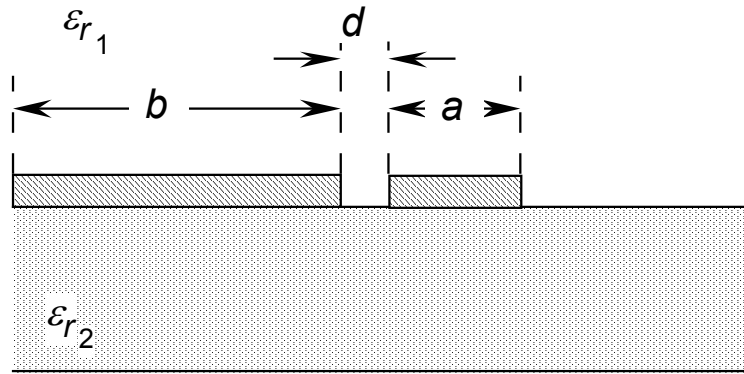


Figure 3.4.2.1: Micro-Coplanar Stripline

26. In section 4.4.3 β_1 is undefined. The necessary relations are:

$$\beta_1 = \sqrt{\frac{1.0 - y^2}{1.0 - k_1^2 y^2}} \quad (4.4.3.13)$$

$$y = \frac{s}{s + 2.0 w} \quad (4.4.3.14)$$

$$k_1 = \frac{s + 2.0 w}{s + 2.0 w + 2.0 d} \quad (4.4.3.15)$$

27. On page 79, the equation is correct but does not follow the format used elsewhere in the book. Replace Equation (3.4.3.1) with

$$Z_0 = \frac{h_0}{2.0 \sqrt{\epsilon_{eff}}} \frac{1.0}{\frac{K(k)}{K(k')} + \frac{K(k_1)}{K(k_1')}}} \quad (3.4.3.1)$$

28. On page 233, the first line references Cohn [3]. The correct reference is Cohn [2].

29. The equations for three coplanar strips (Section 3.4.8) have errors present in the original reference. The corrections are:

$$Z_0 = \frac{\eta_0}{4.0 \sqrt{\epsilon_{eff}}} \frac{1.0}{\frac{K(k_1')}{K(k_1)} + \frac{t}{b-a}} \quad (\Omega) \quad (3.4.8.1)$$

$$\epsilon_{eff} = 1.0 + \frac{(\epsilon_r - 1.0)}{2.0} \frac{\frac{K(k_2')}{K(k_2)}}{\frac{K(k_1')}{K(k_1)} + \frac{t}{b-a}} \quad (3.4.8.2)$$

Thanks to Paul Levin, and Stuart M. Wentworth.

30. On page 204, (4.5.1.59) should read:

$$P_4 = 1.0 + 2.751 [1.0 - e^{-(\varepsilon_r / 15.916)^8}] \quad (4.5.1.59)$$

31. On page 71, in (3.3.5.1) the variable ε is e , the Napierian constant (2.71828...).

32. On page 246, the equation for k_2 , (4.8.1.8), should read (sign change in denominator):

$$k_2 = \sqrt{\frac{1.0 + \tan^2 \mathcal{G}_2'}{1.0 + \tan^2 \mathcal{G}_1'}} \quad (4.8.1.8)$$

Note, that in (4.8.1.6), (4.8.1.8), (4.8.1.9), and (4.8.1.10) the function tg is the tangent and th is the hyperbolic tangent.

Thanks to Santana Roy, Derek Tong, and Yunyi Wang.

33. On page 158, (3.9.6.7) the first line should read (change to first coefficient in numerator of third term):

$$= \left\{ 1.045 - 0.365 \ln \varepsilon_r + \frac{6.3 (w/h) \varepsilon_r^{0.945}}{238.64 + 100.0 w/h} \right.$$

Equations (3.9.6.1-4) were incorrectly converted from \log_{10} to \ln and should read:

$$\begin{aligned} Z_0 = & 72.62 - 15.283 \ln \varepsilon_r + \frac{50.0 (w/h - 0.02)(w/h - 0.1)}{w/h} \\ & + 0.434 \ln (w/h \infty 10^2) (44.28 - 8.503 \ln \varepsilon_r) \\ & - [0.139 \ln \varepsilon_r - 0.11 + w/h (0.465 \ln \varepsilon_r + 1.44)] \\ & \infty (11.4 - 2.636 \ln \varepsilon_r - h/\lambda \infty 10^2)^2 \end{aligned} \quad (3.9.6.1)$$

$$\begin{aligned} \varepsilon_{eff} = & \left(\frac{\lambda_g}{\lambda_0} \right)^{-2} \\ = & [0.923 - 0.195 \ln \varepsilon_r + 0.2 w/h \\ & - (0.126 w/h + 0.020) \ln (h/l_0 \infty 10^2)]^{-2} \end{aligned} \quad (3.9.6.2)$$

and for $0.2 \leq w/h \leq 1.0$

$$\begin{aligned} Z_0 = & 113.19 - 23.257 \ln \varepsilon_r + 1.25 w/h (114.59 - 22.531 \ln \varepsilon_r) \\ & + 20.0 (w/h - 0.2) (1.0 - w/h) \end{aligned}$$

$$- [0.15 + 0.0999 \ln \varepsilon_r + w/h (-0.79 + 0.899 \ln \varepsilon_r)]$$

$$\infty \{ [10.25 - 2.171 \ln \varepsilon_r + w/h (2.1 - 0.617 \ln \varepsilon_r) - h/\lambda \infty 10^2]^2 \} \quad (3.9.6.3)$$

$$\varepsilon_{eff} = \left(\frac{\lambda_g}{\lambda_0} \right)^{-2}$$

$$= [0.987 - 0.210 \ln \varepsilon_r + w/h (0.111 - 0.0022 \varepsilon_r)$$

$$- (0.0525 + 0.0408 w/h - 0.00139 \varepsilon_r) \ln(h/\lambda \infty 10^2)]^{-2} \quad (3.9.6.4)$$

Thanks to Ján Zehentner.

33. On page 250, (4.8.2.4) the variables H and P should be H_e and P_e . Equation (4.8.2.10) should be the equation for T_e rather than P_e .

34. On page 347, the λ in equation (5.6.2.3) should be λ_g , the guide wavelength.

Thanks to Dave Mesaros.

35. On page 130, equation (3.6.3.7) should read:

$$C_f = \frac{\varepsilon_r \varepsilon_0}{p} \left\{ 2.0 \ln \left[\frac{1.0}{g(b-g)} \right] + \frac{1.0}{g(b-g)} \left[F\left(\frac{t}{2.0b}\right) - F(c_l/b) \right] \right\}$$

36. On page 495, *Appendix B Common Questions and Answers* the first sentence of the third question's answer should be corrected to read:

Unless one conductor is completely shielded, it is impossible to have no ($-\infty$ dB) coupling.

Thanks to Larry Tichauer.

37. Equation (2.7.1.5) should be:

$$d = \sqrt{\frac{2.0}{\omega \mu \sigma}} = \frac{1.0}{\sqrt{\pi f \mu \sigma}} = \text{skin depth} \quad (2.7.1.5)$$

38. Correct (4.5.4.1) to read:

$$h = \left(\frac{b_{sl} - s_{sl}}{4.0} \right) \quad (4.5.4.1)$$

Thanks to Dennis Hand.

39. The second equation in section 12.2.1 Hyperbolic Functions on page 465 should read:

$$e^x = \cosh x + \sinh x$$

Thanks to Anson Whealler.

40. Equations (3.9.6.7-8) have typos, the factors 6.4 and 1.8 should be changed to 6.3 and 1.0:

$$\begin{aligned} \varepsilon_{eff} &= \left(\frac{\lambda_g}{\lambda_0} \right)^{-2} \\ &= \left\{ 1.045 - 0.365 \ln \varepsilon_r + \frac{6.3 (w/h) \varepsilon_r^{0.945}}{238.64 + 100.0 w/h} \right. \\ &\quad \left. - \left[0.148 - \frac{8.81 (\varepsilon_r + 0.95)}{100.0 \varepsilon_r} \right] \ln \frac{h}{\lambda_0} \right\}^{-2} \end{aligned} \quad (3.9.6.7)$$

$$\begin{aligned} Z_0 &= 133.0 + 10.34 (\varepsilon_r - 1.8)^2 + 2.87 [2.96 + (\varepsilon_r - 1.582)^2] \\ &\quad \left\{ (w/h + 2.32\varepsilon_r - 0.56) [(32.5 - 6.67 \varepsilon_r)(100.0 h / \lambda_0)^2 - 1.0] \right\}^{1/2} \\ &\quad - (684.45 h / \lambda_0)(\varepsilon_r + 1.35)^2 + 13.23 [(\varepsilon_r - 1.722) w / \lambda_0]^2 \end{aligned} \quad (3.9.6.8)$$

Thanks to Stephen Maas.

41. In 5.5.13.6 the numerator of the second term should be “+”. In 5.5.13.7 the sign for the last term should be “+”.

$$A = \left(\frac{1.0 + a}{1.0 - a} \right)^{2.0} a \left[\frac{1.0 + \sqrt{1.0 - \left(\frac{2.0 w_{eff,1}}{D \lambda_1} \right)^2}}{1.0 - \sqrt{1.0 - \left(\frac{2.0 w_{eff,1}}{D \lambda_1} \right)^2}} \right] - \frac{1.0 + 3.0 a^2}{1.0 - a^2} \quad (5.5.13.6)$$

$$B = \left(\frac{1.0 + a}{1.0 - a} \right)^a / 2.0 \left[\frac{1.0 + \sqrt{1.0 - \left(\frac{2.0 w_{eff,2}}{D \lambda_2} \right)^2}}{1.0 - \sqrt{1.0 - \left(\frac{2.0 w_{eff,2}}{D \lambda_2} \right)^2}} \right] + \frac{3.0 + a^2}{1.0 - a^2} \quad (5.5.13.7)$$

Thanks to Stephen Maas.

42. In (3.2.3.7) the “-” sign should be “+.”

$$\alpha_c = \alpha_{c,centered} \left[1.0 + \frac{2.0 e^2}{k} + \frac{e^2 k^2}{(k^2 - 1.0) \log k} \right] \quad (\text{dB / m}) \quad (3.2.3.7)$$

Thanks to Edward Wollack.

43. In (5.5.13.11) swap the words “symmetrical” and “asymmetrical.”

$$\Delta = \begin{cases} 1 & \text{for asymmetrical steps} \\ 2 & \text{for symmetrical steps} \end{cases} \quad (5.5.13.11)$$

Thanks to Stephen Maas.

44. In Table 9.2.4.1 the $\tan \delta$ for Kapton should read “0.0025.” The decimal point is missing.

45. In (5.5.1.1) the equation is for the total inductance ($2L$) so it should be divided by 2.

$$L/h = \frac{100.0}{2.0} (4.0 \sqrt{w/h} - 4.21) \text{ (nH/m)} \quad (5.5.1.1)$$

Also (5.5.1.5) is an equation for L/h not L as indicated.

$$L = 0.22 h \left[1.0 - 1.35 e^{-0.18(w/h)^{1.39}} \right] \text{ (nH)} \quad (5.5.1.5)$$

Thanks to C. James.

46. Equation (5.5.1.4) has an incorrect constant. The constant 5.44 should be 5.64.

$$C = 0.001 h \left[(10.35 \epsilon_r + 2.5) (w/h)^2 + (2.6 \epsilon_r + 5.64) (w/h) \right] \text{ (pF)} \quad (5.5.1.4)$$

47. In section 4.3.2 there are two undefined variables, C and D . They are:

$$C = s + d \quad (4.3.2.1.7b)$$

$$D = \frac{w - C}{2.0} \quad (4.3.2.1.7c)$$

Thanks to John Beeley.

48. In (1.9) the X should be subscripted

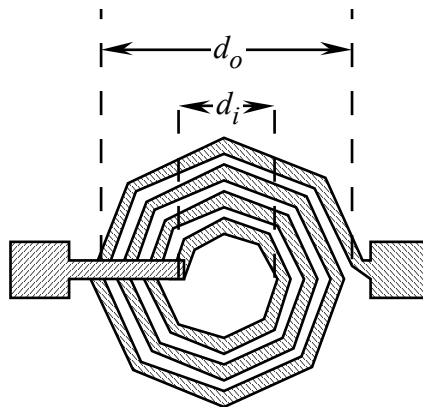
$$C = \frac{-1.0}{X_C \omega} \quad (1.9)$$

Thanks to Dennis Han.

49. In (3.4.1.12) the units should read Ω/o .

50. In reference [9] in section 6.4.2 the word *Microwave* is misspelled.

51. Figure 6.4.5.1 is missing notations for d_o and d_i and a, c, n in the associated equation 6.4.5.1 are undefined. The missing information is:



$$a = \frac{d_o + d_i}{4.0}$$

$$c = \frac{d_o - d_i}{2.0}$$

and n is the number of turns.

52. In (6.5.1.1) the units of h are cm. The reference should be [3]. The reference of table 6.5.1 should be [2].

Thanks to Walid Ali-Ahmad.

53. Equation (6.5.2.1) gives μH when a and R are in cm.

54. Equation (6.2.1.2) yields a unitless number for x in cm.

55. Equations (6.2.2.1), (6.2.2.2), and (6.2.2.3) are in μH .

56. Equation (6.2.3.1) a parenthesis is in the wrong place. It should read:

$$L = 0.002 l \left[\ln \left(\frac{2.0 l}{\rho_1} \right) + \ln \zeta - 1.0 \right] \quad (\mu\text{H}) \quad (6.2.3.1)$$

Example of calculating complete elliptic integrals of the first, $K(k)$ and second kind $E(k)$

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For example, let's calculate $K(0.3420)$

(complete elliptic integral of the first kind)

using equations of 12.2.2.1, p. 465:

iteration n	an	bn	cn	K(k) at iteration N = n
0	1	0.939693	0.34202	1.57079 63268
1	0.969846	0.969377	0.030154	1.61963 42758
2	0.969612	0.969612	0.000234	1.62002 58752
3	0.969612	0.969612	1.42E-08	1.62002 58989
4	0.969612	0.969612	0	1.62002 58989
5	0.969612	0.969612	0	1.62002 58989
6	0.969612	0.969612	0	1.62002 58989

To check with the CRC values we need to calculate

$$\arcsin(k) = 0.349066 \text{ radians} = 20 \text{ degrees}$$

As you can see, this agrees to 4 places with the values given in the CRC p. 433 after only a few iterations.

Similarly, to calculate $E(0.4226)$:

iteration n	an	bn	cn	$2^{**}n$	F(k) at iteration N = n	E(k) at iteration N = n
0	1	0.906308	0.422618	1	1.57079 63268	1.43051 93524
1	0.953154	0.952002	0.046846	2	1.64799 86449	1.49721 06366
2	0.952578	0.952578	0.000576	4	1.64899 50658	1.49811 47932
3	0.952578	0.952578	8.71E-08	8	1.64899 52165	1.49811 49302
4	0.952578	0.952578	2E-15	16	1.64899 52165	1.49811 49302
5	0.952578	0.952578	0	32	1.64899 52165	1.49811 49302
6	0.952578	0.952578	0	64	1.64899 52165	1.49811 49302

Again, to check against the CRC we need a different parameter, so we calculate

$$\arcsin(k) = 0.436332 \text{ radians} = 25 \text{ degrees}$$

and again, we see that this agrees to 4 places with the CRC p. 435 after only a few iterations.

Compare Abramowitz and Stegun, Tables 17.2, pp. 610-611. Agreement is in 8-9 places.