Far-Field Fallacy

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If you've ever attended a regional VHF or UHF conference that featured antenna-gain measurements, you've no doubt heard the arguments. "The range was too short," a disgruntled contestant laments. "My antenna didn't give a good account for itself because it was in the near field. I *know* it has more gain that that!" And as much as it sounds like sour grapes, he may have a point. Put simply, the performance of DX antennas needs to be measured under DX conditions. But why, exactly, is there a near-field restriction? And how can we know how far afield is far enough? Immediately following the 1987 West Coast VHF/UHF Conference (where my antenna didn't do as well as I *know* it should have), I set out on a quest of discovery. Here is what I found.

The Traditional Explanation

Short electromagnetic waves travel through free space in straight lines, and antennas know this (even if antenna designers don't). Try as we might, we can't really direct electromagnetic radiation in a pencil-thin beam: The wavefront ahead of a radiating antenna spreads out with distance. Visualize the expanding radiation pattern, as shown in Fig 1, and you will see why antennas have a definable beamwidth.

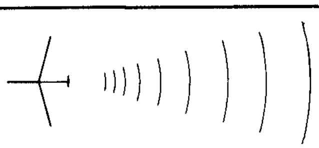

Fig 1—Visualizing the beamwidth for a radiating antenna.

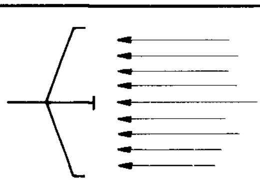

Fig 2—Planar wavefront arriving at a receiving antenna.

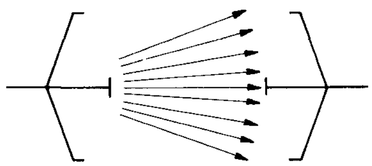

Fig 3—The near-field problem occurs because a nonplanar wave front appears at the receiving antenna.

To intercept the greatest amount of incoming energy, we design our receiving antennas to capture as much of the spreading beam as possible. This is normally accomplished by making antennas physically large, although a number of techniques exist for increasing the capture area of an antenna (that is, making it electrically large, even though it is physically small). We increase antenna gain by intercepting as many of the rays of radiated energy as possible—see Fig 2.

The problem is this: To function efficiently, the receiving antenna needs to intercept a planar wavefront. That is, the individual rays need to be arriving in parallel. If the distance between the transmitting and receiving antennas is great, this is very nearly the case. If the physical size (or capture area) of the receiving antenna is great relative to its distance from the energy source, however, a problem occurs. As Fig 3 shows, the received energy arrives as nonparallel rays that basically reach the receiving antenna out of phase with each other, and partially cancel. Hence the gain of antennas measured in the "near field" (where the received energy is not a planar wavefront) will be in error.

The Analytical Approach

The engineering textbooks describe the field in front of a radiating antenna as being divided into three distinct regions: a Fresnel zone, or near field; a Fraunhofer zone, or far field; and a transition zone. The significance of these three regions to antenna measurements is as follows: The power collected by a receiving antenna within the transmitting antenna's near field is very nearly constant, varying perhaps ±2 dB about a mean value with changes in distance. When antenna spacing is increased to far-field distances, recovered power will vary inversely with the square of distance. Within the transition zone, neither constant power nor the inverse square law holds.

The near-field region produces maximum power density at a fixed distance, which can be readily predicted:

$$d = \frac{0.2\ D^2}{\lambda} \qquad \text{(Eq 1)}$$

where

- d = the distance from the radiating antenna at which maximum power density occurs
- D = the diameter of the antenna (assuming a parabolic reflector)
- λ = the operating wavelength

All three dimensions are expressed in like units. For a parabolic reflector antenna, the near field extends outward for a distance approximately equal to

$$d = \frac{\pi\ D^2}{8\lambda} \qquad \text{(Eq 2)}$$

where d now represents the near-field boundary, and the other literals are as defined above.

The distance d to the beginning of the far-field region is approximated by:

$$d = \frac{2\ D^2}{\lambda} \qquad \text{(Eq 3)}$$

with d now representing the far-field boundary, and all other factors are as defined above. Note that the far-field boundary is a factor of ($16/\pi$), or 5, times as far from the antenna as the near-field boundary. The region between near and far fields is considered the transition zone.

For antenna gain measurements, it is desirable for the receiving antenna to be in the far field of the transmitting antenna, and vice versa. Eq 3 thus becomes the most significant of the above relationships for our purposes. Note that the far-field boundary varies directly with the *square* of antenna diameter, and inversely with wavelength. Thus for physically large antennas operated at high frequencies (a

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situation frequently encountered by microwave hams), the required path distance for antenna measurements can become quite great.

A Philosophical Objection

The problem with the above equations is that they tend to obscure the physical mechanism that we are trying to study. Being able to predict mathematically the distances defining the near-field and far-field boundaries is a far cry from visualizing exactly *why* these distances make a difference in antenna measurements. If we desire to emphasize concepts rather than computations, we're going to have to come up with an explanation, perhaps invoking mechanical analogies, of exactly *why* all this matters.

That's where I got stumped. The equations were just too complex, and the fudge-factors too arbitrary, to point to an obvious relationship. Furthermore, no amount of research led me to an explanation of what physical constraints led to the boundaries being exactly where the equations say they are. I found in the literature an extensive body of knowledge on near- and far-field considerations, but no one bothered to go beyond the math. The numbers were considered sufficient unto themselves.

Well, not for me. Being perhaps more philosophical than technological, I consider the universe to be an orderly place, with all physical laws ultimately knowable and inherently simple. If it takes a complex set of equations to describe a phenomenon, I contend, it's only because we don't yet fully comprehend it. Once a relationship is fully understood, it becomes intuitively obvious, no longer requiring justifying mathematics. This is the level of understanding that we generally describe as inspiration, that gives rise to sudden exclamations of "Aha!" Unfortunately, as I contemplated antenna measurements near and far, no such inspiration presented itself.

Let Logic Prevail!

The only thing more mysterious than the workings of antennas is the workings of the human mind. I had pretty much put the whole dilemma out of my consciousness for about two weeks, when inspiration hit me over the head like a falling section of Rohn 25. Early one morning from a sound sleep, I literally awoke with a start, and said out loud "Aha! So *that's* why!" My wife Suk, WA6PLF, who after nearly twenty years is accustomed to such outbursts, got up to make coffee. I sat down at the word processor and attempted to document what was suddenly, inexplicably, intuitively obvious. I wondered, as I so often have, "Why didn't I see it before?" Here is the thought process that led to that revelation:

Consider two ideal, lossless, perfectly matched isotropic antennas, one radiating, the other receiving. Let's separate these from each other in free space by a distance of, say, 25 wavelengths at the operating frequency. (I chose 25 wavelengths because this distance corresponds to exactly 50 dB of isotropic free-space path loss.) If we apply exactly 1 W of RF to the transmitting antenna, the power recovered by the receiving antenna will be just 50 dB less, or 10 μW. This makes a calibrated path for antenna gain measurement.

Now replace the isotropic antennas with two identical gain antennas, one at each end of the path. Assume that the power collected by the receiving antenna is accurately measured at 10 mW. This is exactly 30 dB more than the signal power received when both antennas were isotropic, which leads us to the conclusion that, between them, the antennas had 30 dB of gain. Since the two antennas are identical, each has a gain of +15 dBi.

So far we have simply described a standard measurement of antenna gain employing the power ratio method. The technique is an accepted method of calibrating standard-gain horns. It doesn't require that we actually perform a measurement between isotropic antennas (which we can't really build, buy, or find in nature anyway), because isotropic free-space path loss is readily calculable.

We can continue the above process by replacing the two 15-dB-gain test antennas with two more antennas, still identical, each producing a gain of, say, +20 dBi. The total antenna gain is now +40 dB, and the path loss is unchanged, at 50 dB. Our received signal power can thus be expected to be a total of 10 dB weaker than that transmitted, or 100 mW. Power ratio measurements should still be valid.

Now comes the interesting part. Let's increase the size (and hence gain) of our two identical antennas once more, to an assumed gain of +30 dBi each. Total path loss is still 50 dB. Total antenna gain is +60 dBi. Therefore, the power received is going to equal 10 dB more than the power transmitted, or 10 W. Right?

"Wait a minute," you say. "That's impossible!"

Aha!

Clearly, the received power cannot exceed that transmitted; that would violate the principle of conservation of energy. This means that, as we continue to increase antenna gain, we reach a point where the received power can't continue to increase. For the wavelength at which we're operating, at the distance we've selected, with the antennas we're trying to measure, we have just entered the twilight zone—er—near field.

This happened just where the combined gain of the two antennas *exactly* equaled the free-space isotropic path loss between them. Of course, the same analysis could have been made by holding the size (hence gain) of the two antennas constant and decreasing distance (hence free-space path loss) between them. We would still have reached a point where recovered power could no longer increase. Is the mechanism becoming clear?

Good engineering practice suggests that, whether we're increasing antenna gain or decreasing distance, we should stop several decibels *before* we run out of available received power—which suggests to us roughly where the far field should start. All of this leads to the following conclusion: "To accurately measure antenna gain, the distance between transmitting and receiving antennas must be sufficient to produce a free-space isotropic path loss that *significantly exceeds* the total gain of the receiving and transmitting antennas."

Okay, how much additional path loss is "significant"? By comparing Eqs 2 and 3, we determined that the far field starts five times as far from the antenna as the near field ends. The difference in free-space isotropic path loss for a distance factor of five is: $10 \log (5)^2 = 14$ dB. Thus, to be at the far-field boundary, we need to make the free-space isotropic path loss at least 14 dB greater than the combined gain of the two antennas involved.

This would place us right at the far-field boundary. For good measure, let's restrict ourselves to operating well within the far field, by doubling the minimum distance. Doing so adds exactly 6 dB of additional path loss (remember, twice the distance is half the recovered voltage, or a quarter of the recovered power, or 6 dB less signal). As a practical guideline, then, the path loss should be at least 20 dB greater than the combined gain of the two antennas.

As an example of how this guideline might be used to determine the required length of an antenna range, let's consider a 10 ft dish at 1296 MHz (expected gain: +30 dBi). Let the antenna at the other end of the range be a standard-gain horn (expected gain: +15 dBi). The minimum range length is that which exhibits significantly more than 45 dB of free-space path loss.

Our guidelines suggest that a −65 dB path is acceptable. This translates to a distance of 32.5 meters, or 106 feet. If the length of the range at last year's Conference was shorter than this, and your 10-ft dish didn't measure up to your expectations, you may have a valid gripe.

On the other hand, maybe for no good reason, your dish just doesn't have as much gain as the equations say it should. Antennas are like that, you know.