Gaining on the Decibel

Part 3: Antennas—Bigger *is* better! Taller, wider and deeper, that's about the size of it.[†]

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Previous chapters of this opus have not only succeeded in keeping your humble servant occupied for the better part of a bel, but have generated significant spurious comment within the amateur community. Public response to these articles has indeed been underwhelming, and I am amplified to find myself firmly established as the belwether of a powerful group of gainsayers. However, in reviewing your homework papers from last class session (see Part 2, Case 5), I find myself still about 1 dB shy of achieving my goal of total double-talk. Hence, I am compelled to chime in with this third and final installment.

All seriousness aside, this concluding part of the series explores the numeric gain limitations of practical antennas, documents noise-parameter conversions and presents an actual system-analysis example for your consideration.

One need merely attend the antenna-measuring competition at one of the various regional VHF/UHF conferences to realize how little agreement exists between our fellow experimenters as to what physical antenna attributes produce high gain. The variety of antenna designs on display is staggering, but the successful antennas all have one feature very much in common: They are *large*!

Especially with respect to parasitic arrays (such as the Yagi) and driven arrays (like the log-periodic or collinear antennas), the common wisdom seems to suggest that more elements will produce more gain. In fact, the antenna designs presented in the pages of *QST* do little to dispel this myth. However, consider that the parabolic reflector antenna, which was first developed by Heinrich Rudolph Hertz[10] some 97 years ago, really has only two elements—one driven (the feed), the other parasitic (the reflector or mirror). Or consider waveguide horn antennas. Two physicists at Bell Labs in Holmdel, New Jersey, used one to detect the background radiation left over from the Big Bang some 18 billion years ago. Their horn, with but a single element, had enough gain to "hear" all the way to the edge of the universe, earning Arno Penzias and Robert Wilson (*real* DXers!) a Nobel prize.

A well-known VHFer brought to a recent antenna competition a monstrosity of a 1296-MHz Yagi, 80 elements on a 10-meter boom. The antenna proved every bit as ungainly as it looked, for every time its builder removed a director, the needle on the dB meter went up! Like a taxpayer on April 16, he had passed the point of diminishing returns. Clearly, something besides number of elements determines antenna performance.

It has been shown that for Yagi-type antennas, the primary determinant of antenna gain is boom length.[11] Certainly the number, placement and dimensions of the elements on the boom do contribute somewhat to antenna performance, but given two properly designed antennas, the one with the longer boom will produce the higher gain, even though it may sport fewer elements. What the actual number of elements seems to influence most strongly is factors such as impedance matching and bandwidth.

Yet if longer booms provide higher gain than shorter, why do deep parabolic dishes (with their corresponding short focal lengths) often outperform their shallow, high-focal-length counterparts? The fact is, the primary determinant of antenna gain is not necessarily a physical dimension, but rather an electrical one: effective aperture, often called capture area.

The effective aperture of an antenna determines how much of an electromagnetic wave it will capture in receiving service, or the degree to which it will focus electromagnetic waves in a desired direction in transmitting service. Consequently, effective aperture is closely correlated to antenna gain. It is important here to note that the effective aperture of an antenna is related to both its physical frontal area and its length (or depth). Additionally, antenna gain is influenced by such factors as radiation resistance, impedance matching, efficiency, and the surface conductivity of the driven and parasitic elements. However, with all these factors properly considered, the generalization still holds: Big antennas have the highest gain.

Gain of Parabolic Reflectors

Of the various antennas which the microwave experimenter is likely to encounter, one for which the effective aperture closely correlates to its physical frontal area is Hertz's well-known parabolic reflector, or dish antenna. Thus its gain can be estimated with fairly high accuracy, from its physical dimensions alone.

For a perfect (lossless) parabolic reflector illuminated by an electromagnetic wave of wavelength λ at far-field,[12] the EMF incident upon the reflector's surface varies directly with the diameter D of the reflector, and inversely with λ. The equality is:

$$Av = \frac{\pi D}{\lambda} \qquad \text{(Eq 1)}$$

where Av represents voltage ratio (or gain) relative to an isotropic radiator, and diameter and wavelength are both measured in the same units.

Since we are measuring across a constant impedance (that of free space), the power incident upon the surface of the parabolic reflector varies with the square of the incident EMF. The power ratio is:

$$Ap = \left[\frac{\pi D}{\lambda}\right]^2 \qquad \text{(Eq 2)}$$

To collect this power we place some sort of feed antenna at the focal point of the curved reflector, and the feed illumination in the real world is going to be less than 100% efficient. Power gain for the fed reflector thus becomes:

$$Ap = \eta \left[\frac{\pi D}{\lambda}\right]^2 \qquad \text{(Eq 3)}$$

where η (the Greek letter eta) represents the illumination efficiency factor, a number between 0 and 1. Typical illumination efficiency for commercial parabolic reflector antennas is on the order of 55%, or $\eta = 0.55$.

The last step is to convert to dB, by taking 10 times the common logarithm of power ratio. Parabolic antenna

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[†] Parts 1 and 2 of this article appeared in QST for February and March 1986. This is the concluding part.

[10] Notes and references appear on page 31.

performance is thus:

$$\text{dB} = 10 \log_{10} \left[\frac{\eta \pi^2 D^2}{\lambda^2} \right] \qquad \text{(Eq 4)}$$

which, with the exception of efficiency factor (which we can approximate), predicts gain purely as a factor of physical reflector diameter.

Converting Noise Units

Frequently we have a need to convert between the various noise units introduced in Part 2 of this series. Although computer programs are readily available to perform the conversions between noise figure, noise factor and noise temperature, the algebra required is relatively trivial and lends itself well to solution with a handheld calculator.

If noise factor F (as a power ratio) is known, convert to noise figure NF (in dB) and equivalent noise temperature T_{eq} (in kelvins) as follows:

$$\text{NF (dB)} = 10 \log_{10} F \qquad \text{(Eq 5)}$$

$$T_{eq}\ (\text{K}) = 290(F - 1) \qquad \text{(Eq 6)}$$

If you know the noise figure NF (in dB), calculate noise factor F as follows:

$$F = 10^{\frac{NF}{10}} \qquad \text{(Eq 7)}$$

and determine equivalent noise temperature T_{eq} from Eq 6.

Given the equivalent noise temperature T_{eq} (in kelvins, or degrees on the absolute scale), the conversion to noise factor F is:

$$F = \frac{T_{eq}}{290} + 1 \qquad \text{(Eq 8)}$$

and noise figure NF is found from Eq 5.

It should be pointed out that in all of these conversions, it is assumed that the receiving equipment in question is operating at the standard earth temperature of 290 K. This may not be the case, especially for receivers operating aboard orbiting satellites or other spacecraft. There the operating temperature may be considerably lower, reducing the thermal noise with which the signal must compete. When the actual operating temperature (in kelvins) is known, it should be substituted for the numeric constant 290 in the foregoing conversion equations.

Signal-To-Noise Ratio

Through link analysis, we have seen that the signal amplitude available to the receiver, and the thermal noise power with which it must compete, can be readily determined. The difference between these two quantities, in dB, is variously referred to as RF signal-to-noise ratio (RF SNR) or carrier-to-noise ratio (CNR). Obviously, the decibel value can be either positive or negative, depending upon whether the received signal is above or below the noise level. And remember that we have thus far been considering only the effects of thermal noise at the receiver input circuitry. Any ham who has ever operated in a noisy mobile environment, or in the presence of strong local QRM, is well aware that other external factors can easily impair copiability.

Neglecting the external factors, do these numbers accurately predict the actual signal-to-noise ratio (and corresponding copiability) of the demodulated signal that forms sounds in the headphones or pictures on the CRT? Not exactly! It is well known that, for a given CNR, the readability of AM, FM and SSB signals may differ widely.

One factor influencing recovered (or demodulated) signal-to-noise ratio (SNR) is the bandwidth of the emission. Bandwidth effects, however, can be confusing. For example, the noise improvement which frequency modulation boasts over equivalent amplitude-modulation modes is no illusion—you can observe it any day on the local VHF repeater—and is attributed to the wider bandwidth employed. That is, for signals above the detector threshold, an FM signal that is 12 kHz wide will provide twice the demodulated SNR as an equivalent AM signal of half the bandwidth. That's a 3-dB improvement for using twice the spectrum. But on the other hand, a single-sideband AM signal with suppressed carrier, which uses only 3 kHz of spectrum, will *also* provide a 3-dB improvement in audio SNR as compared to double-sideband AM. And that's a 3-dB improvement for using *half* the spectrum. Confused? Me too!

The full explanation of this paradox is, as we say in the university environment, beyond the scope of this course. But it relates to the distribution of energy in the modulation sidebands, those portions of the signal that actually carry the intelligence. To further complicate matters, various signal-conditioning techniques exist to boost the recovered SNR for a given CNR, for any type of modulation. Examples range from the simple compression of audio employed in speech processors commonly used in HF SSB transceivers[13] to frequency-tailoring circuits (preemphasis and deemphasis) commonly used with FM, to digital signal enhancement and amplitude compandoring techniques currently being explored by a number of experimenters.

The bottom line is that, although an improvement in CNR will result in improved demodulated SNR, the precise relationship between the two depends on the modulation mode, bandwidth and signal-conditioning techniques employed. For a given modulation and demodulation scheme, on-the-air experience will indicate the input CNR required to produce intelligible signals.

System Analysis Example

As this installment is being written, a small group of dedicated microwave amateurs in Colorado is hard at work developing the circuitry to provide an upcoming OSCAR satellite with an S-band downlink. Their projected link analysis is indicative of the very calculations we have been discussing in the preceding sections.[14]

The proposed downlink will operate at a frequency of 2401.33 MHz. You may recall that the operating wavelength, in centimeters, is found by dividing the numeric constant 30 (derived from the speed of light) by the frequency in GHz. Thus, an operating wavelength of 12.49 cm will apply. This information is needed to calculate both free-space path loss and antenna gain.

Unlike the linear translators employed in earlier OSCARs, it is expected that the S-band transponder will operate as a "soft-limiting" FM repeater. Given adequate uplink power, the 2.4-GHz transmitter output power will be relatively constant, at a planned 2 W. Converting to dBm, we have:

$$P_{out} = 10 \log_{10} (2000 \text{ mW}) = +33 \text{ dBm}$$

Plans call for a virtually lossless transmission line connecting the transmitter output to an 8-turn helix antenna, which will radiate a circularly polarized signal while providing an estimated gain of 14 dBi. We can now calculate expected *E*ffective *I*sotropic *R*adiated *P*ower:

$$\begin{aligned} \text{EIRP} &= P_{out}\ (\text{dBm}) + \text{Ant Gain (dBi)} \\ &= (+33 \text{ dBm}) + (+14 \text{ dBi}) \\ &= +47 \text{ dBm.} \end{aligned}$$

Next we must determine the path attenuation which the downlink signal will experience when propagated between the spacecraft and an earth-bound user. We are interested in free-space propagation (that is, operation when the satellite is above the user's horizon), and we find by analyzing the mechanics of the planned orbit[15] that the maximum communications range (satellite at apogee, user at the edge of the circle of illumination) is on the order of 40,000 km. We now apply the free-space path loss equation discussed in Part 2 of this series:

$$\begin{aligned} \alpha &= 10 \log_{10} \left(\frac{4\pi D}{\lambda} \right)^2 \\ &= 10 \log_{10} \left(\frac{4\pi \times 40{,}000 \text{ km}}{12.49 \text{ cm}} \right)^2 \\ &= 10 \log_{10} \left[\frac{4\pi \times (40{,}000 \times 1000) \text{ m}}{0.1249 \text{ m}} \right]^2 \\ &= 192 \text{ dB} \end{aligned}$$

so the power reaching an isotropic antenna on the earth, when it is directly in the beam of the spacecraft transmitting antenna, will be:

$$\begin{aligned} \text{Received power} &= \text{EIRP} - \text{Path Loss} \\ &= +47 \text{ dBm} - 192 \text{ dB} \\ &= -145 \text{ dBm.} \end{aligned}$$

This is a pretty weak signal (on the order of a millionth of a billionth of a milliwatt), so if we hope to receive it, we're going to need a combination of high receiving-antenna gain and low receiver noise. A little luck wouldn't hurt, either.

We can improve the odds quite a bit by employing a parabolic receiving antenna of moderate diameter. If you recall our discussion about factors affecting parabolic antenna gain, you may wonder why I say "moderate," rather than "huge." The answer involves two considerations. First, for a satellite with an orbit not synchronized to the earth's rotation (that is, not "geostationary"), it will be necessary to rotate the antenna in at least two planes to track the satellite as it moves across the sky. The larger the physical antenna size, the greater the mechanical challenge this task presents. Less obvious, but an equally critical factor, is that the beamwidth of an antenna diminishes as its gain increases, making accurate aiming of the antenna all the more difficult. As a first-order approximation,

$$\phi = \frac{\lambda}{D} \qquad \text{(Eq 9)}$$

where ϕ represents the 3-dB beamwidth in radians (not degrees),[16] and wavelength and diameter, as usual, must be expressed in like units.

Let's consider the beamwidth of a parabolic antenna that is 1 meter in diameter, at our intended operating wavelength. From this relationship, beamwidth is found to equal 0.1249 radians, or about 7 degrees. Since a much narrower beamwidth will likely make aiming too critical for the average user, this is the antenna size we will assume.

From Eq 4, we can now calculate the gain of our receiving antenna. Assuming an illumination efficiency of 50% (and this can be readily obtained with a cylindrical-waveguide feed horn fashioned from a 1-pound coffee can), the antenna gain is found to be +25 dBi. The power available to our receiver is thus equal to the sum of incident power plus antenna gain, or −120 dBm. We're now up to a millionth of a millionth of a milliwatt. Unlikely as it may seem, such signal levels are within the sensitivity limits of high-performance receivers.

The current state of the art in S-band GaAs field-effect transistors suggests that a 75 K receiver noise temperature is not unfeasible. Since the proposed transponder will employ narrow-band frequency modulation, a practical receiver bandwidth on the order of 20 kHz is indicated. The resulting thermal noise power, which the desired signal must override at the input of the receiver, is found thus:

$$\begin{aligned} P_n &= kTB \\ &= (1.38 \times 10^{-23})\,(290\text{ K} + 75\text{ K}) \times (20 \times 10^{3}\text{ Hz}) \\ &= 1.0 \times 10^{-16}\text{ watts} \\ &= 1.0 \times 10^{-13}\text{ milliwatts} \\ &= -130\text{ dBm} \end{aligned}$$

Finally, comparing the signal incident to the receiver (−120 dBm) to the receiver's input noise (−130 dBm), we find that the receiver input signal-to-noise ratio is their algebraic difference, or +10 dB. Does this represent enough signal to make bels flash and lights ring? A 10-dB CNR is well above the threshold level for "QSO quality" copy of modern FM detector circuits, and in fact, with proper signal conditioning (preemphasis and deemphasis), can result in an audio signal-to-noise ratio approaching 30 dB. That is, the audio signal power available from the speaker or headphones will exceed the accompanying audio noise power by a factor of a thousand. Clearly, the system performance criteria outlined here will result in usable signals.

Such computations as this example illustrates, although cumbersome, can be utilized to quantify the performance of any electronic communications path. With the proliferation of personal computers in the ham shack, along with the availability of suitable software, system analysis may in time become a routine part of Amateur Radio.

I hope you've found this series of articles destructional, and not overly punderous. If you have mastered the concepts I have presented, you are now in a position to gain considerable notoriety at local ham club meetings. In fact, you should be the bel of the ball!

Notes

[10] Hertz was probably the world's first DXer. He wrote, "As soon as I had succeeded in proving that the action of an electric oscillation spreads out as a wave in space, I planned experiments with the object of concentrating this action and making it perceptible at greater distances by putting the primary conductor (ie, dipole) in the focal line of a large concave parabolic mirror."

[11] Gunter Hoch, DL6WU, "Extremely Long Yagi Antennas," *VHF Communications*, March 1982, p 130.

[12] Far-field considerations were touched upon in Part 2 of this series. For meaningful measurements, the minimum distance between transmitting and receiving antennas is determined by $D >> A / \lambda$, where A represents the effective aperture of the antenna under test, and λ is the operating wavelength (all dimensions in like units).

[13] One well-known contest operator defines the RF speech processor as "a device cleverly designed to disguise your voice so that your own mother won't recognize it."

[14] The specifications used in this example were provided by William D. McCaa, Jr, K0RZ, AMSAT's Coordinator of S-Band Transponder Development.

[15] See Martin R. Davidoff, *The Satellite Experimenter's Handbook* (Newington: ARRL, 1985, Chap 8).

[16] To convert radians to degrees, multiply by 180 and divide by π.

Tribander

(continued from page 28)

but stainless steel. You usually discover that at some inconvenient time! One item I am wary of purchasing is compression (hose) clamps. These clamps are ideal for securing telescoping pieces of antenna tubing, but some compression clamps have screws that are not stainless steel; only the circular band is of stainless steel. I will not purchase any compression clamps unless they are stamped "all stainless steel" on the screw housing.

It's a good idea to clean all metal joints and give them a coating of No-Alox®, Oxiban® or a similar compound before reassembly.[1] This will ensure good metal-to-metal contact at these points.

No Bugs Allowed

How do you keep invaders from entering your newly cleaned traps? Good question. I know of no guaranteed way to do that, but perhaps some aluminum screening taped over the trap drain holes would discourage them. Not having any screening on hand, I decided to try a different approach. I first applied some aluminum duct tape to the supporting mast and at a couple of places on the antenna boom. Over this tape I applied a material known as Tree Tanglefoot; it's a sticky substance used to keep insects from making successful journeys up and down tree trunks and plant stems. (Tanglefoot is available at most garden-material suppliers.) Of course, this measure may not be entirely successful with airborne invaders. The tape was first applied to aid in removal of the Tanglefoot by simply peeling off the tape and Tanglefoot together, should I need to handle the antenna again.

In an effort to reduce the drain-hole size, I covered each hole with electrical tape and scored it with an "X" to allow water to drain. Only time will tell how successful these measures are.[2]

Summary

Armed with this information, you should be better able to handle any difficulties you may have with your trapped Yagi antenna. A bit of time and a few parts may be all you need to get it back into shape again. Oh . . . what happened to the desperado who "killed" my antenna? He was observed hastily leaving the scene of the crime during the opening of one of the traps. I, the jury, found him guilty.

Notes

[1] Available from electrical supply houses.

[2] During a later conversation I had with Bob Schetgen, KU7G, ARRL's *TIS specialist, he* suggested surrounding each trap drain hole with a circle of RTV® sealant. The sealant would be used to secure some fiberglass screening over the holes.