Gaining on the Decibel

Part 2: Money is power, and the decibel is an expression of a power ratio. Wouldn't you like to receive a 3-dB increase in spending money?†

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In the first part of this article we introduced the decibel, a logarithmic expression of *power* ratio, and demonstrated why it is inappropriate to apply this measurement tool directly to changes in EMF or current. We also presented standards for the proper capitalization of dB and explained how it can be used to express either absolute or relative power. You may wish to review the previous part before reading further.

In this part we will explore various applications, both proper and improper, of the dB to electronic communications in general and Amateur Radio in particular.

Antenna Gain

Most of us have considerable difficulty in visualizing how an antenna can have gain. Being a passive device, there's just no way an antenna with an applied input of 100 watts can possibly put out anything greater than 100 watts! The whole idea of antenna gain relates to the fact that the same 100-watt transmitter can deliver varying amounts of power *in a specified direction*, when connected to different antennas. Similarly, a receiver of specified sensitivity may recover widely varying signal-to-noise ratios, from a specific distant station *in a certain direction*, when fed with different antennas.

If you get the impression that antenna gain involves the performance of a particular antenna as compared to that of a specified reference antenna, you're absolutely right! The problems start in trying to specify the appropriate reference antenna.

A popular reference antenna for theoretical evaluations is the isotropic radiator, the only truly omnidirectional antenna. (Remember, "omnidirectional" means that the antenna radiates equally poorly in all directions.) An isotropic antenna connected to a transmitter disperses the radiant energy in a perfectly uniform sphere. An isotropic receiving antenna will similarly respond uniformly to applied signals from any direction in three-dimensional spherical space.

The only problem with referencing the performance of any physical antenna to that of an isotropic radiator is that the perfect isotrope doesn't really exist. You cannot build one, buy one or observe one in nature. Nothing is that uniform.[6]

An antenna whose radiation pattern is *nearly* uniform, in *most* directions, is the half-wave dipole. Simple to visualize and easy to implement, the half-wave dipole radiates a fairly uniform pattern in all directions except off its ends, where deep nulls appear. Does a dipole have gain, relative to an isotrope? Yes! All of the power fed to a properly matched dipole system must be radiated. And since there are nulls off the ends, the energy that would have gone into those nulls, if the dipole were an isotrope, has to go in some other direction. In actual fact, it adds to the power radiated *broadside* to the dipole, making its familiar "doughnut" radiation pattern a little fatter. Redirecting the energy from the nulls makes the signal available from a dipole, in the direction of its maximum radiation (broadside), about 2 dB greater than that from an isotrope.

Knowing the above, we now have a way of determining an antenna's gain, relative to an isotropic radiator, even though we do not have an isotropic reference antenna lying around the shack. Simply compare the signal power received from a distant station with the antenna under test to that received from the *same* station with a dipole.[7] The resulting power ratio can be converted to dB just as you've always converted power ratios to dB, by calculating 10 times its common log. The resulting figure is antenna gain in dB *relative to a dipole*, or dBd. Since you know the relationship between a dipole and an isotrope, you can now find antenna gain in dBi (decibels relative to an isotropic reference) simply by adding 2 dB to dBd.

The most common mistake made in antenna-gain measurements is that of not specifying the reference to which the antenna under test was physically or mathematically compared. An antenna gain of +10 dBi means something very different from a gain of +10 dBd. And an antenna gain expressed simply as +10 dB means something else again. It means the person specifying the gain was either trying to mislead and deceive, or he simply doesn't understand dB!

Free-Space Path Loss

Even before Congress passed the Inverse Square Law, it was well known that S-meter readings vary inversely with the distance to the DX station. To understand the relationship between distance and attenuation, we need to consider two points (A and B) of a communications path, separated by distance D and communicating via electromagnetic waves of wavelength λ. And to remove from the analysis the effects of antenna gain, beamwidth, radiation pattern or effective aperture, we will assume that both the transmitter (at Point A) and the receiver (at Point B) are connected to perfectly matched, ideal, lossless isotropic antennas.

As long as the distance D is great relative to the wavelength λ (the far-field restriction mentioned in Ref 7), it can be shown that the EMF recovered by the receiving antenna is a fraction of the EMF applied

†Part 1 appears in Feb 1986 *QST*. Part 3, the conclusion, will appear in a subsequent issue.

[6]Notes and references appear on page 31.

to the transmitting antenna, which varies with the ratio λ over D. The equality is:

$$Av = \frac{\lambda}{4\pi D}$$

where

Av is the voltage ratio $\frac{(V\ \text{received})}{(V\ \text{transmitted})}$

and the constant 4π comes to us from spherical trigonometry, representing the number of steradians in a sphere.

Of course, since Av is a unitless ratio (volts over volts cancels), it is important that λ and D be expressed in the same units.

Since we defined our antennas as being ideal, they are perfectly matched to free space. Thus, the potentials transmitted and received are measured across the same impedance, and power ratio becomes the square of potential ratio. We can therefore say

$$Ap = Av^2 = \left(\frac{\lambda}{4\pi D}\right)^2$$

And we know how to convert power ratios to dB:

$$dB = 10 \log Ap$$
$$= 10 \log \left(\frac{\lambda}{4\pi D}\right)^2$$

This yields a *negative* number, since path gain is less than unity. If we change the sign, it follows that free-space path *loss* α (the Greek letter alpha, lower case) would be:

$$\alpha = -10 \log_{10} \left(\frac{\lambda}{4\pi D}\right)^2$$

Since $-10 \log(x) = 10 \log(1/x)$, it follows that

$$\alpha = 10 \log_{10} \left(\frac{4\pi D}{\lambda}\right)^2$$

This relationship allows us to predict free-space path loss at any frequency, over any line-of-sight distance, as long as we measure distance and wavelength in the same units. It is certainly easier to employ than the various nomographs provided for that purpose in the literature, and is far easier to remember than those published equations that contain fudge factors to compensate for distance expressed in, say, miles, and wavelength in inches. Furthermore, if you understand the meaning of the decibel (and you should by now), the above equation should allow you to visualize the relationship in a physical sense.

Effective Isotropic Radiated Power

Moonbouncers use EIRP a lot. This is total output punch, measured in dBm. Think of it as a measure of the goo you have going out, in dB relative to a 1-milliwatt transmitter, connected through a lossless transmission line to an ideal isotropic antenna.

EIRP is calculated by adding together transmitter output power in dBm, feed-line loss in *negative* dB and antenna gain in dBi. Thus, a transmitter output of +40 dBm, applied through a 6-dB lossy transmission line to an antenna whose gain is +10 dBi, will generate an effective isotropic radiated power of (+40 dBm) + (−6 dB) + (+10 dBi) = +44 dBm.

It bothers some that we can mix such obviously diverse units as dB, dBi and dBm, but in each case, we are comparing a particular signal level to a *specified* reference. Only the reference changes for each element analyzed; the units of measure, dB (10 times the log of a power ratio) remains consistent throughout the calculation. Note that the transmitter output in the above example is 40 dB more than a milliwatt, the feed-line gain is 6 dB less than a lossless transmission line, and the antenna gain is 10 dB more than that of an isotrope. The resulting EIRP is then a power level, measured in dB relative to a specified (though perhaps elusive) reference power, or 44 dB more than the power radiated in a given direction, if 1 milliwatt were applied through a lossless transmission line directly to an isotropic antenna.

Actually, we mix units in other fields of endeavor with minimal confusion. Consider the technician earning $12 an hour, who receives a 10% raise. What is his new hourly salary? If you've been paying close attention, you might be tempted to say, "Wait a minute. You can't mix percents with dollars!" But of course you can. The final unit of measure will still be *dollars*. Percent simply signifies a *change*. Similarly, a power level in dBm (or dBW) can be thought of as an absolute level, like a wage in dollars. Cable loss in dB, path loss in dB, antenna gain in dBi (or dBd) and amplifier gain in dB all represent changes to the original signal level, much as a 10% raise represents a change in salary. The resulting power level, after all these changes have been accomplished, is of course measured in the original unit, dBm or dBW.

Receiver Sensitivity

A previously published article defines the major factors affecting receiver sensitivity.[8] Here we shall concern ourselves with how receiver sensitivity can be measured in dB.

In the absence of interference, any signal applied to the input of a receiver is competing with noise. For a signal to be heard, its power must exceed the total noise power by a specified amount (called signal-to-noise ratio) that varies as a function of modulation type, modulation percentage, signal conditioning, any special coding on the signal and the type of detector circuitry employed. Given the required signal-to-noise ratio, the receiver sensitivity is limited by the amount of noise power the signal has to override.

The noise power present at the input of a theoretically perfect receiver (that is, one which generates in its circuitry no additional noise above that occurring naturally in the environment) is a function of heat and bandwidth. Mathemagically,

$$Pn = kTB$$

where

- Pn represents noise power in watts
- k is Boltzmann's Constant (1.38×10^{-23} joules per kelvin)
- T is the temperature of the receiver circuitry, in degrees absolute (or kelvins)
- B represents the narrowest bandwidth (typically the IF bandwidth) of the circuitry preceding the detector stage, in Hz.

Since noise power can be calculated in watts, we can further convert it to milliwatts (simply multiply by 1000) and express it in decibels compared to a milliwatt, or dBm.

Consider the sensitivity of an ideal, noiseless receiver with a bandwidth of 1 Hz, operating at a temperature of 290 K (an accepted standard temperature for earth-based equipment). The resulting noise power with which any signal would have to compete will equal:

$$\begin{aligned} Pn &= kTB \\ &= (1.38 \times 10^{-23}\ \text{joules/K}) \times (290\ \text{K}) \times (1\ \text{Hz}) \\ &= 4 \times 10^{-21}\ \text{watts} \\ &= 4 \times 10^{-18}\ \text{mW} \\ &= -174\ \text{dBm} \end{aligned}$$

You may have read that the noise threshold (that is, the sensitivity at unity signal-to-noise ratio) of an ideal, noiseless receiver is −174 dBm per Hz of bandwidth, and you can see where this figure came from—except for one thing. The above value holds *only* at the so-called standard temperature of 290 K. The same receiver in the cold depths of space will experience significantly less thermal noise, and thus will exhibit higher sensitivity than the "−174 dBm/Hz" approximation would indicate.

Until now we have been talking about an ideal, noiseless receiver. In truth, the receiver circuitry itself is going to contribute some noise to its own input; thus the actual sensitivity of any receiver will be less than we have predicted by kTB. We can quantify the noise contribution of the receiver circuitry (and its resulting impact on sensitivity) in three different ways: noise factor, noise figure or noise temperature.

Noise factor (often abbreviated F) is a measure of the degree to which the receiver's internal noise increases the noise power, kTB. It represents a power ratio. Thus, if kTB, in watts or milliwatts, is known, multiplying it by noise factor yields the actual noise power level which the applied signal must override. In the preceding example of a receiver with a 1-Hz bandwidth operating at standard temperature, a receiver noise factor of 2 would raise the actual noise threshold to:

$$\begin{aligned} Pn &= F \times (kTB) \\ &= 2 \times (4 \times 10^{-18}\ mW) \\ &= 8 \times 10^{-18}\ mW \\ &= -171\ dBm \end{aligned}$$

Noise figure (usually abbreviated NF) is simply noise factor expressed in dB. Since noise factor is a power ratio, we can convert it to dB by multiplying its common log by 10. To find a receiver's noise threshold when NF is known, simply add NF (in dB) to the dBm equivalent of kTB, that is, 10 times the common log of (kTB × 1000).

In the previous example, NF = 10 $\log_{10}$ 2 = 3 dB. Thus, the actual noise threshold was:

$$\begin{aligned} Pn &= 10 \log_{10} (kTB \times 1000) + NF \\ &= (-174\ dBm) + (3\ dB) \\ &= -171\ dBm \end{aligned}$$

You can see from this calculation that the 3-dB NF effectively degraded the sensitivity of our sample receiver by exactly 3 dB.

If a receiver's internal noise is expressed in noise temperature, we know that the equivalent thermal noise to which the receiver is subject exceeds its physical temperature by a specified amount. To find a receiver's noise threshold when noise temperature (sometimes called T_{eq}) is known, simply *add* noise temperature to 290 K (or whatever other physical temperature may apply) and utilize this sum when calculating noise power from kTB.

If noise temperature equals 290 K (equivalent to a 3-dB noise figure, or a noise factor of 2) and the receiver is operated at standard temperature, then the receiver's noise threshold is:

$$\begin{aligned} Pn &= k \times (290 + T_{eq}) \times B \\ &= k \times (290 + 290) \times B \\ &= 8 \times 10^{-18}\ mW \\ &= -171\ dBm \end{aligned}$$

The preceding three examples illustrate that when calculating receiver sensitivity, whether employing noise factor, noise figure or noise temperature, proper use of the decibel yields consistent results.

Link Analysis

Link analysis, perhaps the most elegant application of decibel calculations in electronic communications, allows us to quantify all of the elements of a communications system and predict its success. It combines all of the foregoing examples, in an attempt to predict the overall performance of a communications link. It is also the one application of decibels least favored by the Amateur Radio community.

The true ham, so legend has it, shuns any calculation that might dissuade him from any desired endeavor. After all, it is through analysis that the engineering community has determined that this or that objective is impossible, and thus expends no effort toward achieving it. The ham, it is argued, by not knowing that something is impossible, simply sets about accomplishing it . . . and frequently succeeds.

The argument is certainly appealing. If you want to know how far you can communicate with a particular combination of equipment and conditions, the time-honored method is to point your antenna and call CQ. Who ever bothered to calculate EIRP, path loss, receiver sensitivity and required signal-to-noise ratio before getting on the air?

Yet there are applications where the analytical approach does make sense. Consider the world of communications satellites, where countless thousands of hours and hundreds of thousands of dollars may be expended in preparing a payload for orbit. There is certainly an advantage to making our OSCARs accessible to the greatest number of experimenters, and this can be assured by predicting, in advance of a launch, the precise user equipment necessary to access the satellite. If we wait until after a spacecraft achieves orbit, only to discover that its transponder is not accessible to stations operating within legal amateur power limits, we have done the user community a disservice.

Link analysis can be performed through multiplication of power ratios, that is, by multiplying transmitter power by antenna gain by path loss by receiving-antenna gain by required signal-to-noise ratio, and comparing the resulting power level to the receiver noise threshold, kTB. But this becomes awkward in the extreme. A far better approach might be to add logarithms. After all, isn't that why they were developed in the first place?

If we express transmitter power in dBm, transmitting-antenna gain in dBi, path loss in dB and receiving-antenna gain in dBi, the sum of these four quantities (less any feed-line losses along the way, in dB) will give us an accurate picture of the power level, in dBm, available to the distant receiver. We can compare this figure to the receiver sensitivity, in dBm, found from k, T, B, required signal-to-noise ratio and noise figure, and discern the available signal margin in the link, in dB. If this figure happens to be negative, we can explore various ways of improving link performance, before investing significant resources in what might otherwise prove a fruitless effort.

Of course, there will always be times when simply pointing the antenna and calling CQ is the appropriate way to quantify a communications path. But when prior knowledge of performance is required, proper use of the decibel can make the mathematics almost painless.

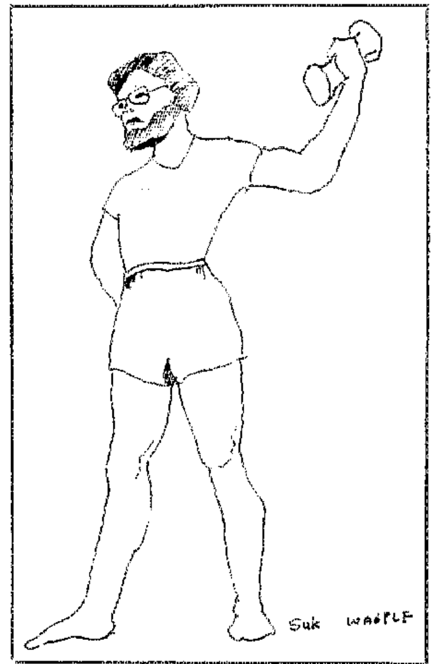


Fig. 2—The author lifting one Db (see text). *(drawing by WA6PLF)*

More Creative Misapplications

Gruchalla has cited a number of examples of creative misapplication of the decibel.[9] His powerful presentation bears some amplification, if we are to gain a full misunderstanding. Recognizing that using decibels is a way of expressing power ratios, consider the following case studies.

Case 1: Finance

A gallium-pesticide transistor delivers 12 dB of gain in a particular application and costs $9. A GLASSFET delivers 16 dB of gain in the same circuit and sells for $18. Which active device is the more cost effective?

The hollow-state device delivers a 4-dB gain advantage, at twice the unit cost. Ten times the common log of (twice the cost) equals 3 dB. Thus, the latter device delivers 4 dB of additional performance for 3 dB more dollars, for a net cost vs performance advantage of 1 dB. And the analysis is easily justifiable on the obvious basis, confirmed by countless economists, that money is power.

Case 2: Time Management

An engineer toils from 9 AM to 6 PM. Can you express his workday in dB? Let dB equal 10 times the common log of (time out over time in). Dividing 1800 hours by 0900 hours, and solving the above relationship, yields a 3-dB work day.

Except that the engineer takes an hour off for pretzels and bridge. Dividing 1300 hours by 1200 hours, we find that the employee has enjoyed a 0.35-dB lunch hour, and thus should be paid for only 2.65 dB of labor.

The proof of the above relationship derives from a simple syllogism. Since time is money (just ask any busy executive), and money is power (see Case 1 above), and power is measured in dB, time can be measured in dB. If you don't understand this completely, come back in 10 dB and I'll explain it again.

Case 3: Athletics

You may recall our discussion about proper capitalization in Part 1. Fig 2 depicts an athlete lifting 1 Db.

During the Los Angeles Olympics, a weightlifter from West Hernia beat the world's record in his event by 0.6 dB. This figure was found in the usual way, by first dividing the weight he lifted by the previous record, then taking 10 times the log. And of course, dB is the appropriate unit, since the West Hernian was a power lifter.

Case 4: Municipal Planning

The mayor of the booming metropolis of Hictown (pop 37) comes to the startling discovery that not a single radio amateur resides within his jurisdiction. Upon researching the matter, he attributes this phenomenon to an obscure law, one that has been on the books since colonial times, prohibiting "the erection of any flagpole, standard, mast or similar structure, which exceeds the height of the Giant Sycamore gracing the town square." Said sycamore was struck by lightning in the Great Storm of '08, with only a gnarled stump remaining. Hence, all antennas but TV rabbit ears are prohibited.

Recognizing the many public service benefits of ham radio, this astute leader promptly and permanently rescinds all antenna ordinances. Obviously, Hictown soon becomes a mecca for our brethren, who immigrate in significant numbers, erect impressive towers, swell the population to 138,214 and change the name of their town to Antlerville.

What, you may ask, was the population gain in dB in the above example? Ten times the common log of the ratio (population now over population then) equals 35.7 dB, but is this a valid application of the dB? It is if you, as I, were a college student during the turbulent '60s, when the watchword was "Power to the People!"

Case 5: Literature

This last example will constitute your homework assignment; please complete the analysis and turn it in at the beginning of the next class period. You are asked to assess the extent to which this article has expanded the available literature in the area of dB analysis. Count the number of words in both parts of this article, as well as those in Gruchalla's paper (Ref 9). The number of dB by which this paper increases human knowledge can be estimated as 10 times the common log of the quantity (words here) divided by the sum (words here plus words elsewhere).

Why is dB notation appropriate here? It was Thomas Hobbes who wrote, "Knowledge is Power." Furthermore I remind you, as is mentioned every month in *Reader's Digest,* "It Pays to Enrich Your Word Power."

Notes and References

[6]The sun's radiation pattern comes close, but remember that the sun is not perfectly spherical. Because of its rotation on its axis, the sun is oblate, like the earth (that is, fatter around the equator than at the poles). Since the sun's radiation pattern is closely correlated to its shape, the sun cannot be a perfect isotropic radiator. Neither is any physically realizable antenna.

[7]For meaningful measurements to result, the antenna under test must be evaluated at *far-field*—that is, at a measurement distance which is very great, relative to both wavelength and antenna aperture.

[8]J. R. Fisk, "Receiver Sensitivity, Noise Figure and Dynamic Range—What the Numbers Mean," *Ham Radio*, Oct 1975, p 8. This article, penned 10 years ago by the late W1HR, represents *the* definitive work on the subject of receiver performance. I consider it to be one of those landmark papers that should be reviewed (and hopefully reprinted) periodically.

[9]M. Gruchalla, "Defining the Decibel," *Ham Radio*, Feb 1985, p 51.

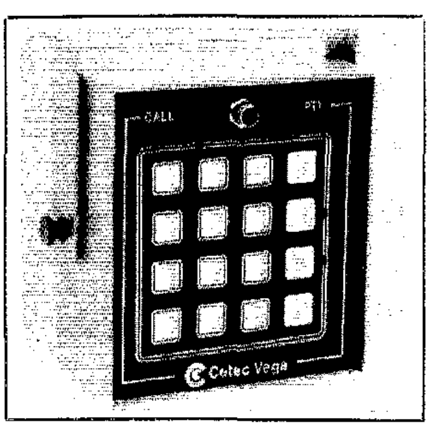
New Products

CETEC VEGA MODEL ED-707 MOBILE DTMF ENCODER/DECODER

□ Cetec Vega's new Model ED-707 dual-tone, multifrequency (DTMF) mobile encoder/decoder is designed for tough service. It has a comprehensive set of operational features, including: (1) selective, group, and all call (2- to 6-digit messages); (2) single-tone transpond; (3) full DIP-switch programmability; (4) command reset; (5) audible encode sidetone; (6) fully sealed keypad with 12 DTMF digits as well as horn, speaker, and "T" switch; and (7) wrong-digit reset or wrong-digit lockout (jumper selectable).

Construction features include: (1) rugged aircraft-alloy case; (2) fully sealed DTMF/control switch keypad; (3) watertight Neoprene™ panel gasket; and (4) stainless-steel fasteners.

The unit provides a resistive load for the radio's single-ended audio output or bridge-output power amplifiers when the speaker is switched off through the ED-707, as well as adjustable timers for sounder/horn, tone-burst transpond, off delay, PTT delay and interdigit time. For additional information contact Cetec Vega, 9900 Baldwin Pl, El Monte, CA 91731, tel 818-442-0782. —*Bruce O. Williams, WA6IVC*



Next Month in *QST*

Several construction and tutorial articles await you in April *QST*. Among them is an article on SuperSCAF and Son—a team of switched-capacitor audio filters that can't be beat, and Part 1 of a four-part series on OSCAR operation. The first installment introduces you to some basic satellite terminology and concepts. And no April issue would be complete without a variety of antenna projects. Having trouble meeting the code requirements for that Extra Class ticket? Check out the article on one ham's system for cracking the 20-WPM barrier. Also, if contests are your thing, you won't want to miss the results from the 160-Meter and EME contests and Straight Key Night, and the rules for the Great Armadillo Run.