Amateur Extra Math and Engineering Formula Guide

A comprehensive formula companion for the Amateur Extra class license

64 formula entries • 192 worked examples • Indexed reference and glossary

This guide develops the math needed for the numerical and formula-based topics in the current United States Element 4 question pool. It includes the foundation skills those problems assume and selected engineering formulas that make the underlying ideas easier to understand.

Edition basis. NCVEC 2024–2028 Extra Class Question Pool, with fourth errata dated February 4, 2026. The pool is valid July 1, 2024 through June 30, 2028. Source and withdrawal checks were completed for this study edition on September 17, 2026.

How to use each entry

Read the purpose and assumptions, identify every symbol and unit, then cover the worked answer and solve each example yourself. Compare the result and the sign or physical interpretation. Each entry has exactly three examples, including substitutions and a short explanation.

Label	Study priority
Pool calculation	Direct numerical or arithmetic topic in the active pool. Learn and practice these first.
Pool concept	The pool tests the relationship or interpretation. Worked numbers reinforce the concept.
Foundation	Earlier-license math and calculator skills needed to solve the Extra problems.
Supporting	Additional engineering explanation. Do not mistake this label for a new required exam formula.

What the verification establishes

All 192 examples were recalculated. The checks cover 226 reported numerical outputs, 37 official-answer comparisons, and 34 inverse or identity checks. Definitions, units, signs, reference levels, and important model assumptions were reviewed. Details and the checked pool results appear in the verification appendix.

This is an independently written study companion. Use it with your class materials and the full pool for regulations, procedures, component identification, diagrams, and other nonmathematical subjects. It is not an official ARRL publication.

Contents and study route

Start with the direct calculations, then return to any foundation topic that slows you down. Formula identifiers remain useful if you later edit the Word version and its pages move.

A practical study sequence

First: units, decibels, reactance, phase, resonance, Q, op-amp gain, and antenna power. Next: digital resolution and sampling, modulation bandwidth, feed-line behavior, and exposure math. Finally: use the question index to revisit each relevant pool topic.

Calculator habits

Use DEG mode for phase-angle answers. Use EXP or scientific notation for μ, n, and p. Put the full denominator in parentheses. Keep extra digits until the final answer. Check whether the problem asks for signed gain, absolute gain, watts, dBm, or a ratio.

Glossary terms are alphabetized near the end. A formula’s local symbol definitions take precedence because some engineering letters have several meanings.

Quick reference for circuits

A reminder sheet for formulas already explained in full. Read the cited entry for units, assumptions, and examples.

F05 Ohm law and DC power • page 9

$$V = IR, \quad P = VI = I^2R = V^2/R, \quad W = Pt$$

F09 RC and RL time constants • page 13

$$\tau_{RC} = RC, \quad \tau_{RL} = L/R; \quad x(t) = x_f + (x_i - x_f)e^{-t/\tau}$$

F10 Inductive reactance • page 14

$$X_L = 2\pi fL, \quad Z_L = jX_L$$

F11 Capacitive reactance • page 15

$$X_C = \frac{1}{2\pi fC}, \quad Z_C = -jX_C$$

F14 Admittance conductance and susceptance • page 18

$$Y = 1/Z = G + jB = \frac{R - jX}{R^2 + X^2}, \quad Y_p = \sum Y_i, \quad Z_p = 1/Y_p$$

F15 Phase angle and lead or lag • page 19

$$\theta = \tan^{-1}\left(\frac{X_L - X_C}{R}\right) \quad (R > 0)$$

F17 LC resonance • page 21

$$f_0 = \frac{1}{2\pi\sqrt{LC}}, \quad C = \frac{1}{(2\pi f_0)^2 L}$$

F19 Resonator bandwidth • page 23

$$BW = f_H - f_L = \frac{f_0}{Q}, \quad Q = \frac{f_0}{BW}$$

Quick reference for signals and antennas

A reminder sheet for formulas already explained in full. Read the cited entry for units, assumptions, and examples.

F20 Power ratios in decibels • page 24

$$G_{\text{dB}} = 10\log_{10}(P_2/P_1), \quad P_2/P_1 = 10^{G_{\text{dB}}/10}$$

F22 Absolute power in dBm and dBW • page 26

$$P_{\text{dBm}} = 10\log_{10}(P_{\text{W}}/10^{-3}), \quad P_{\text{W}} = 10^{(P_{\text{dBm}}-30)/10}, \quad P_{\text{dBm}} = P_{\text{dBW}} + 30$$

F24 Link budgets and link margin • page 28

$$P_r = P_t + G_t + G_r - L_c - L_p, \quad M = P_r - (P_{\min} + SNR_{\text{req}})$$

F32 Inverting operational amplifier • page 36

$$A_v = -R_f/R_{in}, \quad V_o = A_v V_i$$

F38 ADC resolution and quantization • page 42

$$N_{levels} = 2^n, \quad q = V_{span}/2^n, \quad n_{min} = \lceil \log_2(V_{span}/q_{req}) \rceil$$

F41 FM modulation index and deviation ratio • page 45

$$\beta_{FM} = \Delta f/f_m, \quad DR_{dev} = \Delta f_{max}/f_{m,max}$$

F47 Reflection coefficient and SWR • page 51

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}, \quad SWR = \frac{1+|\Gamma|}{1-|\Gamma|}, \quad |\Gamma| = \frac{SWR-1}{SWR+1}$$

F49 Line velocity factor and electrical length • page 53

$$VF = v_p/c, \quad \lambda_{line} = VF\,c/f, \quad \ell = \frac{\theta}{360^\circ}\lambda_{line}, \quad t_d = \ell/(VF\,c)$$

F01 Units and engineering notation

Foundations | Foundation

$$x_{\text{base}} = x_{\text{prefix}}\,10^{n}$$

x = numerical value; n = prefix exponent. Prefixes: G 10^{9}, M 10^{6}, k 10^{3}, m 10^{-3}, µ 10^{-6}, n 10^{-9}, p 10^{-12}.

Convert to base units before using a formula unless the formula explicitly specifies MHz, µH, or another scaled unit. A number in engineering notation uses an exponent that is a multiple of three.

Watch for this. M means mega; m means milli. A µF is a million times larger than a pF.

Example 1. Convert 47 pF to farads.

$$C = 47 \times 10^{-12} = 4.7 \times 10^{-11}\ \text{F}$$

Enter 47 EXP −12 on a scientific calculator.

Example 2. Convert 3.505 MHz to hertz.

$$f = 3.505 \times 10^{6} = 3\,505\,000\ \text{Hz}$$

Preserve the decimal position when applying the prefix.

Example 3. Convert 0.0022 A to milliamperes.

$$I = 0.0022 \times 10^{3} = 2.2\ \text{mA}$$

To express a base value in a smaller unit, divide by the prefix multiplier.

Source keys: SI. See Sources and further reading.

F02 Algebra roots logarithms and angles

Foundations | Foundation

$$x = \sqrt{a^2 + b^2}, \quad \theta = \tan^{-1}(b/a), \quad y = \log_{10}(x)$$

a, b = perpendicular components; x = magnitude; θ = angle; y = base ten logarithm.

Rearrange the equation before inserting numbers. Use parentheses around a complete denominator. Use degrees for exam phase angles; use radians in waveform arguments. The inverse tangent is not the reciprocal of tangent.

Watch for this. Use atan2(b,a) for a general complex angle so the quadrant is correct. A logarithm takes a positive, dimensionless ratio.

Example 1. Find the hypotenuse for components 30 and 40.

$$x = \sqrt{30^2 + 40^2} = 50$$

Square both components, add, then take the square root.

Example 2. Find the angle for vertical 50 and horizontal 100.

$$\theta = \tan^{-1}(50/100) = 26.565^\circ$$

Use DEG mode.

Example 3. Solve a power ratio from a 13 dB gain.

$$r = 10^{13/10} = 19.953$$

The inverse of log base ten is ten raised to a power.

Source keys: PHY, DB. See Sources and further reading.

F03 Frequency period and phase delay

Foundations | Foundation | E4A01, E5C05

$$T = 1/f, \quad \omega = 2\pi f, \quad \phi = 360^\circ f \Delta t$$

f = frequency in Hz; T = period in s; ω = angular frequency in rad/s; Δt = delay in s; φ = phase displacement in degrees.

One period is one cycle. A delay equal to one quarter of a period is 90 degrees. The equation gives the magnitude of a delay; a delayed waveform has negative phase relative to its reference.

Watch for this. Convert microseconds to seconds when frequency is in hertz. Phase may be reduced modulo 360 degrees.

Example 1. Find the period at 2 MHz.

$$T = 1/(2 \times 10^6) = 0.5\ \mu\text{s}$$

Two million cycles fit in one second.

Example 2. Find angular frequency at 1 kHz.

$$\omega = 2\pi(1000) = 6283.19\ \text{rad/s}$$

Angular frequency is not frequency in hertz.

Example 3. Find the phase lag for a 25 ns delay at 10 MHz.

$$|\phi| = 360(10^7)(25 \times 10^{-9}) = 90^\circ$$

The delayed output is −90 degrees relative to the input.

Source keys: P, PHY. See Sources and further reading.

F04 Wavelength and wave velocity

Foundations | Pool concept | E3A10, E9D05, E9F01

$$\lambda = v/f, \quad v = c/n, \quad \lambda_{\text{free}} \simeq 300/f_{\text{MHz}}\ \text{m}$$

λ = wavelength in m; v = wave speed in m/s; c = 299792458 m/s exactly; n = refractive index; fMHz = frequency in MHz.

The exam approximation c ≈ 3 × 10^8 m/s gives 300 divided by MHz for wavelength in meters. Physical antenna dimensions differ from ideal fractions of free-space wavelength because of conductor geometry and surroundings.

Watch for this. Do not apply a coaxial cable velocity factor to a free-space wavelength unless calculating wavelength inside that line.

Example 1. Find free-space wavelength at 14.1 MHz using the exam approximation.

$$\lambda \simeq 300/14.1 = 21.277\ \text{m}$$

An ideal half wavelength is about 10.638 m.

Example 2. Find an ideal quarter wavelength at 146 MHz.

$$\ell \simeq 300/(4 \times 146) = 0.5137\ \text{m}$$

This is an electrical starting point, not a finished antenna cutting length.

Example 3. Find wave speed for refractive index 1.5.

$$v = c/1.5 = 199\,861\,639\ \text{m/s}$$

A larger refractive index gives lower phase velocity in this simple model.

Source keys: P, PHY, SI. See Sources and further reading.

F05 Ohm law and DC power

Circuits | Foundation | E5D11

$$V = IR, \quad P = VI = I^2R = V^2/R, \quad W = Pt$$

V = voltage in V; I = current in A; R = resistance in Ω; P = power in W; W = energy in J when t is seconds.

Ohm law relates voltage, current, and resistance for a resistive element. Power is the rate of energy transfer. For AC, these power shortcuts apply to a purely resistive load when voltage and current are RMS.

Watch for this. The italic variable W for energy differs from the upright unit W for watt. Reactive loads need the power-factor treatment in F16.

Example 1. Find the current through 6 Ω connected to 12 V.

$$I = 12/6 = 2 \text{ A}$$

Divide voltage by resistance.

Example 2. Find the heating power in 50 Ω carrying 2 A.

$$P = 2^2(50) = 200 \text{ W}$$

The current must be squared.

Example 3. Find the energy used by a 100 W load in 60 s.

$$W = 100(60) = 6000 \text{ J}$$

Energy and power are different quantities.

Source keys: P, PHY. See Sources and further reading.

F06 Series and parallel resistance

Circuits | Pool calculation | E5B04

$$R_s = \sum R_i, \quad R_p = \left(\sum 1/R_i\right)^{-1}, \quad R_{p,2} = \frac{R_1 R_2}{R_1 + R_2}$$

Rs = series resistance; Rp = parallel resistance; Ri = an individual resistance; all in Ω.

Series elements carry the same current. Parallel elements have the same voltage. For N identical resistors, series resistance is NR and parallel resistance is R/N.

Watch for this. A parallel resistance must be less than the smallest positive branch resistance.

Example 1. Combine 100 Ω and 220 Ω in series.

$$R_s = 100 + 220 = 320\ \Omega$$

The same current flows through both.

Example 2. Combine two 1 MΩ resistors in parallel.

$$R_p = (1 \times 1)/(1 + 1) = 0.5\ \mathrm{M\Omega}$$

This is the resistance used in pool question E5B04.

Example 3. Combine 100 Ω, 200 Ω, and 300 Ω in parallel.

$$R_p = (1/100 + 1/200 + 1/300)^{-1} = 54.545\ \Omega$$

Add conductances, then take the reciprocal.

Source keys: P, PHY. See Sources and further reading.

F07 Combining capacitors and inductors

Circuits | Pool calculation | E5B04, E7H04

$$C_p = \sum C_i, \quad C_s = \left(\sum 1/C_i\right)^{-1}; \quad L_s = \sum L_i, \quad L_p = \left(\sum 1/L_i\right)^{-1}$$

C = capacitance in F; L = inductance in H; subscripts s and p mean series and parallel; i labels each component.

Capacitors combine opposite to resistors. Uncoupled ideal inductors combine like resistors. The inductor expressions assume negligible mutual inductance between coils.

Watch for this. Nearby coupled coils require a mutual-inductance term. Equal capacitors in series halve capacitance but do not automatically share voltage equally.

Example 1. Combine two 220 µF capacitors in parallel.

$$C_p = 220 + 220 = 440\ \mu\text{F}$$

This is the capacitance used in E5B04.

Example 2. Combine 100 pF and 150 pF in series.

$$C_s = \frac{100(150)}{100 + 150} = 60\ \text{pF}$$

The result is below either individual capacitance.

Example 3. Combine uncoupled 10 µH and 15 µH inductors in parallel.

$$L_p = \frac{10(15)}{10 + 15} = 6\ \mu\text{H}$$

For a series connection the same coils would total 25 µH.

Source keys: P, PHY. See Sources and further reading.

F08 Voltage dividers and meter loading

Circuits | Pool concept | E4B02, E7B10

$$V_o = V_i \frac{R_b}{R_t + R_b}, \quad R_b = R_2 \parallel R_L, \quad R_m = s_m V_{\text{range}}$$

Vi, Vo = input and output voltages; Rt = top resistor; R2 = bottom resistor; RL = load; Rm = meter resistance; sm = sensitivity in Ω/V.

A divider output is measured across the bottom resistor. A finite load or voltmeter is in parallel with that resistor and lowers the output. Analog meter input resistance depends on its selected voltage range.

Watch for this. Use the selected full-scale range, not the voltage currently indicated, when calculating meter resistance.

Example 1. Find unloaded output for 12 V, top 10 kΩ, bottom 5 kΩ.

$$V_o = 12 \frac{5}{10 + 5} = 4 \text{ V}$$

With no load, the bottom resistor alone sets the ratio.

Example 2. Find input resistance of a 20 kΩ/V meter on its 10 V range.

$$R_m = 20\,000(10) = 200\,000 \ \Omega$$

The result is 200 kΩ.

Example 3. Load a 10 kΩ over 10 kΩ divider at 12 V with 10 kΩ.

$$R_b = 5 \text{ k}\Omega; \quad V_o = 12 \frac{5}{10 + 5} = 4 \text{ V}$$

The unloaded output was 6 V; loading reduces it.

Source keys: P, PHY. See Sources and further reading.

F09 RC and RL time constants

Circuits | Pool calculation | E5B01, E5B04

$$\tau_{RC} = RC, \quad \tau_{RL} = L/R; \quad x(t) = x_f + (x_i - x_f)e^{-t/\tau}$$

τ = time constant in s; R = effective resistance in Ω; C in F; L in H; xi, xf = initial and final voltage or current; t = elapsed time.

After one time constant, a rising quantity completes 63.2 percent of its change and a decaying quantity retains 36.8 percent. Use the resistance seen by the storage component. The RL equation is supporting background.

Watch for this. Five time constants means about 99.33 percent complete, not exactly 100 percent.

Example 1. Find τ for two 1 MΩ resistors and two 220 µF capacitors, all in parallel.

$$\tau = (0.5 \times 10^6)(440 \times 10^{-6}) = 220 \text{ s}$$

Combine each component type before multiplying.

Example 2. A 10 V capacitor discharges for 2τ. Find its remaining voltage.

$$V = 10e^{-2} = 1.3534 \text{ V}$$

The final voltage is zero in this example.

Example 3. Find the time constant of 100 mH in series with 20 Ω.

$$\tau = 0.1/20 = 0.005 \text{ s} = 5 \text{ ms}$$

More series resistance makes this RL decay faster.

Source keys: P, PHY. See Sources and further reading.

F10 Inductive reactance

AC and resonance | Pool calculation | E5C11, E5D02

$$X_L = 2\pi f L, \quad Z_L = jX_L$$

XL = inductive reactance magnitude in Ω; f in Hz; L in H; j = square root of −1; ZL = inductor impedance.

Inductive reactance grows in direct proportion to frequency and inductance. An ideal inductor has positive imaginary impedance. Its voltage leads its current by 90 degrees.

Watch for this. 18 µH means 18 × 10^{-6} H. Do not use 18 directly with frequency in hertz.

Example 1. Find reactance of 18 µH at 3.505 MHz.

$$X_L = 2\pi(3.505 \times 10^6)(18 \times 10^{-6}) = 396.41\ \Omega$$

A series 300 Ω resistor would give 300 + j396.41 Ω.

Example 2. Find reactance of 10 µH at 1 MHz.

$$X_L = 2\pi(10^6)(10^{-5}) = 62.832\ \Omega$$

Doubling frequency would double this result.

Example 3. Find L for 100 Ω inductive reactance at 7.1 MHz.

$$L = \frac{100}{2\pi(7.1 \times 10^6)} = 2.2416\ \mu\text{H}$$

Rearrange before substituting.

Source keys: P, PHY. See Sources and further reading.

F11 Capacitive reactance

AC and resonance | Pool calculation | E5C10, E5C12

$$X_C = \frac{1}{2\pi f C}, \quad Z_C = -jX_C$$

XC = positive magnitude of capacitive reactance in Ω; f in Hz; C in F; ZC = capacitor impedance.

Capacitive reactance decreases when frequency or capacitance increases. In this guide XC is a positive magnitude; the minus sign is applied when constructing impedance.

Watch for this. Do not make XC negative and then subtract it again. Capacitor current leads voltage by 90 degrees.

Example 1. Find reactance of 38 pF at 14 MHz.

$$X_C = \frac{1}{2\pi(14 \times 10^6)(38 \times 10^{-12})} = 299.16\ \Omega$$

With 400 Ω in series, Z = 400 − j299.16 Ω.

Example 2. Find reactance of 19 pF at 21.2 MHz.

$$X_C = \frac{1}{2\pi(21.2 \times 10^6)(19 \times 10^{-12})} = 395.12\ \Omega$$

This is capacitive, so the impedance term is negative imaginary.

Example 3. Find capacitance for 50 Ω reactance at 10 MHz.

$$C = \frac{1}{2\pi(10^7)(50)} = 318.31\ \text{pF}$$

The reciprocal applies to the entire product.

Source keys: P, PHY. See Sources and further reading.

F12 Rectangular impedance and complex arithmetic

AC and resonance | Pool concep | E5C01, E5C06, E5C09

$$Z = R + jX, \quad X = X_L - X_C, \quad Z_s = \sum Z_i, \quad j^2 = -1$$

Z = complex impedance in Ω; R = resistance; X = signed net reactance; Zs = total series impedance.

Add real parts to real parts and imaginary parts to imaginary parts. Multiplication follows ordinary algebra with $j^2 = -1$. A phasor is a magnitude and phase representation of a sinusoidal quantity.

Watch for this. Resistance and reactance are perpendicular components. Never add their magnitudes to obtain impedance magnitude.

Example 1. Add series impedances 30 + j40 Ω and 20 − j10 Ω.

$$Z = (30 + 20) + j(40 - 10) = 50 + j30\ \Omega$$

The reactive parts partially cancel.

Example 2. Combine R = 100 Ω, XL = 75 Ω, XC = 25 Ω in series.

$$Z = 100 + j(75 - 25) = 100 + j50\ \Omega$$

Positive net reactance means inductive.

Example 3. Multiply the dimensionless phasors (3 + j4) and (2 − j).

$$(3 + j4)(2 - j) = 6 - 3j + 8j - 4j^2 = 10 + j5$$

Replace j^2 with −1 at the final simplification.

Source keys: P, PHY. See Sources and further reading.

F13 Polar and rectangular conversion

AC and resonance | Pool concept | E5C02, E5C03, E5C08

$$|Z| = \sqrt{R^2 + X^2}, \quad \theta = \operatorname{atan2}(X, R); \quad R = |Z|\cos\theta,\ X = |Z|\sin\theta$$

|Z| = magnitude in Ω; θ = phase angle; R, X = rectangular components in Ω; ∠ denotes polar angle.

Rectangular notation is convenient for addition. Polar notation is convenient for multiplication and division: multiply magnitudes and add angles, or divide magnitudes and subtract angles.

Watch for this. Keep the sign of the angle. A negative imaginary part means a negative angle for positive resistance.

Example 1. Convert 30 + j40 Ω to polar form.

$$|Z| = \sqrt{30^2 + 40^2} = 50; \quad \theta = 53.130^\circ$$

The polar impedance is 50 ∠53.130° Ω.

Example 2. Convert 50 ∠−60° Ω to rectangular form.

$$R = 50\cos(-60^\circ) = 25; \quad X = 50\sin(-60^\circ) = -43.301$$

The answer is 25 − j43.301 Ω.

Example 3. Divide 100 ∠30° volts by 20 ∠−15° ohms.

$$I = (100/20)\angle(30^\circ + 15^\circ) = 5\angle 45^\circ\ \mathrm{A}$$

Subtract the denominator angle, including its minus sign.

Source keys: P, PHY. See Sources and further reading.

F14 Admittance conductance and susceptance

AC and resonance | Pool concept | E5B02, E5B03, E5B05, E5B06, E5B12

$$Y = 1/Z = G + jB = \frac{R - jX}{R^2 + X^2}, \quad Y_p = \sum Y_i, \quad Z_p = 1/Y_p$$

Y = admittance; G = conductance; B = susceptance; all in siemens S. Zp = parallel impedance; Yp = total admittance.

Admittances add in parallel. In polar form, invert impedance magnitude and reverse its angle. A capacitive impedance has positive susceptance; an inductive impedance has negative susceptance.

Watch for this. For a mixed R + jX load, conductance is not simply 1/R and susceptance is not simply 1/X.

Example 1. Convert Z = 50 + j50 Ω to admittance.

$$Y = \frac{50 - j50}{50^2 + 50^2} = 0.01 - j0.01 \text{ S}$$

Both conductance and susceptance have units of siemens.

Example 2. Convert a pure capacitive impedance −j100 Ω.

$$Y = 1/(-j100) = j0.01 \text{ S}$$

The sign changes when taking the reciprocal.

Example 3. Find the parallel combination of 100 Ω and j100 Ω.

$$Y = 0.01 - j0.01; \quad Z = 1/Y = 50 + j50\ \Omega$$

Compute branch admittances before adding.

Source keys: P, PHY. See Sources and further reading.

F15 Phase angle and lead or lag

AC and resonance | Pool calculation | E5B07, E5B08, E5B09, E5B10, E5B11

$$\theta = \tan^{-1}\left(\frac{X_L - X_C}{R}\right) \quad (R > 0)$$

θ = voltage phase minus current phase in degrees; R, XL, XC in Ω; XL and XC are positive magnitudes.

Positive θ means voltage leads current and the circuit is net inductive. Negative θ means voltage lags current and the circuit is net capacitive. At series resonance, net reactance and phase angle are zero.

Watch for this. Always state which waveform leads. “The phase angle is 27 degrees” is incomplete without sign or lead/lag.

Example 1. Find phase for R = 1000 Ω, XL = 250 Ω, XC = 500 Ω.

$$\theta = \tan^{-1}(-250/1000) = -14.036^\circ$$

Voltage lags current by about 14 degrees.

Example 2. Find phase for R = 100 Ω, XL = 100 Ω, XC = 300 Ω.

$$\theta = \tan^{-1}(-200/100) = -63.435^\circ$$

Voltage lags current; the pool rounds to 63 degrees.

Example 3. Find phase for R = 100 Ω, XL = 75 Ω, XC = 25 Ω.

$$\theta = \tan^{-1}(50/100) = 26.565^\circ$$

Voltage leads current; the pool rounds to 27 degrees.

Source keys: P, PHY. See Sources and further reading.

F16 Real reactive and apparent AC power

AC and resonance | Pool calculation | E5D03, E5D09, E5D11, E5D12

$$P = VI\cos\theta = I^2R, \quad Q_r = VI\sin\theta = I^2X, \quad |S| = VI = \sqrt{P^2 + Q_r^2}$$

V, I = RMS values; P = real power in W; Qr = reactive power in var; |S| = apparent power in VA; power factor PF = cos θ = P/|S|.

These relations assume sinusoidal steady state. An ideal reactive element exchanges stored energy with the source but consumes no average power. Inductive reactive power is positive under the passive sign convention.

Watch for this. Qr is reactive power, not quality factor Q. For distorted waveforms, true power factor need not equal cos θ.

Example 1. A series load has R = 100 Ω, XL = 100 Ω, and I = 1 A RMS. Find real power.

$$P = I^2R = 1^2(100) = 100\ \mathrm{W}$$

Reactance contributes reactive power, not resistor heat.

Example 2. A load takes 120 V RMS, 2 A RMS, with PF = 0.8. Find real power.

$$P = 120(2)(0.8) = 192\ \mathrm{W}$$

Apparent power is 240 VA.

Example 3. Find reactive power for I = 2 A RMS and net X = −30 Ω.

$$Q_r = 2^2(-30) = -120\ \mathrm{var}$$

The negative sign indicates a capacitive load.

Source keys: P, PHY. See Sources and further reading.

F17 LC resonance

AC and resonance | Pool calculation | E5A02, E5A03, E5A04, E5A08, E5A10, E5D07

$$f_0 = \frac{1}{2\pi\sqrt{LC}}, \quad C = \frac{1}{(2\pi f_0)^2 L}$$

f0 = resonant frequency in Hz; L in H; C in F. With L in µH and C in pF, f0 in MHz is 159.155/√(LµH CpF).

At resonance, inductive and capacitive reactance magnitudes are equal. Series RLC impedance is its series resistance. For an ideal parallel R, L, C model, input impedance is its parallel resistance.

Watch for this. The simple parallel result assumes the resistance is a shunt branch. A lossy coil modeled with series resistance needs model conversion.

Example 1. Find resonance for 50 µH and 40 pF.

$$f_0 = \frac{159.155}{\sqrt{50(40)}} = 3.5588\ \mathrm{MHz}$$

Series resistance 22 Ω does not enter this ideal resonance formula.

Example 2. Find resonance for 50 µH and 10 pF.

$$f_0 = \frac{159.155}{\sqrt{50(10)}} = 7.1176\ \mathrm{MHz}$$

Quartering capacitance doubles resonant frequency.

Example 3. Find C to resonate 10 µH at 7.1 MHz.

$$C = \frac{1}{[2\pi(7.1 \times 10^6)]^2(10^{-5})} = 50.249\ \mathrm{pF}$$

Use the frequency squared.

Source keys: P, PHY. See Sources and further reading.

F18 Quality factor and internal magnification

AC and resonance | Pool concep | E5A01, E5A09, E5A13, E9D04

$$Q_s = X/R_s, \quad Q_p = R_p/X, \quad V_L = V_C \simeq Q_s V_{\text{applied}}$$

Q = dimensionless quality factor; X = either reactance magnitude at resonance; Rs = series loss resistance; Rp = equivalent parallel resistance.

Use the resistance model that matches the circuit. High Q means low loss relative to stored energy. In a simple series RLC at resonance, individual reactive voltages can greatly exceed the applied voltage.

Watch for this. Do not use the parallel formula on a coil’s series resistance. Loaded Q includes source and load effects.

Example 1. Find series Q for X = 200 Ω and Rs = 4 Ω.

$$Q_s = 200/4 = 50$$

Less series loss raises Q.

Example 2. Find parallel Q for Rp = 10 kΩ and X = 200 Ω.

$$Q_p = 10\,000/200 = 50$$

More parallel resistance raises Q.

Example 3. A series resonator has Q = 30 and applied voltage 5 V RMS. Find inductor voltage.

$$V_L = 30(5) = 150 \text{ V RMS}$$

Capacitor voltage has the same magnitude and opposite reactive phase.

Source keys: P, PHY. See Sources and further reading.

F19 Resonator bandwidth

AC and resonance | Pool calculation | E4B08, E5A05, E5A11, E5A12, E9D08

$$BW = f_H - f_L = \frac{f_0}{Q}, \quad Q = \frac{f_0}{BW}$$

BW = half-power bandwidth in Hz; fH, fL = upper and lower half-power frequencies; f0 = resonant frequency; Q = loaded quality factor.

The half-power points are approximately 3.01 dB below peak power. For a simple narrowband resonator, increasing Q narrows bandwidth. Use the same frequency units in numerator and denominator.

Watch for this. Do not mix MHz with kHz without converting. Antenna SWR bandwidth and resonator half-power bandwidth are related concepts, not identical definitions.

Example 1. Find BW at 7.1 MHz with Q = 150.

$$BW = 7.1 \times 10^6/150 = 47.333 \text{ kHz}$$

This agrees with the pool answer 47.3 kHz.

Example 2. Find BW at 3.7 MHz with Q = 118.

$$BW = 3.7 \times 10^6/118 = 31.356 \text{ kHz}$$

This agrees with the pool answer 31.4 kHz.

Example 3. Find Q for resonance at 10 MHz and half-power BW of 50 kHz.

$$Q = 10\,000/50 = 200$$

Both numbers in this division are in kHz.

Source keys: P, PHY. See Sources and further reading.

F20 Power ratios in decibels

Signals and measurements | Pool calculation | E4C06, E1C10, E8D09

$$G_{\mathrm{dB}} = 10\log_{10}(P_2/P_1), \quad P_2/P_1 = 10^{G_{\mathrm{dB}}/10}$$

GdB = power gain or signed change in dB; P2 = output or compared power; P1 = input or reference power, in matching units.

Positive dB means gain and negative dB means loss. An attenuation quoted as a positive loss is subtracted in a link budget. A ratio of 2 is 3.0103 dB; a ratio of 10 is 10 dB.

Watch for this. dB is a ratio, not an absolute power. A −30 dB distortion component has one thousandth the reference power.

Example 1. Find gain from 5 W to 100 W.

$$G = 10\log_{10}(100/5) = 13.0103\ \mathrm{dB}$$

A twentyfold power ratio is about 13 dB.

Example 2. Find output after 6 dB loss from 100 W.

$$P_o = 100(10^{-6/10}) = 25.119\ \mathrm{W}$$

Six dB is approximately, but not exactly, a factor of four.

Example 3. Find the power of a component 43 dB below a 100 W carrier.

$$P = 100(10^{-43/10}) = 0.005012\ \mathrm{W}$$

This is 5.012 mW; regulatory applicability requires the complete rule.

Source keys: P, DB. See Sources and further reading.

F21 Voltage and current ratios in decibels

Signals and measurements | Foundation | E6A08

$$G_{\mathrm{dB}} = 20\log_{10}|V_2/V_1| = 20\log_{10}|I_2/I_1| \quad \text{equal resistances}$$

V1, V2 = compared voltages; I1, I2 = compared currents. Use consistent RMS or peak values and equal resistances.

The factor twenty comes from power being proportional to voltage squared or current squared. With unequal resistances, calculate actual powers first. The sign of amplifier voltage gain represents inversion, not negative power.

Watch for this. Using ten times the logarithm of a voltage ratio gives the wrong power gain at equal impedances.

Example 1. Voltage doubles across the same resistance. Find the dB increase.

$$G = 20\log_{10}(2) = 6.0206\ \mathrm{dB}$$

Power increases by a factor of four.

Example 2. Voltage falls to 0.7071 of its previous value. Find the change.

$$G = 20\log_{10}(0.7071) = -3.0104\ \mathrm{dB}$$

This is approximately a half-power point.

Example 3. Find the voltage ratio for 20 dB gain at equal impedances.

$$V_2/V_1 = 10^{20/20} = 10$$

The power ratio is 100.

Source keys: P, DB. See Sources and further reading.

F22 Absolute power in dBm and dBW

Signals and measurements | Pool calculation | E4D14

$$P_{\mathrm{dBm}} = 10\log_{10}(P_{\mathrm{W}}/10^{-3}), \quad P_{\mathrm{W}} = 10^{(P_{\mathrm{dBm}}-30)/10}, \quad P_{\mathrm{dBm}} = P_{\mathrm{dBW}} + 30$$

PdBm = power relative to 1 mW; PdBW = power relative to 1 W; PW = power in watts.

Absolute decibel units let you add gains and subtract losses while keeping a power reference. Zero dBm is one milliwatt; zero dBW is one watt.

Watch for this. A negative dBm value is a small positive power, not negative physical energy.

Example 1. Convert 10 W to dBm.

$$P_{\mathrm{dBm}} = 10\log_{10}(10/0.001) = 40\ \mathrm{dBm}$$

Ten watts is also 10 dBW.

Example 2. Convert −100 dBm to watts and picowatts.

$$P = 10^{(-100-30)/10} = 10^{-13}\ \mathrm{W} = 0.1\ \mathrm{pW}$$

This is the pool’s minimum-discernible-signal conversion.

Example 3. Convert 250 mW to dBm.

$$P_{\mathrm{dBm}} = 10\log_{10}(250) = 23.9794\ \mathrm{dBm}$$

The logarithm here uses milliwatts relative to one milliwatt.

Source keys: P, DB. See Sources and further reading.

F23 Gain chains and radiated power

Signals and measurements | Pool calculation | E9A02, E9A06, E9A07

$$G_{\text{net}} = \sum G - \sum L, \quad ERP = P_t 10^{G_{\text{net,dBd}}/10}, \quad EIRP = P_t 10^{G_{\text{net,dBi}}/10}$$

Pt = transmitter output in W; G = gains in dB; L = positive losses in dB; ERP = dipole-referenced effective radiated power; EIRP = isotropic-referenced equivalent radiated power.

Subtract cable, duplexer, and circulator losses before applying antenna gain. The radiation reference matters: dBd produces ERP and dBi produces EIRP. These are directional equivalent powers, not total power created by the antenna.

Watch for this. Never add a dB number directly to watts. Antenna gain redistributes radiation.

Example 1. Find ERP for 150 W, 2 dB line loss, 2.2 dB duplexer loss, and 7 dBd antenna gain.

$$G = 7 - 2 - 2.2 = 2.8; \quad ERP = 150(10^{2.8/10}) = 285.819\ \text{W}$$

The pool rounds to 286 W.

Example 2. Find ERP for 200 W, losses 4, 3.2, and 0.8 dB, and gain 10 dBd.

$$G = 10 - 4 - 3.2 - 0.8 = 2; \quad ERP = 200(10^{0.2}) = 316.979\ \text{W}$$

The pool rounds to 317 W.

Example 3. Find EIRP for 200 W, losses 2, 2.8, and 1.2 dB, and gain 7 dBi.

$$G = 7 - 2 - 2.8 - 1.2 = 1; \quad EIRP = 200(10^{0.1}) = 251.785\ \text{W}$$

The pool rounds to 252 W.

Source keys: P, DB. See Sources and further reading.

F24 Link budgets and link margin

Signals and measurements | Pool calculation | E4D12, E4D13

$$P_r = P_t + G_t + G_r - L_c - L_p, \quad M = P_r - (P_{\min} + SNR_{\text{req}})$$

Pt, Pr, Pmin in dBm; Gt, Gr = antenna gains in dBi; Lc = total cable and component losses in dB; Lp = path loss in dB; M = link margin in dB.

Add the gains and subtract every loss using consistent references. In the pool's margin convention, add the required SNR to the given minimum signal level to get the required received level.

Watch for this. A real receiver specification may already include a required SNR or error rate. Do not add it a second time. Positive margin means headroom under the stated assumptions.

Example 1. Use 40 dBm transmit, 6 dBi transmit gain, 3 dBi receive gain, and 100 dB path loss.

$$P_r = 40 + 6 + 3 - 100 = -51\ \text{dBm}$$

No cable loss is specified here.

Example 2. Use 40 dBm, total gain 10 dB, cable loss 3 dB, path loss 136 dB, minimum −103 dBm, required SNR 6 dB.

$$P_r = -89; \quad P_{\text{req}} = -103 + 6 = -97; \quad M = 8\ \text{dB}$$

This follows the pool's E4D12 convention.

Example 3. A link receives −95 dBm and needs −90 dBm. Find margin.

$$M = -95 - (-90) = -5\ \text{dB}$$

Five more dB of improvement is needed to reach the stated threshold.

Source keys: P, DB. See Sources and further reading.

F25 Thermal noise and noise igure

Signals and measurements | Pool calculation | E4C04, E4C05, E4C06

$$P_n = kTB, \quad N_{\mathrm{dBm}} \simeq -174 + 10\log_{10}(B_{\mathrm{Hz}}) + NF, \quad F = \frac{SNR_{in}}{SNR_{out}},\ NF = 10\log_{10} F$$

k = 1.380649 × 10^{-23} J/K; T = temperature in K; B = equivalent noise bandwidth in Hz; F = linear noise factor; NF = noise figure in dB.

Available thermal noise is approximately −174 dBm per hertz at 290 K. Noise figure expresses the receiver's SNR degradation. Treat the bandwidth as equivalent noise bandwidth; a filter's nominal width can differ.

Watch for this. The −174 constant is a rounded room-temperature value. External antenna noise may greatly exceed it.

Example 1. Increase receiver bandwidth from 50 to 1000 Hz. Find noise increase.

$$\Delta N = 10\log_{10}(1000/50) = 13.0103\ \mathrm{dB}$$

The pool rounds to 13 dB.

Example 2. Estimate input noise in 2400 Hz with receiver NF = 5 dB.

$$N \simeq -174 + 10\log_{10}(2400) + 5 = -135.198\ \mathrm{dBm}$$

This uses the rounded 290 K reference.

Example 3. Input SNR is 20 and output SNR is 10, both linear. Find NF.

$$F = 20/10 = 2; \quad NF = 10\log_{10}(2) = 3.0103\ \mathrm{dB}$$

Do not divide SNR values that are already in dB.

Source keys: P, SI, AD. See Sources and further reading.

F26 Dynamic range and third order intercept

Signals and measurements | Pool concept | E4D01, E4D10

$$DR = P_{\text{block}} - N, \quad IIP3 = P_{in} + \Delta/2, \quad P_{IM3,in} \simeq 3P_{in} - 2IIP3$$

DR = dynamic range in dB; Pblock = blocking threshold in dBm; N = noise floor in dBm; IIP3 = input third-order intercept in dBm; Δ = carrier-to-IM3 separation in dB.

Blocking dynamic range compares the noise floor with a specified blocking threshold. The intercept formulas are supporting two-tone estimates for equal tones in the weakly nonlinear region. Each tone is specified separately.

Watch for this. IP3 is an extrapolated intercept. The equipment normally compresses before an actual signal reaches it. Do not confuse input and output intercepts.

Example 1. Find blocking range for a −130 dBm floor and −20 dBm blocking threshold.

$$DR = -20 - (-130) = 110 \text{ dB}$$

The threshold definition must be specified by the measurement.

Example 2. Two equal −20 dBm input tones produce IM3 60 dB below each tone. Find IIP3.

$$IIP3 = -20 + 60/2 = 10 \text{ dBm}$$

Third-order products grow 3 dB for each 1 dB rise in tone power.

Example 3. Estimate input-referred IM3 for each tone at −30 dBm and IIP3 = 10 dBm.

$$P_{IM3,in} = 3(-30) - 2(10) = -110 \text{ dBm}$$

This estimate assumes the usual equal-tone intercept model.

Source keys: P, AD. See Sources and further reading.

F27 RMS voltage peak voltage and PEP

Signals and measurements | Pool concept | E8A05, E8A06, E8A07

$$V_{rms} = V_p/\sqrt{2} = V_{pp}/(2\sqrt{2}), \quad PEP = V_{p,env}^2/(2R), \quad P_{avg} = PEP/K_p$$

Vp = sine peak voltage; Vpp = peak-to-peak voltage; Vp,env = peak RF voltage at the envelope crest; R = resistive load; Kp = PEP-to-average ratio.

The square-root-of-two relations apply to a sine wave. PEP is RF-cycle average power at the envelope crest. For unprocessed SSB speech the pool uses an approximate PEP-to-average ratio of 2.5; actual speech varies.

Watch for this. Do not use sine-wave RMS conversion on arbitrary pulses. PEP is not the instantaneous peak of v^2/R, which is twice the sine-cycle average at that crest.

Example 1. A sine wave is 200 V peak-to-peak. Find RMS voltage.

$$V_{rms} = 200/(2\sqrt{2}) = 70.711 \text{ V}$$

Half the peak-to-peak value first gives 100 V peak.

Example 2. At the envelope crest, RF peak voltage is 100 V into 50 Ω. Find PEP.

$$PEP = 100^2/[2(50)] = 100 \text{ W}$$

A purely resistive load is assumed.

Example 3. Estimate average SSB power for 100 W PEP using the pool ratio 2.5.

$$P_{avg} = 100/2.5 = 40 \text{ W}$$

Treat 40 W as the result of the stated ratio, not a universal meter reading.

Source keys: P, PHY. See Sources and further reading.

F28 Duty cycle and battery endurance

Circuits | Pool calculation | E7D09

$$D = t_{on}/T, \quad I_{avg} = DI_{tx} + (1 - D)I_{rx}, \quad t_{run} = C_{Ah}/I_{avg}$$

D = on or transmit fraction; T = whole cycle or averaging interval; Itx, Irx = transmit and receive currents in A; CAh = usable capacity in ampere-hours; trun in h.

First calculate average current over a complete operating cycle. Then divide usable battery capacity by that current. This is an estimate; capacity depends on temperature, discharge rate, age, and cutoff voltage.

Watch for this. Ampere-hours measure charge, not energy. Do not mix a transmit duty factor with a modulation factor unless calculating the quantity that needs both.

Example 1. A transmitter is on 2 minutes and off 3 minutes. Find duty cycle.

$$D = 2/(2 + 3) = 0.4 = 40\%$$

The denominator includes both on and off time.

Example 2. Find average current for 10 A transmit, 1 A receive, and 20 percent transmit time.

$$I_{avg} = 0.2(10) + 0.8(1) = 2.8 \text{ A}$$

Include the receive current during the remaining time.

Example 3. Find estimated runtime for 20 usable Ah and average load 2.8 A.

$$t_{run} = 20/2.8 = 7.143 \text{ h}$$

Real runtime can be shorter if the stated capacity is not usable under these conditions.

Source keys: P, PHY. See Sources and further reading.

F29 E iciency and linear regulator heat

Circuits | Pool calculation | E6F09, E7D12, E7D13

$$\eta = P_o/P_i, \quad P_{heat} = (V_i - V_o)I_o, \quad V_i \geq V_o + V_{drop}$$

η = efficiency fraction; Pi, Po = input and useful output power; Vi, Vo = regulator input and output voltages; Io = output current; Vdrop = required dropout voltage.

An idealized series regulator dissipates voltage drop times output current. Neglecting its own supply current, its efficiency is approximately output voltage divided by input voltage. Photovoltaic efficiency compares electrical output power with incident optical power.

Watch for this. Add heat-sinking margin and use the actual device data sheet for engineering design. These equations are study calculations, not thermal qualification.

Example 1. A linear regulator reduces 18 V to 13.8 V at 2 A. Find its dissipation.

$$P_{heat} = (18 - 13.8)(2) = 8.4 \text{ W}$$

This heat is concentrated in the pass device and associated losses.

Example 2. An RF amplifier delivers 100 W from 160 W DC input. Find efficiency.

$$\eta = 100/160 = 0.625 = 62.5\%$$

The remaining input power becomes heat and other losses.

Example 3. A 12 V regulator requires 2 V dropout. Find minimum input.

$$V_{i,min} = 12 + 2 = 14 \text{ V}$$

The input must stay above this value even at ripple valleys.

Source keys: P, PHY. See Sources and further reading.

F30 Transformer turns and impedance ratios

Circuits | Supporting | E7C04

$$V_s/V_p = N_s/N_p = a, \quad I_s/I_p = 1/a, \quad Z_p = (N_p/N_s)^2 Z_L$$

Ns, Np = secondary and primary turns; a = secondary-to-primary turns ratio; V and I = corresponding ideal AC voltage and current; ZL = load; Zp = reflected primary impedance.

An ideal transformer exchanges voltage for current while conserving power. Impedance transforms as the square of the turns ratio. This is supporting background for impedance matching.

Watch for this. A 4-to-1 impedance ratio requires a 2-to-1 turns ratio. Practical RF transformers also have bandwidth and core limits.

Example 1. A 100-turn primary and 20-turn secondary receive 120 V RMS. Find output.

$$V_s = 120(20/100) = 24 \text{ V RMS}$$

This is a five-to-one step-down in voltage.

Example 2. A 2-to-1 primary-to-secondary turns ratio drives 50 Ω. Find reflected impedance.

$$Z_p = 2^2(50) = 200\ \Omega$$

The impedance ratio is four-to-one.

Example 3. Find the primary-to-secondary turns ratio to reflect 50 Ω as 450 Ω.

$$N_p/N_s = \sqrt{450/50} = 3$$

Nine-to-one impedance transformation uses three-to-one turns.

Source keys: PHY. See Sources and further reading.

F31 Transistor current gain

Circuits | Pool concept | E6A06

$$\beta_{ac} = \Delta I_C/\Delta I_B, \quad \beta_{DC} = I_C/I_B, \quad I_E = I_C + I_B$$

β = common-emitter current gain; IC, IB, IE = collector, base, and emitter currents in A; Δ means a change about an operating point.

The pool defines beta as the change in collector current divided by the change in base current. DC beta is a related ratio at an operating point. Current gain varies with device, current, temperature, and frequency.

Watch for this. Use consistent current units. The simple relationship assumes active-region operation rather than a saturated switch.

Example 1. Collector current changes by 20 mA while base current changes by 0.2 mA.

$$\beta_{ac} = 20/0.2 = 100$$

Both current changes are in mA.

Example 2. Estimate collector current for DC beta 80 and base current 0.5 mA.

$$I_C = 80(0.5) = 40 \text{ mA}$$

This is an operating-point approximation.

Example 3. Find emitter current when IC = 20 mA and IB = 0.2 mA.

$$I_E = 20 + 0.2 = 20.2 \text{ mA}$$

Emitter current includes both other terminal currents.

Source keys: P, PHY. See Sources and further reading.

F32 Inverting operational amplifier

Circuits | Pool calculation | E7G07, E7G09, E7G10, E7G11

$$A_v = -R_f/R_{in}, \quad V_o = A_v V_i$$

Av = signed voltage gain; Rf = feedback resistance; Rin = input resistance; Vi, Vo = input and output voltages.

This is the ideal closed-loop inverting amplifier, with the non-inverting input at reference potential. Its minus sign means output polarity reverses. The pool sometimes asks for absolute gain, which drops that sign.

Watch for this. The output must remain within supply and output-swing limits. The pool's Figure E7-3 is an inverting configuration.

Example 1. Find signed gain with Rin = 10 Ω and Rf = 470 Ω.

$$A_v = -470/10 = -47$$

Absolute voltage gain is 47, as in E7G07.

Example 2. Find output for Rin = 1 kΩ, Rf = 10 kΩ, and input +0.23 V.

$$V_o = -(10/1)(0.23) = -2.3 \text{ V}$$

The circuit must have supply headroom for a negative output.

Example 3. Find absolute gain with Rin = 1.8 kΩ and Rf = 68 kΩ.

$$|A_v| = 68/1.8 = 37.778 \simeq 38$$

Use the nearest listed exam value; signed gain is negative.

Source keys: P, TI. See Sources and further reading.

F33 Noninverting gain and gain bandwidth

Circuits | Pool concept | E7G06, E7G08

$$A_v = 1 + R_f/R_g, \quad BW \simeq GBW/A_{noise}, \quad A_{noise} = 1 + R_f/R_{in} \text{ for an inverting stage}$$

Rg = resistor from non-inverting amplifier feedback node to reference; GBW = gain-bandwidth product in Hz; Anoise = noise gain; BW = approximate closed-loop bandwidth.

An ideal op-amp has no frequency-dependent limitation; real op-amps do. For a dominant-pole voltage-feedback device, closed-loop bandwidth is approximately GBW divided by noise gain. In a noninverting stage, noise gain equals signal gain.

Watch for this. For an inverting stage, use one plus the resistor ratio for bandwidth, not the magnitude of signal gain alone.

Example 1. Find noninverting gain with Rf = 90 kΩ and Rg = 10 kΩ.

$$A_v = 1 + 90/10 = 10$$

The output has the same polarity as the input.

Example 2. Estimate bandwidth for GBW = 3 MHz and noninverting gain 10.

$$BW \simeq 3 \times 10^6/10 = 300 \text{ kHz}$$

This assumes a suitable dominant-pole device.

Example 3. Estimate bandwidth for an inverting gain of −9 and GBW = 1 MHz.

$$A_{noise} = 10; \quad BW \simeq 10^6/10 = 100 \text{ kHz}$$

The noise gain is 10 even though signal gain magnitude is 9.

Source keys: P, TI. See Sources and further reading.

F34 Filter cutoff and shape factor

Circuits | Pool concept | E7C11, E7G02

$$f_c = 1/(2\pi RC), \quad SF = BW_{60}/BW_6$$

fc = first-order RC cutoff in Hz; R in Ω; C in F; SF = shape factor; BW60, BW6 = widths at 60 dB and 6 dB attenuation.

A simple RC low-pass falls to 0.707 of its passband voltage at cutoff. A capacitor across an inverting op-amp feedback resistor creates a low-pass response in the ideal model. Shape factor compares two explicitly specified attenuation widths.

Watch for this. Shape-factor definitions may use other attenuation levels. State the levels. A smaller ratio closer to one means steeper skirts.

Example 1. Find cutoff for 10 kΩ and 10 nF.

$$f_c = 1/[2\pi(10^4)(10^{-8})] = 1591.55 \text{ Hz}$$

Use the effective R seen by the capacitor.

Example 2. Find shape factor for 6 kHz width at 60 dB and 2.4 kHz width at 6 dB.

$$SF = 6/2.4 = 2.5$$

The two widths must use the same frequency units.

Example 3. Find C for an ideal feedback low-pass with Rf = 10 kΩ and cutoff 3 kHz.

$$C = 1/[2\pi(10^4)(3000)] = 5.3052 \text{ nF}$$

The op-amp's own bandwidth must be sufficiently greater.

Source keys: P, PHY, TI. See Sources and further reading.

F35 Counters dividers and binary states

Digital and modulation | Pool calculation | E7A02, E7A03, E7A04, E8A09

$$N_{states} = 2^n, \quad f_o = f_i/2^n, \quad n = \log_2(f_i/f_o)$$

n = number of binary stages or bits; Nstates = number of possible states; fi, fo = input and output frequency.

A toggling flip-flop divides by two. Cascaded binary stages divide by successive powers of two. A decade counter divides by ten rather than by a power of two.

Watch for this. Each flip-flop must be configured to toggle. A general flip-flop does not automatically act as a divider.

Example 1. How many binary stages divide a frequency by 16?

$$n = \log_2(16) = 4$$

This is the direct E7A04 calculation.

Example 2. Find output from a 10 MHz input through five binary divider stages.

$$f_o = 10 \times 10^6/2^5 = 312.5\ \mathrm{kHz}$$

Five stages divide by 32.

Example 3. Find output of a decade counter driven at 1 MHz.

$$f_o = 10^6/10 = 100\ \mathrm{kHz}$$

One output pulse occurs for every ten input pulses.

Source keys: P, PHY. See Sources and further reading.

F36 Boolean logic and truth tables

Digital and modulation | Pool concept | E6C08, E6C10, E6C11, E7A07, E7A08, E7A09, E7A10

$$AND = AB,\ OR = A + B,\ NOT = \overline{A},\ NAND = \overline{AB},\ NOR = \overline{A + B},\ XOR = A \oplus B,\ XNOR = \overline{A \oplus B}$$

A, B = Boolean inputs, either 0 or 1; a bar = NOT; + = logical OR; juxtaposition = AND; ⊕ = exclusive OR.

In positive logic, high voltage represents one. AND requires both inputs high; OR requires either. XOR is one only when inputs differ. NAND, NOR, and XNOR invert the corresponding result.

Watch for this. Boolean plus is not ordinary arithmetic: 1 OR 1 is 1. A high-impedance tri-state output is not a third Boolean number.

Example 1. Evaluate all seven operations for A = 0 and B = 0.

$$AND = 0,\ OR = 0,\ NOT(A) = 1,\ NAND = 1,\ NOR = 1,\ XOR = 0,\ XNOR = 1$$

With equal inputs, XNOR is one.

Example 2. Evaluate all seven operations for A = 0 and B = 1.

$$AND = 0,\ OR = 1,\ NOT(A) = 1,\ NAND = 1,\ NOR = 0,\ XOR = 1,\ XNOR = 0$$

With different inputs, XOR is one.

Example 3. Evaluate all seven operations for A = 1 and B = 1.

$$AND = 1,\ OR = 1,\ NOT(A) = 0,\ NAND = 0,\ NOR = 0,\ XOR = 0,\ XNOR = 1$$

NAND is zero only when both inputs are one.

Source keys: P, PHY. See Sources and further reading.

F37 Sampling Nyquist frequency and aliasing

Digital and modulation | Pool concept | E4A01, E4A06, E7F05, E7F10

$$f_s > 2f_{max}, \quad f_N = f_s/2, \quad f_a = |f_{in} - kf_s| \text{ folded into } [0, f_s/2]$$

fs = real sample rate in samples/s; fmax = highest baseband frequency; fN = Nyquist frequency; fa = aliased frequency; k = suitable integer.

The pool states at least twice the highest frequency. Practical designs sample faster to provide an anti-alias filter transition band and avoid the ambiguity at exact Nyquist. These expressions describe ordinary real baseband sampling.

Watch for this. Complex I/Q sampling and bandpass sampling require their own bandwidth interpretation. Do not apply fs/2 blindly to an advertised I/Q bandwidth.

Example 1. Find the theoretical limiting sample rate for a 3 kHz baseband.

$$2f_{max} = 2(3000) = 6000 \text{ samples/s}$$

Choose more than 6 ksample/s in an actual filtered system.

Example 2. Find Nyquist frequency for a 48 ksample/s real ADC.

$$f_N = 48\,000/2 = 24 \text{ kHz}$$

The usable passband must leave room for filtering.

Example 3. A 38 kHz tone is sampled at 48 ksample/s without adequate filtering. Find its alias.

$$f_a = |38 - 48| = 10 \text{ kHz}$$

The undesired tone appears inside the first Nyquist zone.

Source keys: P, AD. See Sources and further reading.

F38 ADC resolution and quantization

Digital and modulation | Pool calculation | E7F06, E7F11, E8A09

$$N_{levels} = 2^n, \quad q = V_{span}/2^n, \quad n_{min} = \lceil \log_2(V_{span}/q_{req}) \rceil$$

n = bit depth; q = nominal quantization step in V; Vspan = full input span; qreq = required maximum step; ceiling brackets mean round upward.

An n-bit ADC encodes 2^n distinct levels. The simple ideal step is full span divided by the number of levels. End-point data-sheet conventions can differ slightly. Real resolution is also limited by noise and nonlinearity.

Watch for this. Always round required bits upward. Ten bits provide 1024 levels; nine provide only 512.

Example 1. How many levels can an 8-bit converter encode?

$$N = 2^8 = 256$$

The codes range from 0 through 255.

Example 2. Find minimum bits for 1 V span and 1 mV required resolution.

$$n = \lceil \log_2(1/0.001) \rceil = 10$$

The ideal ten-bit step is about 0.977 mV.

Example 3. Find the ideal step of a 12-bit ADC with 3.3 V span.

$$q = 3.3/4096 = 0.80566 \text{ mV}$$

Do not confuse full input span with a bipolar endpoint.

Source keys: P, AD. See Sources and further reading.

F39 DSP decimation FFT bins and DDS

Digital and modulation | Supporting | E7F07, E7F08, E7H09, E7H10

$$f_{s,new} = f_s/M, \quad \Delta f = f_s/N_{FFT}, \quad f_{DDS} = K f_{clock}/2^{N_{acc}}$$

M = integer decimation factor; NFFT = transform length; Δf = FFT bin spacing; K = DDS tuning word; Nacc = phase-accumulator bits; fclock = DDS clock.

Decimation lowers sample rate after suitable filtering. An FFT maps time samples to frequency bins. A DDS advances a digital phase accumulator to synthesize a waveform. The pool tests these functions conceptually; these equations deepen understanding.

Watch for this. FFT bin spacing is not necessarily the ability to resolve two tones; windowing matters. Filter before discarding samples.

Example 1. Decimate 192 ksample/s by four. Find new sample rate.

$$f_{s,new} = 192/4 = 48\ \mathrm{ksample/s}$$

The anti-alias filter must suit the new rate.

Example 2. Find bin spacing for a 4096-point FFT at 48 ksample/s.

$$\Delta f = 48\,000/4096 = 11.71875\ \mathrm{Hz}$$

A longer record gives closer bin spacing.

Example 3. Find DDS output for a 32-bit accumulator, tuning word 2^{30}, and 100 MHz clock.

$$f_{DDS} = 2^{30}(100\ \mathrm{MHz})/2^{32} = 25\ \mathrm{MHz}$$

The selected waveform still needs reconstruction filtering.

Source keys: P, AD. See Sources and further reading.

F40 Mixers harmonics and intermodulation frequencies

Digital and modulation | Pool concept | E2A03, E4D11, E7E08, E8A01

$$f_{mix} = |mf_1 \pm nf_2|, \quad f_{IM3} = |2f_1 - f_2|,\ |2f_2 - f_1|, \quad f_h = hf_0$$

f1, f2 = input frequencies; m, n, h = integers; fh = harmonic frequency. A mixer’s simplest desired products use m = n = 1.

Nonlinearity generates sums and differences. Third-order products close to two nearby signals can fall within the same receive band. A symmetric ideal square wave contains odd harmonics; real waveforms depend on symmetry and duty cycle.

Watch for this. Third-order means the sum of coefficient magnitudes is three, not that the product is always three times the carrier.

Example 1. Mix 14 MHz and 9 MHz. Find the first sum and difference.

$$f_+ = 14 + 9 = 23\ \text{MHz}; \quad f_- = |14 - 9| = 5\ \text{MHz}$$

Input feedthrough and other products may also be present.

Example 2. Find nearby third-order products for 14.100 and 14.110 MHz.

$$2f_1 - f_2 = 14.090; \quad 2f_2 - f_1 = 14.120\ \text{MHz}$$

Both products remain close to the original signals.

Example 3. Find the third and fifth harmonics of a 1 kHz symmetric square wave.

$$f_3 = 3(1) = 3\ \text{kHz}; \quad f_5 = 5(1) = 5\ \text{kHz}$$

Only the harmonic frequencies are calculated here.

Source keys: P, PHY. See Sources and further reading.

F41 FM modulation index and deviation ratio

Digital and modulation | Pool calculation | E8B01, E8B03, E8B04, E8B05, E8B06, E8B09, E1C09

$$\beta_{FM} = \Delta f / f_m, \quad DR_{dev} = \Delta f_{max} / f_{m,max}$$

βFM = FM modulation index; Δf = peak one-sided frequency deviation in Hz; fm = sinusoidal modulation frequency; DRdev = deviation ratio.

For one sinusoidal tone, divide its peak frequency deviation by that tone frequency. Deviation ratio uses the maximum permitted deviation and highest modulation frequency. The pool uses that maximum-frequency form in several index questions.

Watch for this. “Plus or minus 5 kHz” is 5 kHz deviation, not 10 kHz. FM beta is unrelated to transistor beta.

Example 1. Find index for ±3 kHz deviation from a 1 kHz tone.

$$\beta = 3/1 = 3$$

Use matching units in numerator and denominator.

Example 2. Find deviation ratio for ±5 kHz and highest audio frequency 3 kHz.

$$DR_{dev} = 5/3 = 1.6667$$

The pool rounds to 1.67.

Example 3. Find deviation ratio for ±7.5 kHz and highest audio frequency 3.5 kHz.

$$DR_{dev} = 7.5/3.5 = 2.1429$$

The pool rounds to 2.14.

Source keys: P, FCCBW. See Sources and further reading.

F42 Carson bandwidth estimate

Digital and modulation | Supporting | E8B01

$$BW \simeq 2(\Delta f + f_{m,max})$$

BW = approximate FM occupied bandwidth in Hz; Δf = peak one-sided deviation; fm,max = highest significant modulating frequency.

Carson's rule estimates the bandwidth containing roughly 98 percent of a sinusoidally frequency-modulated signal's power. It is a useful engineering estimate, distinct from the specific FSK convention in F45.

Watch for this. FM has theoretically infinitely many sidebands. This is an estimate, not a sharp spectral boundary or universal compliance test.

Example 1. Estimate bandwidth for ±5 kHz deviation and 3 kHz audio.

$$BW \simeq 2(5 + 3) = 16\ \mathrm{kHz}$$

Deviation is one-sided.

Example 2. Estimate bandwidth for ±2.5 kHz deviation and 3 kHz audio.

$$BW \simeq 2(2.5 + 3) = 11\ \mathrm{kHz}$$

Reducing deviation reduces estimated bandwidth.

Example 3. With ±6 kHz deviation and a 2 kHz tone, estimate bandwidth.

$$BW \simeq 2(6 + 2) = 16\ \mathrm{kHz}$$

The corresponding modulation index is 3.

Source keys: FCCBW. See Sources and further reading.

F43 Sideband frequencies and band edge clearance

Digital and modulation | Pool calculation | E1A01, E1A02, E1A03, E1A04

$$f_{USB} = f_c + f_a, \quad f_{LSB} = f_c - f_a; \quad f_{c,max} = f_{edge,high} - f_{a,max}$$

fc = displayed suppressed-carrier frequency; fa = audio offset; fedge = applicable band or authorized emission-segment edge; all frequencies in matching units.

USB occupies frequencies above the displayed carrier and LSB below it. Keep the full emission within the authorized segment. Use highest transmitted offset for the edge calculation; use the difference between audio endpoints for actual sideband width.

Watch for this. Do not simply place the dial at a band edge. Real filters have skirts, so leave operating margin. Numerical band-edge examples follow the current pool; confirm current rules for operation.

Example 1. Find the highest frequency of a USB signal at 14.348 MHz with a 3 kHz upper offset.

$$f_{high} = 14.348 + 0.003 = 14.351\ \mathrm{MHz}$$

This extends 1 kHz beyond 14.350 MHz, as tested in E1A01.

Example 2. Find the lowest LSB dial frequency for a 3 kHz lower offset and lower edge 3.600 MHz.

$$f_{c,min} = 3.600 + 0.003 = 3.603\ \mathrm{MHz}$$

This is the mathematical boundary; practical operation needs margin.

Example 3. Use a data-segment upper edge of 14.150 MHz and a USB upper offset of 2.8 kHz.

$$f_{c,max} = 14.150 - 0.0028 = 14.1472\ \mathrm{MHz}$$

This matches the specific E1A03 calculation.

Source keys: P, FCC97. See Sources and further reading.

F44 AM modulation depth and power

Digital and modulation | Supporting

$$m = \frac{V_{max} - V_{min}}{V_{max} + V_{min}}, \quad P_{avg} = P_c(1 + m^2/2), \quad PEP = P_c(1 + m)^2$$

m = modulation fraction; Vmax, Vmin = maximum and minimum envelope amplitudes; Pc = unmodulated carrier power; Pavg = average modulated power.

These formulas describe conventional full-carrier, double-sideband AM with a single sinusoidal modulating tone and a linear envelope. They provide useful background for envelope measurements.

Watch for this. The equations assume 0 ≤ m ≤ 1 and undistorted modulation. Speech and overmodulation require more care.

Example 1. An AM envelope has maximum 150 V and minimum 50 V. Find modulation depth.

$$m = (150 - 50)/(150 + 50) = 0.5 = 50\%$$

Use amplitudes measured in the same way.

Example 2. Find average power for 100 W carrier at 100 percent sine-wave modulation.

$$P_{avg} = 100(1 + 1^2/2) = 150 \text{ W}$$

The added 50 W is total sideband power.

Example 3. Find PEP for a 25 W carrier at 100 percent modulation.

$$PEP = 25(1 + 1)^2 = 100 \text{ W}$$

AM PEP can be four times carrier power at m = 1.

Source keys: FCCBW, PHY. See Sources and further reading.

F45 CW and FSK bandwidth conventions

Digital and modulation | Pool calculation | E8C05, E8C07, E8C12

$$BW_{CW} \simeq 4w, \quad BW_{FSK} \simeq R_s + 1.2S_{shift}$$

w = Morse speed in words/minute; Rs = FSK symbol rate in baud; Sshift = full mark-to-space separation in Hz; BW in Hz.

The pool's CW estimate is four times words per minute; actual CW spectrum depends strongly on keying rise and fall times. Its FSK example follows Bn = 2M + 2DK with M = Rs/2, D = Sshift/2, and K = 1.2.

Watch for this. The FSK shift here is full tone separation, unlike the one-sided deviation used in F41. Do not substitute Carson's voice-FM formula for this pool convention.

Example 1. Estimate bandwidth of a 13 WPM Morse transmission.

$$BW \simeq 4(13) = 52 \text{ Hz}$$

This is the E8C05 exam approximation.

Example 2. Estimate bandwidth for 9600 baud FSK with 4800 Hz shift.

$$BW \simeq 9600 + 1.2(4800) = 15\,360 \text{ Hz}$$

The pool answer is 15.36 kHz.

Example 3. Apply the same FSK convention to 100 baud with 170 Hz shift.

$$BW \simeq 100 + 1.2(170) = 304 \text{ Hz}$$

This also matches the worked F1B example in 47 CFR 2.202.

Source keys: P, FCCBW. See Sources and further reading.

F46 Symbols bit rate and coding rate

Digital and modulation | Pool concept | E2B01, E8C02, E8C10, E8C11, E8C13

$$b = \log_2 M, \quad R_b = R_s b, \quad R_{payload} = r_c R_b, \quad r_c = k/n$$

M = distinguishable symbol states; b = coded bits per symbol; Rs = baud; Rb = gross coded bit rate; rc = coding rate; k information bits per n coded bits.

More symbol states can carry more bits per symbol. Coding rate expresses the fraction of transmitted coded bits representing information. Protocol headers and other overhead can further reduce delivered throughput.

Watch for this. Baud equals symbols per second, not automatically bits per second. A 3/4 coding rate means 25 percent of transmitted coded bits are redundancy.

Example 1. Find coded bit rate for 1000 baud QPSK with four states.

$$b = \log_2(4) = 2; \quad R_b = 1000(2) = 2000 \text{ bit/s}$$

Two bits are represented by each symbol.

Example 2. Find coded bit rate for 2400 baud with 16 symbol states.

$$R_b = 2400 \log_2(16) = 9600 \text{ bit/s}$$

This calculation excludes error-correction and framing losses.

Example 3. A coded channel sends 1200 bit/s using rate 3/4. Find information bit rate.

$$R_{payload} = 1200(3/4) = 900 \text{ bit/s}$$

The other 300 bit/s are coding redundancy before other overhead.

Source keys: P, PHY. See Sources and further reading.

F47 Reflection coefficient and SWR

Antennas and feed lines | Pool concept | E4A08, E9E07

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}, \quad SWR = \frac{1 + |\Gamma|}{1 - |\Gamma|}, \quad |\Gamma| = \frac{SWR - 1}{SWR + 1}$$

Γ = voltage-wave reflection coefficient at the load; ZL = load impedance; Z0 = real line reference impedance; SWR = standing-wave ratio.

These are the usual lossless-line or real-reference formulas. For a purely resistive positive load, SWR is the larger resistance divided by the smaller. With reactance present, use the complex reflection coefficient.

Watch for this. A 2-to-1 SWR does not mean half the power is reflected. Reflected power fraction is |Γ| squared.

Example 1. Find SWR for a 100 Ω resistive load on a 50 Ω line.

$$\Gamma = (100 - 50)/(100 + 50) = 1/3; \quad SWR = 2$$

The load is higher than the reference impedance.

Example 2. Find SWR for a 25 Ω resistive load on a 50 Ω line.

$$\Gamma = (25 - 50)/(25 + 50) = -1/3; \quad SWR = 2$$

Same SWR as 100 Ω, but reflected voltage has opposite phase.

Example 3. Find SWR for load 50 + j50 Ω on a 50 Ω line.

$$|\Gamma| = |j50/(100 + j50)| = 0.447214; \quad SWR = 2.618$$

Magnitude alone of the load impedance is insufficient.

Source keys: P, TL. See Sources and further reading.

F48 Reflected power return loss and delivered power

Antennas and feed lines | Pool calculation | E4B04, E4B06

$$P_r/P_f = |\Gamma|^2, \quad P_{net} = P_f - P_r, \quad RL = -20\log_{10}|\Gamma|, \quad ML = -10\log_{10}(1-|\Gamma|^2)$$

Pf, Pr = forward and reflected power at the same reference plane; RL = return loss in dB; ML = mismatch loss in dB; Pnet = net power flowing toward the load.

Return loss is positive for a passive mismatch and becomes larger as matching improves. S11 magnitude displayed in dB is negative return loss. Net power at a meter equals load absorption only if the remaining line loss is negligible.

Watch for this. Mismatch loss describes the rejected fraction of a specified incident wave. A real transmitter and lossy feed line can behave differently after multiple reflections.

Example 1. A meter reads 100 W forward and 25 W reflected at a terminating load. Find absorbed power.

$$P_{net} = 100 - 25 = 75\ \mathrm{W}$$

This is the E4B06 assumption of a meter at the load.

Example 2. Find return loss for SWR = 2.

$$|\Gamma| = 1/3; \quad RL = -20\log_{10}(1/3) = 9.5424\ \mathrm{dB}$$

S11 magnitude in dB would be −9.5424 dB.

Example 3. Find mismatch loss when one quarter of incident power is reflected.

$$ML = -10\log_{10}(1-0.25) = 1.2494\ \mathrm{dB}$$

Seventy-five percent of incident power is accepted at that plane.

Source keys: P, TL. See Sources and further reading.

F49 Line velocity factor and electrical length

Antennas and feed lines | Pool calculation | E9F01, E9F03, E9F06

$$VF = v_p/c, \quad \lambda_{line} = VF\,c/f, \quad \ell = \frac{\theta}{360^\circ}\lambda_{line}, \quad t_d = \ell/(VF\,c)$$

VF = velocity factor; vp = line phase velocity; λline = wavelength in line; ℓ = physical length; θ = electrical length in degrees; td = one-way delay.

A line wavelength is shorter than the free-space wavelength because waves travel more slowly in the dielectric. A quarter-wave line is 90 electrical degrees. Use the cable manufacturer's velocity factor at the operating frequency.

Watch for this. Physical length equals the corresponding free-space length multiplied by VF, not divided by VF.

Example 1. Find half-wave air-line length at 14.10 MHz using VF ≈ 1 and c ≈ 300 Mm/s.

$$\ell = 300/(2 \times 14.10) = 10.6383\ \mathrm{m}$$

The pool rounds to 10.6 m.

Example 2. Find quarter-wave coax length at 14.1 MHz with VF = 0.66.

$$\ell = 0.66(300)/(4 \times 14.1) = 3.5106\ \mathrm{m}$$

Connector and end effects can require adjustment.

Example 3. Find electrical length of 2 m of VF = 0.8 line at 30 MHz, using c ≈ 300 Mm/s.

$$\lambda_{line} = 8\ \mathrm{m}; \quad \theta = 360(2/8) = 90^\circ$$

This line is a quarter wavelength at the stated frequency.

Source keys: P, PHY. See Sources and further reading.

F50 Transmission line impedance and stubs

Antennas and feed lines | Pool concept | E9F04, E9F09, E9F10, E9F11, E9F12

$$Z_{in} = Z_0 \frac{Z_L + jZ_0 \tan\theta}{Z_0 + jZ_L \tan\theta}; \quad Z_{short} = jZ_0 \tan\theta, \quad Z_{open} = -jZ_0 \cot\theta$$

Zin = line input impedance; Z0 = real characteristic impedance; ZL = termination; θ = electrical line length; cot θ = 1/tan θ.

For a lossless line, a half wave repeats the termination and a quarter wave inverts it. A shorted eighth-wave stub is inductive; an open eighth-wave stub is capacitive. Exact quarter-wave open and short results are limits of the equations.

Watch for this. Use electrical wavelength in the line. Real loss makes ideal infinite and zero impedances finite.

Example 1. Find input impedance of a shorted 50 Ω eighth-wave stub.

$$\theta = 45^\circ; \quad Z_{in} = j50 \tan 45^\circ = j50\ \Omega$$

The stub acts inductively at this frequency.

Example 2. Find input impedance of an open 50 Ω eighth-wave stub.

$$Z_{in} = -j50 \cot 45^\circ = -j50\ \Omega$$

The stub acts capacitively.

Example 3. Find input impedance of a lossless half-wave line terminated in 25 Ω.

$$\theta = 180^\circ; \quad \tan\theta = 0; \quad Z_{in} = Z_L = 25\ \Omega$$

A half-wave line also repeats an ideal open or short.

Source keys: P, TL. See Sources and further reading.

F51 Quarter wave impedance matching

Antennas and feed lines | Pool calculation | E9E06

$$Z_t = \sqrt{R_s R_L}, \quad Z_{in} = Z_t^2/R_L, \quad \ell = VF\,c/(4f)$$

Zt = characteristic impedance of matching section; Rs = source or feed-line resistance; RL = resistive load; ℓ = quarter-wave physical length.

A quarter-wave section transforms a resistive load according to its characteristic impedance squared divided by load resistance. The ideal matching value is the geometric mean of the two resistances.

Watch for this. This simple match is frequency-sensitive and assumes resistive endpoints. The pool's 75 Ω choice approximates the ideal 70.7 Ω for matching 50 Ω to 100 Ω.

Example 1. Find the ideal section impedance between 50 Ω and 100 Ω.

$$Z_t = \sqrt{50(100)} = 70.7107\ \Omega$$

A listed 75 Ω cable is the suitable practical exam choice.

Example 2. Find the ideal section impedance between 50 Ω and 200 Ω.

$$Z_t = \sqrt{50(200)} = 100\ \Omega$$

This is an exact ideal transformation at the design frequency.

Example 3. A 75 Ω quarter-wave section terminates in 100 Ω. Find input impedance.

$$Z_{in} = 75^2/100 = 56.25\ \Omega$$

This illustrates why 75 Ω is close to, but not exactly, the ideal match in the first example.

Source keys: P, TL. See Sources and further reading.

F52 Smith chart normalization

Antennas and feed lines | Pool concept | E9G01, E9G02, E9G03, E9G08, E9G09, E9G10, E9G11

$$z = Z/Z_0 = r + jx, \quad Z = Z_0 z, \quad \Gamma = (z-1)/(z+1)$$

z = normalized impedance, dimensionless; r = normalized resistance; x = normalized reactance; Z0 = selected reference impedance in Ω.

The chart center is z = 1 + j0. The upper impedance-chart half is inductive, the lower half capacitive. Resistance circles and reactance arcs locate impedance. Constant-SWR circles are centered at the chart center.

Watch for this. The outer wavelength scale uses fractions of electrical wavelength in the line. One complete circuit of the chart corresponds to one half wavelength along a lossless line.

Example 1. Normalize 100 + j50 Ω to a 50 Ω reference.

$$z = (100 + j50)/50 = 2 + j1$$

The chart coordinates are dimensionless.

Example 2. Convert z = 0.5 − j1 to ohms on a 50 Ω chart.

$$Z = 50(0.5 - j1) = 25 - j50\ \Omega$$

The load is capacitive.

Example 3. Find Γ at normalized impedance z = 1 + j0.

$$\Gamma = (1-1)/(1+1) = 0$$

This is a perfect match with SWR = 1 and no reflected wave.

Source keys: P, TL. See Sources and further reading.

F53 Antenna efficiency

Antennas and feed lines | Pool concept | E9A09, E9A10, E9D04

$$\eta = \frac{R_{rad}}{R_{rad} + R_{loss}}, \quad P_{rad} = \eta P_{accepted}$$

η = radiation efficiency; Rrad = radiation resistance; Rloss = total equivalent loss resistance at the same reference point; Paccepted = accepted antenna power.

Radiation resistance represents power radiated as radio waves. Loss resistance represents heat. Ground loss, conductor loss, and loading-coil loss can reduce efficiency. This radiation efficiency excludes mismatch loss.

Watch for this. A good SWR alone does not prove good radiation efficiency; a dummy load can be well matched.

Example 1. Find efficiency for radiation resistance 36 Ω and loss resistance 4 Ω.

$$\eta = 36/(36 + 4) = 0.90 = 90\%$$

Both resistances use the same feed-point equivalent model.

Example 2. Find efficiency for an electrically short antenna with Rrad = 5 Ω and Rloss = 15 Ω.

$$\eta = 5/(5 + 15) = 0.25 = 25\%$$

Loss dominates this example.

Example 3. Find radiated power when efficiency is 60 percent and accepted power is 100 W.

$$P_{rad} = 0.60(100) = 60 \text{ W}$$

The remaining 40 W is dissipated as loss in this model.

Source keys: P, PHY. See Sources and further reading.

F54 Antenna gain references and pattern measurements

Antennas and feed lines | Pool calculation | E9A12, E9B01, E9B02, E9B03, E9B04

$$G_{dBi} = G_{dBd} + 2.15, \quad F/B = G_{front,dB} - G_{back,dB}, \quad BW_{3dB} = \theta_2 - \theta_1$$

GdBi = gain relative to isotropic; GdBd = gain relative to a free-space half-wave dipole; F/B = front-to-back ratio; θ1, θ2 = −3 dB crossings around the main lobe.

Use the same reference for front and back values. Beamwidth is angular separation between the half-power crossings, not between nulls. The 2.15 dB dipole conversion is the conventional rounded free-space value.

Watch for this. For plots crossing 0 degrees, unwrap the angles before subtracting. A −3 dB field-amplitude point is 0.707 of peak field, not half field.

Example 1. Convert 6 dBi to dBd.

$$G_{dBd} = 6 - 2.15 = 3.85 \text{ dBd}$$

This is the E9A12 result.

Example 2. A normalized pattern has front 0 dB and back −18 dB. Find F/B.

$$F/B = 0 - (-18) = 18 \text{ dB}$$

Subtract the signed levels.

Example 3. Half-power crossings occur at −25 and +25 degrees. Find beamwidth.

$$BW_{3dB} = 25 - (-25) = 50^\circ$$

Use the two crossings of the main lobe.

Source keys: P, DB. See Sources and further reading.

F55 Parabolic dish gain

Antennas and feed lines | Pool concept | E9D01

$$G = \eta_a(\pi D/\lambda)^2, \quad G_{dBi} = 10\log_{10} G, \quad \Delta G = 20\log_{10}(f_2/f_1)$$

G = linear gain relative to isotropic; ηa = aperture efficiency; D = dish diameter in m; λ = wavelength in m; f1, f2 = compared frequencies.

For the same electrically large dish and constant aperture efficiency, doubling frequency quadruples gain. The same scaling applies when doubling diameter at fixed frequency.

Watch for this. Constant efficiency is an assumption. Feed illumination, surface accuracy, and polarization can change performance.

Example 1. Double frequency for the same ideal dish. Find gain increase.

$$\Delta G = 20\log_{10}(2) = 6.0206\text{ dB}$$

The pool rounds to 6 dB.

Example 2. Find gain of a 1 m dish with efficiency 0.6 at wavelength 0.1 m.

$$G = 0.6(\pi/0.1)^2; \quad G_{dBi} = 27.724\text{ dBi}$$

This is an idealized aperture calculation.

Example 3. Increase diameter by 50 percent at fixed frequency and efficiency. Find gain change.

$$\Delta G = 20\log_{10}(1.5) = 3.5218\text{ dB}$$

Area increases by 2.25 times.

Source keys: P, ANT. See Sources and further reading.

F56 First Fresnel zone radius

Antennas and feed lines | Pool concept | E9A08

$$r_1 = \sqrt{\frac{\lambda d_1 d_2}{d_1 + d_2}}, \quad r_{mid} = \frac{1}{2}\sqrt{\lambda d}$$

r1 = first-zone radius in m; λ = wavelength in m; d1, d2 = distances to the two endpoints in m; d = total path distance.

The first Fresnel zone describes the region around a line-of-sight path relevant to diffraction. At the path midpoint its radius is largest for a fixed link. Higher frequency means smaller wavelength and a smaller zone.

Watch for this. Use consistent length units. This formula alone does not include Earth curvature, terrain, or a required clearance policy.

Example 1. Find midpoint radius for a 10 km path at wavelength 0.125 m.

$$r = \tfrac{1}{2}\sqrt{0.125(10\,000)} = 17.678 \text{ m}$$

The wavelength corresponds approximately to 2.4 GHz.

Example 2. Find midpoint radius for the same path at 5.8 GHz, using λ ≈ 300/fMHz.

$$\lambda = 300/5800; \quad r = 11.371 \text{ m}$$

This is smaller than at 2.4 GHz.

Example 3. Find radius with λ = 0.3 m, d1 = 1000 m, and d2 = 3000 m.

$$r = \sqrt{0.3(1000)(3000)/4000} = 15 \text{ m}$$

The point is one quarter of the way along the path.

Source keys: P, ANT. See Sources and further reading.

F57 Radio horizon

Antennas and feed lines | Pool concept | E3C06

$$d_{geo} \simeq 3.57(\sqrt{h_1} + \sqrt{h_2}), \quad d_{radio} \simeq 4.12(\sqrt{h_1} + \sqrt{h_2})$$

dgeo, dradio = horizon separation in km; h1, h2 = endpoint antenna heights in m above the relevant smooth surface.

The radio estimate uses an effective Earth radius of four thirds the physical radius, a conventional standard-refraction model. It is about 15 percent farther than the geometric horizon, consistent with the pool.

Watch for this. This is not a coverage guarantee. Terrain, buildings, refraction, antenna patterns, and signal strength can dominate.

Example 1. Estimate radio horizon separation for two antennas each 10 m high.

$$d \simeq 4.12(\sqrt{10} + \sqrt{10}) = 26.057 \text{ km}$$

Both endpoint heights contribute.

Example 2. Estimate separation for heights 30 m and 2 m.

$$d \simeq 4.12(\sqrt{30} + \sqrt{2}) = 28.393 \text{ km}$$

Use meters for the heights.

Example 3. Compare the two horizon constants as a percentage increase.

$$(4.12/3.57 - 1)100 = 15.406\%$$

The constants are rounded; the model ratio is √(4/3).

Source keys: P, ANT. See Sources and further reading.

F58 RF exposure averaging and far field density

RF exposure | Pool concept | E0A02, E0A05

$$P_{avg} = P_{PEP} D_m D_t, \quad S = \frac{P_{avg} G}{4\pi r^2}, \quad S_2/S_1 = (r_1/r_2)^2$$

Dm = modulation average-to-PEP factor during transmission; Dt = transmit fraction in the averaging interval; G = linear gain toward the person; r in m; S in W/m².

This is a free-space far-field calculation. Convert dBi gain to a linear ratio before using it. One W/m² equals 0.1 mW/cm². Real evaluations may require ground reflections, near-field analysis, and multiple sources.

Watch for this. Do not use the inverse-square formula close to the antenna as a complete exposure evaluation. Use current FCC guidance and a suitable validated evaluation method.

Example 1. Find time-average power for 100 W PEP, modulation factor 0.4, and transmit fraction 0.5.

$$P_{avg} = 100(0.4)(0.5) = 20 \text{ W}$$

Use factors appropriate to the actual mode and operation.

Example 2. Find ideal far-field density at 10 m for 100 W average power and linear gain 2.

$$S = 100(2)/[4\pi(10)^2] = 0.15915 \text{ W/m}^2$$

This equals 0.015915 mW/cm² before environmental corrections.

Example 3. At fixed antenna direction, increase far-field distance from 5 to 10 m. Find density ratio.

$$S_2/S_1 = (5/10)^2 = 0.25$$

Density falls to one quarter under the free-space assumptions.

Source keys: P, RF, FCCRF. See Sources and further reading.

F59 Exposure limits and multiple sources

RF exposure | Pool concept | E0A03, E0A04, E0A06

$$U = \sum_i S_i / S_{limit,i} \le 1; \quad S_{limit} = \begin{cases} 180/f^2 & 1.34 \le f < 30 \\ 0.2 & 30 \le f < 300 \\ f/1500 & 300 \le f < 1500 \\ 1 & 1500 \le f \le 100000 \end{cases}$$

U = combined exposure fraction; f = frequency in MHz; Si and Slimit in mW/cm². Listed limits are general-population/uncontrolled, time-averaged values.

These are selected power-density entries from 47 CFR 1.1310. From 0.3 to 1.34 MHz the corresponding value is 100 mW/cm². Below 300 MHz, separate electric and magnetic field limits also matter; listed density is plane-wave equivalent below 30 MHz.

Watch for this. Use the applicable averaging rules, normally up to 30 minutes uncontrolled and 6 minutes controlled. A summed fraction above one exceeds the applicable combined limit. Site mitigation responsibilities include sources contributing at least 5 percent where total exposure exceeds the limit.

Example 1. Calculate the uncontrolled plane-wave-equivalent limit at 14 MHz.

$$S_{limit} = 180/14^2 = 0.91837\ \mathrm{mW/cm^2}$$

Near-field electric and magnetic limits still require attention.

Example 2. Calculate the uncontrolled density limit at 450 MHz.

$$S_{limit} = 450/1500 = 0.3\ \mathrm{mW/cm^2}$$

Use MHz, not Hz, in this regulatory formula.

Example 3. Two appropriately averaged sources contribute 0.04 against a 0.2 limit and 0.15 against a 0.3 limit.

$$U = 0.04/0.2 + 0.15/0.3 = 0.2 + 0.5 = 0.7$$

The combined fraction is 70 percent at the assessed location under the stated model.

Source keys: P, FCCRF. See Sources and further reading.

F60 Frequency accuracy and prescalers

Signals and measurements | Pool concept | E4A05, E4B01

$$\Delta f = f\epsilon_{ppm}10^{-6}, \quad \epsilon_{ppm} = 10^6\Delta f/f, \quad f_{input} = Nf_{counter}$$

Δf = frequency error in Hz; f = nominal frequency in Hz; εppm = error in parts per million; N = prescaler divisor.

A counter's time base controls its accuracy. A prescaler divides high input frequencies into the counter's operating range; multiply the displayed frequency by the divider ratio. Resolution and accuracy are different.

Watch for this. Prescaling does not improve the time base's fractional accuracy. A fine display does not guarantee a correct measurement.

Example 1. Find absolute error for 10 MHz with a 1 ppm time-base error.

$$\Delta f = 10^7(1)(10^{-6}) = 10\ \mathrm{Hz}$$

The same fractional error is larger in hertz at higher frequencies.

Example 2. Find error in ppm for 150 Hz error at 150 MHz.

$$\epsilon = 10^6(150)/(150 \times 10^6) = 1\ \mathrm{ppm}$$

Use the magnitude if only accuracy tolerance is requested.

Example 3. A divide-by-10 prescaler gives a 43.5 MHz counter reading. Find input.

$$f_{input} = 10(43.5) = 435\ \mathrm{MHz}$$

Account for the prescaler before reporting the result.

Source keys: P, PHY. See Sources and further reading.

F61 Stored electric and magnetic energy

Engineering background | Supporting | E5D09, E7D15

$$W_C = \frac{1}{2}CV^2, \quad W_L = \frac{1}{2}LI^2$$

WC, WL = stored energy in J; C in F; V in V; L in H; I in A.

A capacitor stores energy in an electric field; an inductor stores energy in a magnetic field. Energy rises with the square of voltage or current. This explains why charging and switching transients matter.

Watch for this. A capacitor can retain hazardous energy after a supply is disconnected. Calculating energy does not establish that a circuit is safe to touch.

Example 1. Find energy in 1000 µF at 50 V.

$$W_C = \frac{1}{2}(0.001)(50^2) = 1.25 \text{ J}$$

Capacitance must be expressed in farads.

Example 2. Find energy in 10 mH carrying 2 A.

$$W_L = \frac{1}{2}(0.01)(2^2) = 0.02 \text{ J}$$

Interrupting current requires this energy to go somewhere.

Example 3. Find energy in 100 µF at 1000 V.

$$W_C = \frac{1}{2}(100 \times 10^{-6})(1000^2) = 50 \text{ J}$$

High voltage can make modest capacitance store substantial energy.

Source keys: PHY. See Sources and further reading.

F62 Core inductance and turns scaling

Engineering background | Supporting | E6D05, E6D06

$$L = A_L N^2, \quad N = \sqrt{L/A_L}, \quad L_2/L_1 = (N_2/N_1)^2$$

L = inductance; AL = core inductance factor in compatible units per turn squared; N = turns.

For a given core operating in its linear region, inductance approximately scales as turns squared. Core data sheets may specify AL in nH per turn squared. This relation supports the pool's permeability and turns concepts.

Watch for this. Check the data sheet's AL units. Saturation, air gaps, frequency, and winding geometry can change the result.

Example 1. A core has AL = 100 nH/turn^2 and 10 turns. Find inductance.

$$L = 100(10^2) = 10\,000 \text{ nH} = 10\ \mu\text{H}$$

Keep the inductance-factor unit through the calculation.

Example 2. Find turns for 25 µH with AL = 100 nH/turn^2.

$$N = \sqrt{25\,000/100} = 15.811$$

Use a practical integer winding, then measure and adjust.

Example 3. A 10-turn winding measures 10 µH. Estimate inductance at 15 turns.

$$L_2 = 10(15/10)^2 = 22.5\ \mu\text{H}$$

A 50 percent increase in turns gives 2.25 times the inductance.

Source keys: P, PHY. See Sources and further reading.

F63 Skin depth

Engineering background | Supporting | E5D01, E5D08

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}} = \sqrt{\frac{\rho}{\pi f\mu}}, \quad \delta_2/\delta_1 = \sqrt{f_1/f_2}$$

δ = skin depth in m; ρ = resistivity in Ω·m; μ = magnetic permeability in H/m; f in Hz; ω = 2πf.

For a good conductor, RF current density falls with depth from the surface. Increasing frequency reduces skin depth and tends to increase AC resistance. Examples assume copper $\rho = 1.68 \times 10^{-8}$ Ω·m and $\mu \approx 4\pi \times 10^{-7}$ H/m.

Watch for this. The copper resistivity is a representative room-temperature value, not a universal constant. The formula assumes a good conductor and ignores proximity effects.

Example 1. Estimate copper skin depth at 1 MHz.

$$\delta = \sqrt{\frac{1.68 \times 10^{-8}}{\pi(10^6)(4\pi \times 10^{-7})}} = 65.234\ \mu\text{m}$$

Most RF current is concentrated near the surface.

Example 2. Estimate copper skin depth at 10 MHz with the same assumptions.

$$\delta = 65.234/\sqrt{10} = 20.629\ \mu\text{m}$$

Ten times the frequency reduces depth by √10.

Example 3. Find the skin-depth ratio when frequency is multiplied by four.

$$\delta_2/\delta_1 = \sqrt{1/4} = 0.5$$

Skin depth halves.

Source keys: P, PHY. See Sources and further reading.

F64 Free space path loss

Engineering background | Supporting | E4D12, E4D13

$$FSPL = 20\log_{10}(4\pi d/\lambda) \simeq 32.45 + 20\log_{10} f_{MHz} + 20\log_{10} d_{km}$$

FSPL = free-space path loss in dB; d = distance in m in the first form; λ in m; fMHz = frequency in MHz; dkm = distance in km.

This is the ideal far-field propagation loss between isotropic references. It supplies a path-loss term for F24 when free-space assumptions are suitable. Real terrain, obstruction, reflection, and polarization can add losses.

Watch for this. The 32.45 constant requires MHz and kilometers. Antenna gains are separate link-budget terms.

Example 1. Estimate free-space loss at 144 MHz over 100 km.

$$FSPL \simeq 32.45 + 20\log_{10}(144) + 20\log_{10}(100) = 115.617 \text{ dB}$$

This does not establish that a terrestrial path is unobstructed.

Example 2. Estimate loss at 2400 MHz over 1 km.

$$FSPL \simeq 32.45 + 20\log_{10}(2400) = 100.054 \text{ dB}$$

The distance term is zero because log10(1) = 0.

Example 3. Double path distance at the same frequency. Find added free-space loss.

$$\Delta L = 20\log_{10}(2) = 6.0206 \text{ dB}$$

Received power becomes one quarter for fixed isotropic-equivalent gains.

Source keys: ANT. See Sources and further reading.

Verification and scope

Verification was performed against the official pool file and current primary references. The mathematical explanations and most examples are original; selected examples intentionally use pool numbers to make answer checking transparent.

Check	Result
Formula entries and examples	64 entries; exactly 3 examples each; 192 examples total
Calculated example outputs	226 individual scalar, complex-component, and logic outputs passed rounding-aware checks
Official numerical anchors	37 calculations agree with the stated pool answers or specified nearest-choice convention
Independent relationships	34 checks passed using inverse operations, resonance equality, power identities, and Boolean complements
Question references	Every referenced question ID exists in the parsed 599-question active pool
Withdrawn items	E2A13, E4D05, E6D07, and E9E10 excluded from active references
Glossary coverage	295 terms, 144 contextual symbol entries, and 26 unit entries
Final review	Units, complex signs, dB references, waveform assumptions, and printed layout reviewed

How the checks were done

A separate calculation record evaluates each example's reported numeric result using double-precision arithmetic. Acceptance is tied to rounding at the last displayed digit. Complex answers are checked by real and imaginary components. The official-answer checks use the pool's stated rounding or nearest available answer. Inverse checks test relationships such as Z times Y equals one and converting dBm to watts and back.

Important boundaries

Arithmetic verification does not turn an approximation into an exact physical law. The guide explicitly limits the sine-wave RMS rule, ideal transformer and line equations, simple Q models, room-temperature noise estimate, CW and FSK bandwidth conventions, and far-field exposure model. Practical designs require actual component and installation data.

No actual RF installation has been evaluated by this document. For exposure calculations, check the current rule and the method's applicability to the antenna's near field, reflections, operating schedule, and other transmitters. Recheck the pool and withdrawals before an exam taken later in the pool cycle.

The Word file contains editable prose and tables with typeset equation figures. Its page references describe this released layout; editing can change pagination.

Official answer crosschecks

Each row identifies a recalculated pool anchor. The result column follows the official answer's rounding or the question's stated convention.

Question	Checked result	Recalculation
E1A01	Upper edge 14.351 MHz; 1 kHz beyond 14.350	14.351
E1A02	3 kHz above lower edge	3
E1A03	14.1472 MHz	14.1472
E4B06	75 W	75
E4C06	13 dB rounded	13.0103
E4D12	+8 dB	8
E4D13	−51 dBm	-51
E4D14	0.1 pW	0.1
E5A02	3.56 MHz	3.5588127
E5A10	7.12 MHz	7.1176254
E5A11	47.3 kHz	47.333333
E5A12	31.4 kHz	31.355932
E5B04	220 s	220
E5B07	14.0 degrees lag	-14.036243
E5B08	63 degrees lag	-63.434949
E5B11	27 degrees lead	26.565051
E5D11	100 W	100
E7A04	4 flip-flops	4
E7F06	10 bits	10
E7G07	Absolute gain 47	47

For phase questions, a negative calculated angle means voltage lags current. E9E06 selects the suitable listed 75 Ω line; the ideal geometric mean is 70.7107 Ω.

Official answer crosschecks

Each row identifies a recalculated pool anchor. The result column follows the official answer's rounding or the question's stated convention.

Question	Checked result	Recalculation
E7G09	−2.3 V	-2.3
E7G10	Absolute gain 38 rounded	37.777778
E7G11	Absolute gain 14 rounded	14.242424
E8A09	256 levels	256
E8B03	Index 3	3
E8B04	Index 3	3
E8B05	1.67	1.6666667
E8B06	2.14	2.1428571
E8C05	52 Hz	52
E8C07	15.36 kHz	15.36
E9A02	286 W ERP	285.81911
E9A06	317 W ERP	316.97864
E9A07	252 W EIRP	251.78508
E9A12	3.85 dBd	3.85
E9D01	6 dB rounded	6.0205999
E9E06	75 Ω suitable listed cable	75
E9F06	10.6 m	10.638298

For phase questions, a negative calculated angle means voltage lags current. E9E06 selects the suitable listed 75 Ω line; the ideal geometric mean is 70.7107 Ω.

Question to formula index

References include direct calculations and conceptual questions illuminated by the formula. This is a topic lookup, not a claim that every listed question requires arithmetic.

Question	Formula entries	Pages
E0A02	F58	62
E0A03	F59	63
E0A04	F59	63
E0A05	F58	62
E0A06	F59	63
E1A01	F43	47
E1A02	F43	47
E1A03	F43	47
E1A04	F43	47
E1C09	F41	45
E1C10	F20	24
E2A03	F40	44
E2B01	F46	50
E3A10	F04	8
E3C06	F57	61
E4A01	F03, F37	7, 41
E4A05	F60	64
E4A06	F37	41
E4A08	F47	51
E4B01	F60	64
E4B02	F08	12
E4B04	F48	52
E4B06	F48	52
E4B08	F19	23
E4C04	F25	29
E4C05	F25	29
E4C06	F20, F25	24, 29
E4D01	F26	30

Question to formula index

References include direct calculations and conceptual questions illuminated by the formula. This is a topic lookup, not a claim that every listed question requires arithmetic.

Question	Formula entries	Pages
E4D10	F26	30
E4D11	F40	44
E4D12	F24, F64	28, 68
E4D13	F24, F64	28, 68
E4D14	F22	26
E5A01	F18	22
E5A02	F17	21
E5A03	F17	21
E5A04	F17	21
E5A05	F19	23
E5A08	F17	21
E5A09	F18	22
E5A10	F17	21
E5A11	F19	23
E5A12	F19	23
E5A13	F18	22
E5B01	F09	13
E5B02	F14	18
E5B03	F14	18
E5B04	F06, F07, F09	10, 11, 13
E5B05	F14	18
E5B06	F14	18
E5B07	F15	19
E5B08	F15	19
E5B09	F15	19
E5B10	F15	19
E5B11	F15	19
E5B12	F14	18

Question to formula index

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Question to formula index

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Question to formula index

References include direct calculations and conceptual questions illuminated by the formula. This is a topic lookup, not a claim that every listed question requires arithmetic.

Question	Formula entries	Pages
E7H10	F39	43
E8A01	F40	44
E8A05	F27	31
E8A06	F27	31
E8A07	F27	31
E8A09	F35, F38	39, 42
E8B01	F41, F42	45, 46
E8B03	F41	45
E8B04	F41	45
E8B05	F41	45
E8B06	F41	45
E8B09	F41	45
E8C02	F46	50
E8C05	F45	49
E8C07	F45	49
E8C10	F46	50
E8C11	F46	50
E8C12	F45	49
E8C13	F46	50
E8D09	F20	24
E9A02	F23	27
E9A06	F23	27
E9A07	F23	27
E9A08	F56	60
E9A09	F53	57
E9A10	F53	57
E9A12	F54	58
E9B01	F54	58

Question to formula index

References include direct calculations and conceptual questions illuminated by the formula. This is a topic lookup, not a claim that every listed question requires arithmetic.

Question	Formula entries	Pages
E9B02	F54	58
E9B03	F54	58
E9B04	F54	58
E9D01	F55	59
E9D04	F18, F53	22, 57
E9D05	F04	8
E9D08	F19	23
E9E06	F51	55
E9E07	F47	51
E9F01	F04, F49	8, 53
E9F03	F49	53
E9F04	F50	54
E9F06	F49	53
E9F09	F50	54
E9F10	F50	54
E9F11	F50	54
E9F12	F50	54
E9G01	F52	56
E9G02	F52	56
E9G03	F52	56
E9G08	F52	56
E9G09	F52	56
E9G10	F52	56
E9G11	F52	56

Glossary of units

Combine these units with the SI prefixes in F01. Symbols for units are case-sensitive. A unit and a variable may use the same letter; context and typography distinguish them.

Symbol	Unit name	Used for
A	ampere	Electric current
Ah	ampere-hour	Electric charge
bit/s	bits per second	Data rate
F	farad	Capacitance
H	henry	Inductance
Hz	hertz	Cycles per second
J	joule	Energy
K	kelvin	Absolute temperature
m	meter	Length
rad	radian	Angle
s	second	Time
S	siemens	Admittance
V	volt	Voltage
VA	volt-ampere	Apparent power
var	volt-ampere reactive	Reactive power
W	watt	Real power
W/m^2	watts per square meter	Power density
mW/cm^2	milliwatts per square centimeter	Power density

Common exact conversions: 1 Ah = 3600 C of charge; 1 W = 1 J/s; 1 W/m^2 = 0.1 mW/cm^2. The C for coulomb is a unit, while the C in circuit equations usually means capacitance.

Glossary of units

Combine these units with the SI prefixes in F01. Symbols for units are case-sensitive. A unit and a variable may use the same letter; context and typography distinguish them.

Symbol	Unit name	Used for
Ω	ohm	Resistance and impedance
Ω·m	ohm-meter	Resistivity
H/m	henries per meter	Permeability
Ω/V	ohms per volt	Voltmeter sensitivity
dB	decibel	Logarithmic ratio
ppm	parts per million	Fractional measurement
%	percent	One hundredth of a whole
C	coulomb	Electric charge

Glossary of symbols

Subscripts are spelled with an underscore in this lookup. Symbols are defined in context; the same letter can have different meanings in different formula families.

Symbol or notation	Meaning and units
a	Transformer secondary-to-primary turns ratio; also a generic perpendicular component in F02.
A and B	Boolean inputs in F36. A is also the unit ampere; B elsewhere may mean bandwidth or susceptance.
A_L	Inductance factor of a core, often nH per turn squared.
A_noise	Op-amp noise gain, dimensionless.
A_v	Signed voltage gain, dimensionless.
Arithmetic signs	The signs +, −, ×, ÷, /, and = mean addition, subtraction, multiplication, division, division, and equality. Adjacent factors or parentheses can imply multiplication.
b	Bits per symbol in F46; generic perpendicular component in F02.
B	Susceptance in siemens, or equivalent noise bandwidth in hertz; context determines which.
BW	Bandwidth in Hz unless a scaled unit is explicitly shown.
BW_3dB	Angular half-power beamwidth in degrees in F54.
BW_6 and BW_60	Filter widths at 6 dB and 60 dB attenuation.
c	Speed of light in vacuum, exactly 299792458 m/s.
C	Capacitance in farads; C_Ah is usable battery capacity in ampere-hours.
C_p and C_s	Equivalent parallel and series capacitance.
Ceiling brackets	Round upward to the smallest integer at least as large as the value.
d	Path distance; units follow the particular equation.

Glossary of symbols

Subscripts are spelled with an underscore in this lookup. Symbols are defined in context; the same letter can have different meanings in different formula families.

Symbol or notation	Meaning and units
D	Duty fraction in F28, dish diameter in F55, or one-sided FSK deviation in the F45 explanation.
d_1 and d_2	Distances from an assessed path point to the two endpoints.
d_geo and d_radio	Geometric and radio horizon separation in km.
D_m and D_t	Modulation average-to-PEP factor and transmit-time fraction.
DR	Dynamic range in dB; DR_dev denotes FM deviation ratio, which is dimensionless.
e	Base of natural logarithms, approximately 2.71828; used in exponential transients.
EIRP and ERP	Isotropic-referenced and dipole-referenced equivalent radiated powers in W.
f	Frequency in Hz unless the subscript specifies MHz; RF exposure-limit formulas use MHz.
F	Linear noise factor in F25; upright F is the unit farad.
F B ratio	Front-to-back pattern ratio, written F/B in formulas, in dB.
f_0 and f_c	Resonant frequency and filter cutoff or carrier frequency; meaning is local to the formula.
f_a	Audio offset in F43; aliased frequency in F37.
f_clock and f_DDS	DDS clock and output frequency.
f_edge	Specified band or emission-segment boundary.
f_H and f_L	Upper and lower half-power frequencies.
f_h and h	Harmonic frequency and integer harmonic number in F40.

Glossary of symbols

Subscripts are spelled with an underscore in this lookup. Symbols are defined in context; the same letter can have different meanings in different formula families.

Symbol or notation	Meaning and units
f_i f_o f_in f_input	Input and output frequencies; subscripts identify their role.
f_m and f_m,max	Modulating-tone frequency and highest modulating frequency.
f_max and f_N	Highest baseband frequency and Nyquist frequency.
f_s	Sample rate, in samples per second.
FSPL	Free-space path loss in dB.
G	Conductance in S, linear antenna gain, or a dB gain when explicitly labeled.
G_net	Net signed gain after subtracting losses, in dB.
G_t and G_r	Transmit and receive antenna gains in dBi in the link budget.
GBW	Gain-bandwidth product in Hz.
h_1 and h_2	Antenna heights in meters for the horizon approximation.
I	Electric current in A, RMS when specified for AC power.
I_B I_C I_E	Bipolar transistor base, collector, and emitter currents.
I_rx I_tx I_avg	Receive, transmit, and average current.
IIP3	Input-referred third-order intercept level in dBm.
Inequalities and indices	The signs <, >, ≤, ≥ mean less, greater, at most, and at least. A subscript labels a quantity; a superscript can be a power. Dummy indices i label summed components. Braces select cases.
j	Imaginary unit, square root of −1; $j^2 = -1$.

Glossary of symbols

Subscripts are spelled with an underscore in this lookup. Symbols are defined in context; the same letter can have different meanings in different formula families.

Symbol or notation	Meaning and units
k	Boltzmann constant in thermal noise; integer alias index in F37; information-bit count in F46.
K	DDS tuning word in F39; empirical bandwidth coefficient in the F45 explanation; upright K is kelvin.
K_p	PEP-to-average power ratio, dimensionless.
L	Inductance in H; in a link budget, a positive loss in dB.
L_c and L_p	Cable or component loss and path loss in a link budget.
L_s and L_p	Series and parallel inductance when used in a circuit-combination formula.
log log10 log2	Base-ten logarithm in this guide unless another base is shown; log2 uses base two.
M	Number of symbol states, integer decimation factor, or link margin; meaning is local.
m	AM modulation fraction, or an integer mixer coefficient. Upright m is meter.
M in F45	Highest baseband telegraphy frequency, one half the symbol rate in the cited bandwidth convention.
ML	Mismatch loss in dB.
n	Prefix exponent, bit count, refractive index, or integer mixer/coding count; use the local definition.
N	Noise-floor level in dBm, turn count, number of stages, or integer prescaler divisor.
N_acc and N_FFT	DDS phase-accumulator bit width and FFT record length.
N_levels and N_states	Number of converter levels or digital states, dimensionless.
N_p and N_s	Primary and secondary winding turns.

Glossary of symbols

Subscripts are spelled with an underscore in this lookup. Symbols are defined in context; the same letter can have different meanings in different formula families.

Symbol or notation	Meaning and units
NF	Noise figure in dB.
Overbar and ⊕	Boolean NOT and exclusive OR respectively.
P	Power in W; a dBm or dBW subscript changes the reporting unit.
P_1 and P_2	Reference and compared powers in matching units.
P_accepted and P_rad	Power accepted by an antenna and power radiated by it.
P_avg and P_PEP	Average power and peak envelope power.
P_block and P_min	Blocking threshold and minimum signal level in dBm.
P_c	Unmodulated AM carrier power in W.
P_f and P_r	Forward and reflected power in F48; P_r is received power in F24.
P_heat and P_net	Dissipated heat power and net forward power in W.
P_i P_o P_t	Input, output, and transmit powers; use the unit specified by the equation.
P_IM3,in	Input-referred third-order product level in dBm.
P_n and N_dBm	Available noise power, reported in W and dBm respectively.
Parallel bars	The circuit parallel-combination operation, written ‖.
PF	Power factor, dimensionless.
Q	Quality factor, dimensionless; Q_s and Q_p denote series and parallel models.

Glossary of symbols

Subscripts are spelled with an underscore in this lookup. Symbols are defined in context; the same letter can have different meanings in different formula families.

Symbol or notation	Meaning and units
q and q_req	ADC quantization step and required maximum step, in volts.
Q_r	Reactive power in var; deliberately distinguished from quality factor Q.
r	Distance in exposure equations; normalized resistance in Smith-chart equations; generic ratio in F02.
R	Resistance in Ω.
r_1 and r_mid	First Fresnel-zone radius and its midpoint value in meters.
R_b and R_payload	Gross coded bit rate and information bit rate in bit/s in F46.
R_b and R_t	Effective bottom and top divider resistances.
r_c	Coding rate, information bits divided by coded bits.
R_f R_in R_g	Op-amp feedback, input, and reference-leg resistances.
R_L and R_m	Resistive load and meter input resistance.
R_rad and R_loss	Equivalent radiation and loss resistance at the same reference point.
R_s and R_p	Series and parallel resistance; R_s is source resistance in F51.
R_s in F45 and F46	Symbol rate in baud; distinguished by context from resistance R_s.
RL	Return loss in dB in F48; the circuit name RL instead means resistor-inductor.
S	Power density in W/m^2 or mW/cm^2 as specified; apparent power in VA in F16; upright S is siemens.
S_i and S_limit	Source exposure density and its applicable limit in matching units.

Glossary of symbols

Subscripts are spelled with an underscore in this lookup. Symbols are defined in context; the same letter can have different meanings in different formula families.

Symbol or notation	Meaning and units
s_m	Analog voltmeter sensitivity in Ω/V.
S_shift	Full mark-to-space frequency separation in Hz.
SF	Filter shape factor, dimensionless.
sin cos tan cot atan2	Trigonometric functions; atan2 preserves angle quadrant and cot is reciprocal tangent.
SNR_req	Required signal-to-noise ratio in dB in the link-margin formula.
t	Time in seconds unless hours are explicitly used.
T	Waveform or operating-cycle period in seconds; absolute temperature in kelvin for noise.
t_d t_on t_run	Propagation delay, on-time, and battery operating time.
U	Sum of RF exposure fractions, dimensionless.
V	Voltage in V; RMS or peak is specified where needed.
v and v_p	Wave speed and transmission-line phase velocity in m/s.
V_drop	Regulator dropout voltage.
V_i V_o	Input and output voltage; V_i can mean initial voltage in transient notation.
V_max and V_min	Maximum and minimum AM envelope amplitudes.
V_p V_s	Primary and secondary voltage in F30; V_p is peak voltage in F27.
V_pp and V_p,env	Peak-to-peak voltage and peak RF voltage at the envelope crest.

Glossary of symbols

Subscripts are spelled with an underscore in this lookup. Symbols are defined in context; the same letter can have different meanings in different formula families.

Symbol or notation	Meaning and units
V_rms	Root-mean-square voltage.
V_span and V_range	ADC full input span and selected full-scale voltmeter range.
VF	Transmission-line velocity factor, dimensionless.
w	Morse speed in words per minute.
W W_C W_L	Energy in J; capacitor and inductor energy. Upright W is the watt unit.
x and y	Generic mathematical variables; x is normalized reactance in F52 and y is a logarithm in F02.
X X_L X_C	Signed net reactance and positive inductive and capacitive magnitudes in Ω.
x_i and x_f	Initial and final state values in the general transient equation.
Y Y_p	Admittance and total parallel admittance in siemens.
z	Normalized impedance, dimensionless.
Z Z_L Z_0	Impedance, load impedance, and real characteristic or reference impedance in Ω.
Z_in Z_s Z_p	Input, series-total, and parallel-total or reflected-primary impedance in Ω.
Z_t	Characteristic impedance of a quarter-wave matching section in Ω.
β	Transistor beta or FM modulation index; subscripts specify meaning.
Γ	Complex voltage-wave reflection coefficient; |Γ| is its magnitude.
δ	Skin depth in meters.

Glossary of symbols

Subscripts are spelled with an underscore in this lookup. Symbols are defined in context; the same letter can have different meanings in different formula families.

Symbol or notation	Meaning and units
Δ	Change or difference; Δ in the IP3 formula is carrier-to-product separation in dB.
Δf	Frequency error, FM deviation, or FFT bin spacing; context defines which.
ε_ppm	Fractional frequency error expressed in parts per million.
η and η_a	Efficiency and aperture efficiency as fractions, not percentages.
θ and φ	Phase or angular quantities; degrees or radians as specified.
λ	Wavelength in meters; λ_line is wavelength inside a transmission line.
μ	Magnetic permeability in H/m; as a prefix μ means one millionth.
π	Circle constant, approximately 3.141592654.
ρ	Electrical resistivity in Ω·m.
Σ	Sum all indicated terms.
τ	First-order time constant in seconds.
ω	Angular frequency in radians per second.
Ω	Ohm, the SI unit of resistance and impedance.
√ and vertical bars	Principal square root and magnitude or absolute value.
∠	Polar-coordinate phase angle.
≈ and ≃	Approximately equal; flags a rounded result or model approximation.

Glossary of terms

Definitions apply to the use of these terms in this guide. The alphabetical subject index links terms to formula pages and to this glossary.

Term	Meaning
Active region	Transistor bias region where collector current is controlled by base drive without saturation.
ADC	Analog-to-digital converter; maps sampled analog amplitudes to digital codes.
ADC code	One available digital output value of a converter.
Admittance	Reciprocal of impedance, expressed in siemens.
AF	Audio frequency.
Algebra	Using symbols and equation rearrangement to find unknown quantities.
Aliasing	Different analog frequencies producing indistinguishable sampled data.
AM	Amplitude modulation; varying carrier amplitude to convey information.
Ampere hour	Charge delivered by one ampere for one hour; 3600 coulombs.
Amplitude modulation	Amplitude modulation; varying carrier amplitude to convey information.
Analog	A signal representation that varies continuously rather than in discrete codes.
AND	Logic operation that is one only when every input is one.
Angular frequency	Rate of phase rotation in radians per second.
Antenna efficiency	Fraction of accepted antenna power radiated rather than dissipated.
Antenna pattern	Directional distribution of an antenna’s radiation or reception.
Anti aliasing	Filtering that prevents unwanted spectrum from folding into sampled bandwidth.
Aperture efficiency	Effective collecting area divided by physical aperture area.
Apparent power	Product of RMS voltage and RMS current, in volt-amperes.
Arctangent	Inverse tangent; returns the angle associated with a tangent ratio.
ARRL	American Radio Relay League; national amateur radio association and education publisher.

Glossary of terms

Definitions apply to the use of these terms in this guide. The alphabetical subject index links terms to formula pages and to this glossary.

Term	Meaning
Attenuation	Reduction in signal amplitude or power, often stated as a positive dB loss.
Average exposure	RF exposure evaluated over the applicable time interval and conditions.
Band edge	Boundary of a frequency allocation or authorized emission segment.
Bandwidth	Width of a frequency range using specified measurement limits.
Baseband	Message spectrum before translation to a radio-frequency carrier.
Battery runtime	Estimated operating duration from usable capacity and average current.
Baud	One symbol per second; not necessarily one bit per second.
Beamwidth	Angular width of an antenna lobe at specified relative levels.
Beta	Current gain for a transistor, or modulation index for FM; context determines meaning.
Binary	A number system or logic representation using two states.
Bipolar transistor	Semiconductor device with base, collector, and emitter terminals.
Bit depth	Number of bits available to represent each digital sample.
Bit rate	Number of transmitted or processed bits per second.
Blocking dynamic range	Separation between noise floor and a specified strong-signal blocking threshold.
Boltzmann constant	Exact SI constant relating temperature and energy, 1.380649×10^{-23} J/K.
Boolean logic	Algebra of true/false or one/zero values and logical operations.
Capacitance	Charge stored per unit voltage difference; measured in farads.
Capacitive reactance	Magnitude of a capacitor’s opposition to sinusoidal current.
Capacitor impedance	Complex opposition of a capacitor; ideally negative imaginary.
Capacitors	Components that store energy in electric fields.

Glossary of terms

Definitions apply to the use of these terms in this guide. The alphabetical subject index links terms to formula pages and to this glossary.

Term	Meaning
Carson rule	Approximate FM bandwidth estimate based on peak deviation and modulation frequency.
CFR	Code of Federal Regulations.
Characteristic impedance	Traveling-wave voltage-to-current ratio of a uniform transmission line.
Charging	Increasing a storage component's stored electric or magnetic energy.
Circuit	Interconnection of components providing paths for electric current.
Circulating voltage	Reactive-element voltage that can exceed applied voltage in a resonator.
Coaxial cable	Transmission line with a center conductor surrounded by a concentric outer conductor.
Coding rate	Information bits divided by total error-corrected coded bits.
Combined exposure	Sum of individual RF-source exposure fractions at the same assessed location.
Complex numbers	Numbers with real and imaginary components.
Conductance	Real part of admittance; inverse resistance for a pure resistor.
Conjugate	A complex number with its imaginary-part sign reversed.
Core inductance	Inductance produced by a winding on a specified magnetic core.
Coulomb	SI unit of electric charge; one ampere-second.
Counter	Circuit or instrument that counts events or divides an input sequence.
Counter accuracy	Agreement of measured frequency with true frequency, governed partly by time base.
Crest factor	Peak amplitude divided by RMS amplitude of the same waveform.
Current	Rate of electric charge flow, measured in amperes.
Current gain	Output-current change divided by input-current change under specified conditions.
Current lead	Current reaching a reference phase earlier than voltage.

Glossary of terms

Definitions apply to the use of these terms in this guide. The alphabetical subject index links terms to formula pages and to this glossary.

Term	Meaning
Current ratio	One current amplitude divided by another in consistent units.
Cutoff frequency	Specified response boundary; −3 dB for a simple first-order RC filter.
CW	Continuous wave; in amateur use, a carrier keyed for Morse code.
CW bandwidth	Spectrum occupied by a keyed carrier; depends on speed and keying shape.
dBd	Antenna gain relative to an ideal free-space half-wave dipole.
dBi	Antenna gain relative to an isotropic radiator.
dBm	Absolute power level relative to one milliwatt.
dBW	Absolute power level relative to one watt.
DC power	Power transferred by direct voltage and current.
DDS	Direct digital synthesis; generating a waveform using a digital phase accumulator.
Decade counter	Counter producing one output event for each ten input events.
Decibel	Logarithmic expression of a ratio; ten times the log of a power ratio.
Decimation	Reduction of sample rate with filtering to prevent aliasing.
Degrees	Angular units; one complete cycle is 360 degrees.
Delivered power	Net forward-minus-reflected power at a specified measurement plane.
Deviation ratio	Maximum FM deviation divided by highest modulation frequency.
Dielectric	Insulating material affecting electric fields and wave velocity.
Discharging	Releasing energy from a storage component toward a final state.
Dish gain	Directional gain of a parabolic reflector and feed system.
Dominant pole	Response feature that controls a system’s main first-order rolloff.

Glossary of terms

Definitions apply to the use of these terms in this guide. The alphabetical subject index links terms to formula pages and to this glossary.

Term	Meaning
Dropout voltage	Minimum input-to-output voltage difference needed for regulation.
DSP	Digital signal processing; numerical manipulation of sampled signals.
Duplexer	Frequency-selective network allowing transmitter and receiver to share an antenna.
Duty cycle	On-time divided by the complete operating interval.
Efficiency	Useful output power divided by input power.
EIRP	Equivalent isotropic radiated power; antenna input power times isotropic-referenced gain.
Electric field energy	Energy stored by separated electric charge, such as in a capacitor.
Electrical length	Length expressed as wave phase or a fraction of wavelength in its medium.
Energy	Capacity transferred or stored; power integrated over time, in joules.
Engineering notation	Scientific notation using powers of ten that are multiples of three.
Envelope	Slowly varying amplitude outline of a modulated RF waveform.
ERP	Effective radiated power referenced to an ideal free-space half-wave dipole.
Fading	Variation in received signal strength over time.
Far field	Region where radiation pattern shape is effectively independent of distance.
FCC	Federal Communications Commission, the United States communications regulator.
FEC	Forward error correction; redundancy enabling correction without requesting retransmission.
Feed line loss	Power dissipated or otherwise lost in the line between radio and antenna.
Feedback	Returning part of a circuit output to its input to control response.
FFT	Fast Fourier transform; an efficient algorithm for a discrete Fourier transform.
Filter shape factor	Ratio of two bandwidths measured at stated attenuation levels.

Glossary of terms

Definitions apply to the use of these terms in this guide. The alphabetical subject index links terms to formula pages and to this glossary.

Term	Meaning
Filter skirt	Transition region between a filter's passband and stopband.
FIR	Finite impulse response; a digital filter whose impulse response has finite duration.
Flip flop	Bistable digital circuit that can store one bit.
FM	Frequency modulation; varying instantaneous carrier frequency to convey information.
FM bandwidth	Frequency span assigned to or occupied by an FM signal under a stated definition.
Free space path loss	Ideal propagation loss between isotropic references in unobstructed far field.
Frequency	Number of cycles per second, measured in hertz.
Frequency division	Producing an output frequency that is a fraction of an input frequency.
Frequency resolution	Ability to distinguish frequency differences; definition depends on instrument.
Fresnel zone	Region around a propagation path defined by a specified path-length difference.
Front to back ratio	Difference in gain between forward and rear directions, usually in dB.
FSK	Frequency-shift keying; selecting between frequencies to encode symbols.
FSK bandwidth	Frequency span of frequency-shift keying under a stated spectral convention.
Full scale	Specified maximum input span or reading range of an instrument.
Gain bandwidth	Approximate product of gain and frequency for a dominant-pole op-amp response.
Gain chain	Series of gains and losses combined to calculate overall signal change.
Geometric horizon	Line-of-sight horizon from straight rays over a smooth spherical Earth.
Geometric mean	Square root of the product of two positive numbers.
Ground loss	RF power dissipated in earth or the antenna's ground-return system.
Half power	Half the reference power; approximately −3.01 dB.

Glossary of terms

Definitions apply to the use of these terms in this guide. The alphabetical subject index links terms to formula pages and to this glossary.

Term	Meaning
Harmonics	Components at integer multiples of a fundamental frequency.
HF	High frequency; 3 to 30 MHz.
I Q	In-phase and quadrature components, separated by 90 degrees.
IIP3	Input-referred third-order intercept point for extrapolated equal-tone intermodulation.
Impedance	Complex ratio of sinusoidal voltage to current, in ohms.
Impedance transformation	Changing the impedance presented to a source through a network.
Inductance	Flux-linkage change per unit current change; measured in henries.
Inductance factor	Core constant relating winding inductance to turns squared.
Inductive reactance	Positive reactance of an ideal inductor at a specified frequency.
Inductor impedance	Complex opposition of an inductor; ideally positive imaginary.
Inductors	Components that store energy in magnetic fields.
Intercept point	Extrapolated level where desired signal and a distortion product would be equal.
Intermodulation	Nonlinear generation of components involving two or more input frequencies.
Inverse square law	Density or intensity falling as the reciprocal of distance squared in ideal spreading.
Inverting amplifier	Amplifier whose output has opposite polarity to its input.
Isotropic radiator	Ideal reference antenna radiating equally in every direction.
LC resonance	Frequency at which inductive and capacitive effects cancel in an ideal resonator.
Linear regulator	Supply regulator controlling a pass or shunt element continuously.
Linearity	Property under which superposition applies and gain does not depend on signal amplitude.
Link budget	Accounting of transmit power, gains, and losses to predict received power.

Glossary of terms

Definitions apply to the use of these terms in this guide. The alphabetical subject index links terms to formula pages and to this glossary.

Term	Meaning
Link margin	Received level above or below the required receiving threshold.
Load	Circuit or device receiving electrical power from a source.
Loaded Q	Quality factor including loading from source and connected circuits.
Logarithms	Exponents to which a base must be raised to produce a specified positive number.
Lossless	Idealization in which no power is dissipated in the component or line.
Low pass filter	Filter passing lower frequencies and attenuating higher frequencies.
LSB	Lower sideband; in ADC contexts it can instead mean least significant bit.
Magnetic field energy	Energy associated with magnetic fields, such as around an inductor.
Magnitude	Nonnegative size of a scalar or complex quantity.
Meter loading	Change in a circuit caused by the measuring instrument's finite impedance.
Microwave path	Radio propagation route at microwave frequencies.
Mismatch loss	Loss of accepted fraction of a specified incident wave due to reflection.
Mixer	Nonlinear or time-varying circuit producing translated frequency components.
Modulation depth	Fractional change of AM envelope relative to its carrier amplitude.
Modulation index	Dimensionless measure of modulation; for single-tone FM, deviation divided by tone frequency.
Morse speed	Rate in words per minute under the stated Morse timing convention.
MPE	Maximum permissible exposure; an applicable RF field or power-density limit.
Mutual inductance	Coupling in which changing current in one coil induces voltage in another.
NAND	NOT of AND; zero only when all inputs are one.
NCVEC	National Conference of Volunteer Examiner Coordinators; its committee maintains the examination pools.

Glossary of terms

Definitions apply to the use of these terms in this guide. The alphabetical subject index links terms to formula pages and to this glossary.

Term	Meaning
Near field	Region close to an antenna where simple far-field relationships may not apply.
Noise factor	Linear SNR degradation ratio; noise figure is its dB form.
Noise figure	Receiver SNR degradation expressed in decibels.
Noise floor	Noise level under specified bandwidth and measurement conditions.
Noise gain	Op-amp closed-loop gain seen by a voltage source at its noninverting input.
Noninverting amplifier	Amplifier preserving input-output polarity.
NOR	NOT of OR; one only when all inputs are zero.
Normalization	Dividing values by a reference to obtain dimensionless ratios.
NOT	Logic inversion; changes zero to one and one to zero.
Nyquist frequency	Half the sample rate for ordinary real sampling.
Ohm law	Voltage equals current times resistance for a resistive element.
Open stub	Transmission-line segment with an open-circuit termination.
Operational amplifier	High-gain differential amplifier normally operated with feedback.
OR	Logic operation that is one when at least one input is one.
Parabolic antenna	Reflector antenna using a parabolic surface and a feed near its focus.
Parallel impedance	Equivalent impedance of branches sharing the same voltage.
Parallel resistance	Equivalent resistance of resistors connected across the same two nodes.
Parasitic reactance	Unintended capacitance or inductance associated with a physical component.
Parity	A bit-checking convention used to detect some errors in a binary sequence.
Parts per million	Relative fraction multiplied by one million.

Glossary of terms

Definitions apply to the use of these terms in this guide. The alphabetical subject index links terms to formula pages and to this glossary.

Term	Meaning
Passband	Frequency range a filter is intended to pass.
Path loss	Reduction in signal power associated with propagation between references.
Peak envelope power	RF-cycle average power at the crest of a modulation envelope.
Peak to peak	Difference between maximum and minimum instantaneous waveform values.
PEP	Peak envelope power.
Period	Time for one cycle of a repeating waveform.
Permeability	Material parameter relating magnetic flux density and magnetic field strength.
Phase accumulator	Digital register repeatedly advanced by a tuning word in a DDS.
Phase angle	Relative position within a cycle, expressed in degrees or radians.
Phase delay	Time or angle displacement of a sinusoidal waveform relative to a reference.
Phasors	Complex representations of sinusoidal magnitudes and phases at one frequency.
Photovoltaic	Converting incident light energy into electrical energy.
Picowatt	One trillionth of a watt, or 10^{-12} W.
Plane wave	Ideal wave with planar constant-phase surfaces and fixed field relationships.
Polar coordinates	Representation by magnitude and angle.
Polarization	Orientation and time evolution of the electric-field direction of a radio wave.
Positive logic	Convention in which a high electrical level represents Boolean one.
Power density	Power per unit area, commonly W/m^2 or mW/cm^2.
Power dissipation	Conversion of electrical input power into heat or other unrecovered loss.
Power factor	Real power divided by apparent power; $\cos\theta$ for sinusoidal voltage and current.

Glossary of terms

Definitions apply to the use of these terms in this guide. The alphabetical subject index links terms to formula pages and to this glossary.

Term	Meaning
Power ratio	One power divided by another in matching units.
Prescaler	Frequency divider placed ahead of a counter or other circuit.
Protocol overhead	Framing, addressing, and control bits beyond delivered user information.
Pythagorean theorem	Squared hypotenuse equals the sum of squared perpendicular sides.
Q section	Quarter-wave transmission-line impedance transformer.
QAM	Quadrature amplitude modulation; information encoded in amplitude and phase states.
QPC	Question Pool Committee of the NCVEC.
QPSK	Quadrature phase-shift keying; a four-state phase modulation.
Quadrature	A phase separation of one quarter cycle, or 90 degrees.
Quality factor	Measure of energy storage relative to loss in a resonant system.
Quantization	Mapping a continuous range of amplitudes into discrete digital levels.
Quarter wave transformer	A line section one quarter electrical wavelength long used for matching.
Radian	Angle subtending an arc equal in length to the circle radius; 2π radians is one cycle.
Radiation resistance	Equivalent resistance representing antenna power radiated as electromagnetic waves.
Radio horizon	Horizon estimate allowing for atmospheric refraction.
RC circuit	Circuit whose resistance and capacitance determine its response.
Reactance	Imaginary component of impedance associated with energy storage.
Reactive power	Sinusoidal AC energy exchange associated with reactance, in var.
Real power	Average net energy transfer per unit time, in watts.
Rectangular coordinates	Representation by perpendicular real and imaginary components.

Glossary of terms

Definitions apply to the use of these terms in this guide. The alphabetical subject index links terms to formula pages and to this glossary.

Term	Meaning
Reference plane	Specified location at which wave quantities or impedance are defined.
Reflected power	Power in a wave traveling back from a mismatch toward the source.
Reflection coefficient	Complex reflected-to-incident voltage-wave ratio at a reference plane.
Refraction	Change in wave direction or behavior caused by a changing propagation medium.
Refractive index	Ratio of vacuum light speed to phase velocity in a medium.
Resistance	Real opposition to current associated with power dissipation or transfer.
Resolution	Smallest distinguishable or encoded change under a stated instrument definition.
Resonance	Condition where opposing reactive effects balance at a particular frequency.
Resonant frequency	Frequency at which specified reactive effects cancel or a resonant response occurs.
Resonator bandwidth	Width between specified resonator response limits, often half-power points.
Return loss	Negative of reflection-coefficient magnitude expressed with twenty-log scaling.
RF	Radio frequency.
RF safety	Control of exposure to radio-frequency fields and related operating hazards.
RL circuit	Circuit whose resistance and inductance determine its response.
RLC circuit	Circuit containing resistance, inductance, and capacitance.
RMS	Root mean square; square root of the mean squared waveform value.
Rolloff	Rate at which a response falls with increasing or decreasing frequency.
S parameters	Scattering parameters relating incident and outgoing waves at network ports.
S11	Input-port reflection coefficient with other ports matched to their references.
Sampling	Measuring a waveform at discrete times.

Glossary of terms

Definitions apply to the use of these terms in this guide. The alphabetical subject index links terms to formula pages and to this glossary.

Term	Meaning
Saturation	Operating limit where a transistor or magnetic core no longer follows its linear model.
SDR	Software-defined radio; radio functions performed partly in software or digital processing.
Self resonance	Resonance between a component’s intended and parasitic reactances.
Series impedance	Sum of impedances traversed by the same current.
Series resistance	Sum of resistances traversed by the same current.
Shorted stub	Transmission-line segment terminated in a short circuit.
SI prefixes	Powers-of-ten prefixes such as kilo, milli, micro, and pico.
Sidebands	Frequency components produced around a carrier by modulation.
Siemens	SI unit of admittance and conductance; reciprocal ohm.
Signal to noise ratio	Desired signal power divided by noise power in a stated bandwidth.
Skin depth	Depth at which current density falls to 1/e of its surface value in a good conductor.
Skin effect	Concentration of alternating current near a conductor’s surface at high frequency.
Smith chart	Graphical mapping of normalized impedance or admittance into reflection-coefficient space.
SNR	Signal-to-noise power ratio in a specified bandwidth.
Speed of light	Vacuum electromagnetic-wave speed, exactly 299792458 m/s.
Square root	Number whose square equals the specified quantity; principal root is nonnegative.
Square wave	Periodic waveform alternating between two levels; symmetry determines harmonic content.
SSB	Single-sideband modulation with one sideband; the carrier is usually suppressed.
SSB average power	Average RF power of an SSB waveform; depends on speech and processing.
Stopband	Frequency range a filter is intended to attenuate.

Glossary of terms

Definitions apply to the use of these terms in this guide. The alphabetical subject index links terms to formula pages and to this glossary.

Term	Meaning
Stored energy	Energy retained in electric or magnetic fields.
Stub matching	Using a terminated line section to cancel reactance or otherwise create a match.
Superposition	Adding individual responses to obtain a total response in a linear system.
Susceptance	Imaginary part of admittance, expressed in siemens.
SWR	Standing-wave ratio, conventionally the maximum-to-minimum line voltage magnitude.
Symbol rate	Number of modulation symbols transmitted each second; measured in baud.
Thermal noise	Random electrical noise associated with thermal agitation.
Third order distortion	Nonlinear products whose frequency-coefficient order sums to three.
Time base	Frequency or time reference used by a counter or sampling instrument.
Time constant	Characteristic exponential-response time of a first-order circuit.
Transformer	Magnetically coupled windings used to transfer AC energy or transform impedance.
Transmission line	Distributed structure guiding electromagnetic energy with a characteristic impedance.
Transmission line impedance	Input impedance determined by line properties, length, and termination.
Truth table	List of every input combination and its corresponding logic outputs.
Tuning word	Digital integer setting the phase advance per clock in a DDS.
Turns ratio	Ratio of winding turn counts in a transformer or coupled structure.
UHF	Ultra high frequency; 300 MHz to 3 GHz.
Uncontrolled exposure	Exposure of the general public or people lacking the required knowledge or control.
Unit conversion	Changing numerical units without changing the physical quantity.
USB	Upper sideband in this guide; not the computer connector standard.

Glossary of terms

Definitions apply to the use of these terms in this guide. The alphabetical subject index links terms to formula pages and to this glossary.

Term	Meaning
Velocity factor	Wave speed in a transmission line divided by vacuum light speed.
VHF	Very high frequency; 30 to 300 MHz.
Voltage	Electric potential difference, measured in volts or joules per coulomb.
Voltage divider	Series network producing an output that is a fraction of the input voltage.
Voltage gain	Output voltage divided by input voltage, including polarity or phase when needed.
Voltage lead	Voltage reaching a reference phase earlier than current.
Voltage magnification	Reactive voltage exceeding applied voltage in a resonant circuit.
Voltage ratio	One voltage amplitude divided by another in consistent units.
Voltmeter sensitivity	Analog meter input resistance per volt of selected full-scale range.
VSWR	Voltage standing-wave ratio; the usual meaning of SWR.
Wavelength	Distance over which a traveling wave completes one cycle.
Windowing	Weighting a sampled record before frequency analysis to control spectral leakage.
WPM	Words per minute in a stated Morse timing convention.
XNOR	Logic operation that is one for equal binary inputs.
XOR	Logic operation that is one for unequal binary inputs.

Sources and further reading

Primary source links checked for this edition. The official pool determines the exam scope; engineering references support the explanations and their limits.

P NCVEC Extra Class Question Pool

Official 2024–2028 pool and syllabus with fourth errata dated February 4, 2026. Used to identify active numerical and formula-related topics and check answer choices.

Open source

ARRL ARRL question pool dates and withdrawals

Pool valid July 1, 2024 through June 30, 2028. Withdrawn Extra items checked: E2A13, E4D05, E6D07, E9E10.

Open source

MANUAL ARRL Extra Class License Manual resources

Supplement page for the 13th edition, with study-guide and correction links. This guide is independently written and is not an ARRL publication.

Open source

PHY OpenStax University Physics Volume 2

Open physics textbook. Chapters 8–15 cover capacitance, current, circuits, magnetism, inductance, and alternating-current circuits.

Open source

Current pool dates: ARRL question pools

Sources and further reading

Primary source links checked for this edition. The official pool determines the exam scope; engineering references support the explanations and their limits.

DB ARRL Tutorial on the Decibel

Primary ARRL tutorial explaining power and voltage ratios and absolute decibel references.

Open source

SI NIST International System of Units

SP 330 Sections 2 and 3: SI constants, units, and decimal prefixes. Exact values of c and k are distinguished from rounded study approximations.

Open source

TI Texas Instruments op amp specifications

Understanding Operational Amplifier Specifications, SLOA011B. Feedback gain, noise gain, frequency response, and gain-bandwidth assumptions.

Open source

AD Analog Devices ADC and distortion tutorials

Understanding AC Behaviors of High Speed ADCs; sampling, quantization, noise, and distortion concepts. Also see MT-012 for IM3 and intercept behavior.

Open source

Sources and further reading

Primary source links checked for this edition. The official pool determines the exam scope; engineering references support the explanations and their limits.

AD12 Analog Devices intermodulation tutorial

MT-012 Intermodulation Distortion Considerations for ADCs. Used for equal-tone third-order intercept interpretation.

Open source

TL MIT Electromagnetic Fields and Energy

Hermann A. Haus and James R. Melcher. Chapter 14 treats one-dimensional wave dynamics and transmission lines; other chapters cover energy and magnetic diffusion.

Open source

ANT ITU propagation recommendations

P.525 Calculation of free-space attenuation and P.526 Propagation by diffraction. Antenna and horizon concepts also cross-checked against the cited pool topics.

Open source

DIFF ITU diffraction recommendation

P.526 Propagation by diffraction, including Fresnel-zone geometry.

Open source

Sources and further reading

Primary source links checked for this edition. The official pool determines the exam scope; engineering references support the explanations and their limits.

FCCBW FCC bandwidth definitions

47 CFR 2.202, including the FSK bandwidth convention with K = 1.2 and the telephony FM estimate.

Open source

FCC97 FCC authorized emission types

47 CFR 97.305. Used with the pool for sideband and authorized-segment edge calculations.

Open source

FCCRF FCC RF exposure limits

47 CFR 1.1310, Table 1. Defines controlled and uncontrolled field and power-density limits and averaging conditions.

Open source

RF ARRL RF safety guidance

ARRL Handbook RF Safety chapter: exposure evaluation, averaging, field regions, and practical limitations.

Open source

Alphabetical subject index

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