INTRODUCTION TO ANTENNA APERTURE

Bob Zavrel, Author of Antenna Physics: An Introduction

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ANTENNA PHYSICS, SELECTED TOPICS

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This seminar is about antenna theory. Most of the text books (and seminars) on antennas fall into one of two categories:

1. Basic introduction and “how-to” books using various antenna types as examples
2. Advanced textbooks for senior and graduate-level study (Kraus, Balanis, Stutzman, and several more classics some dating back to the 1930s).

For over 30 years the Kraus text has been my “antenna bible” and therefore my intermediate treatment of antenna theory (physics) has an is an attempt to summarize and simplify sections of the Kraus text.

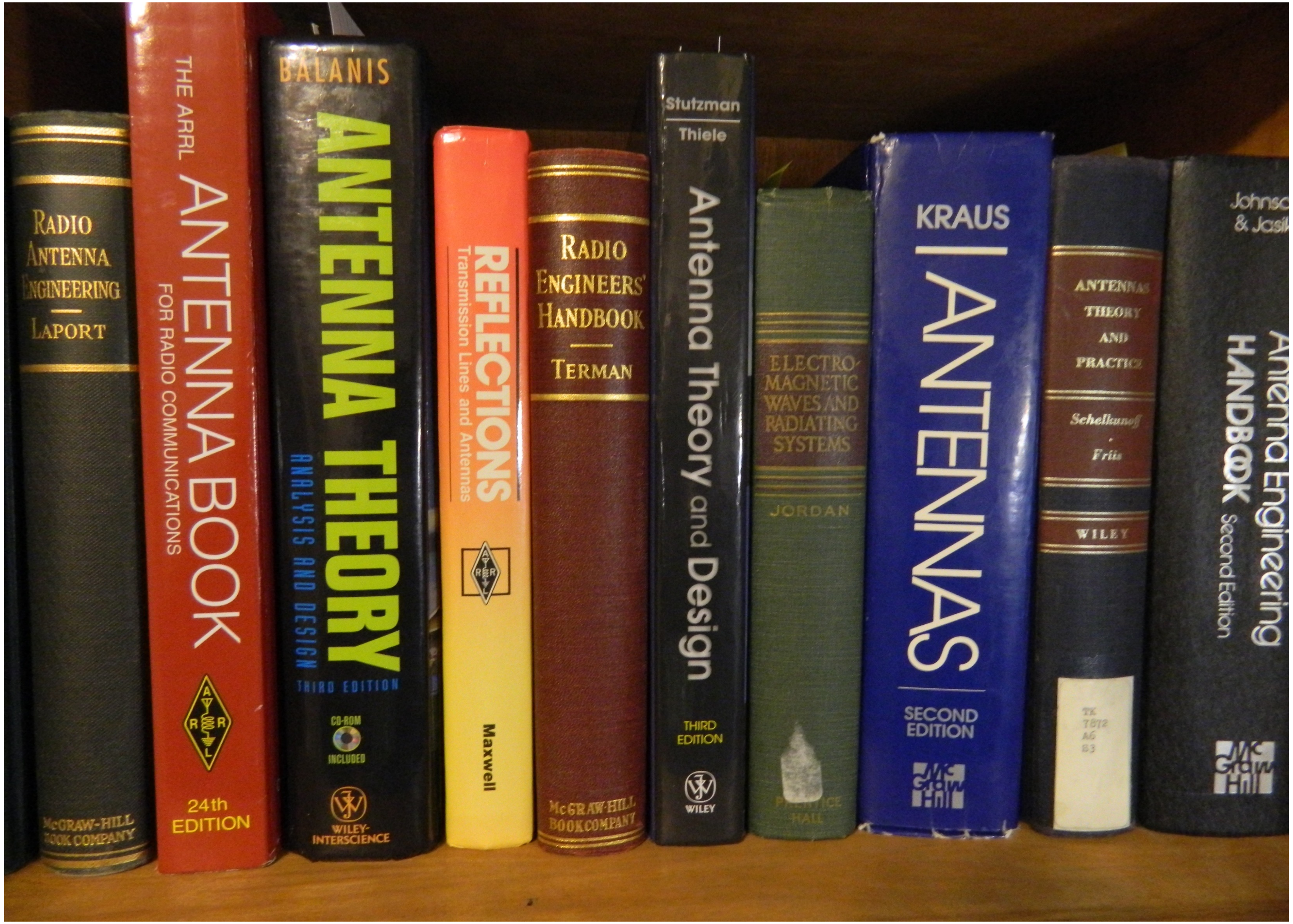
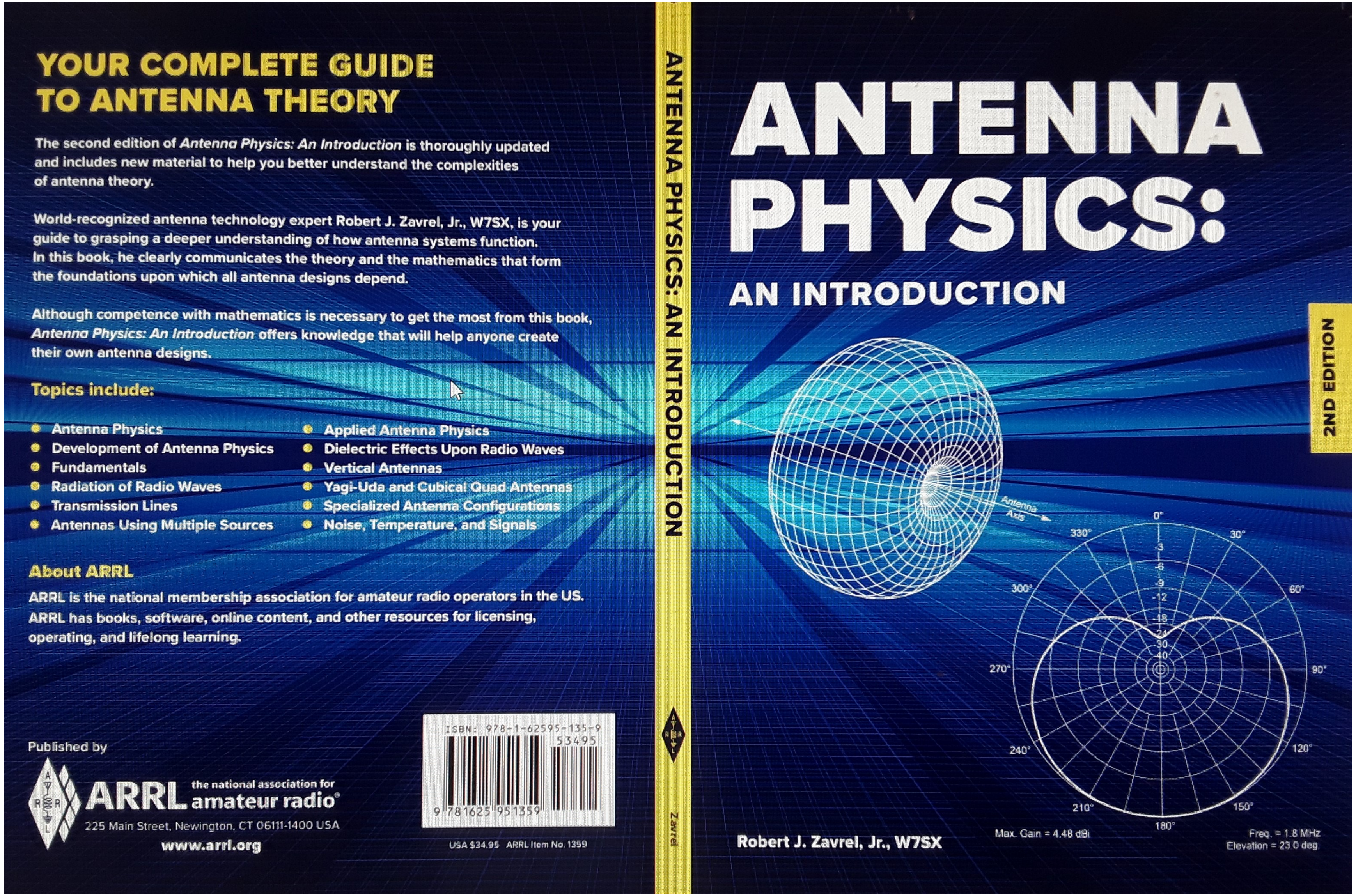


Figure 1 Here is a photo of an important section of my office bookcase.

There is very little in print for “intermediate” level treatments. After many years of studying and working on antennas I came to the conclusion that the traditional advanced academic texts could be simplified into a “transitional” text between basic introductions and the rigor of the formal academic treatments. Also, after decades explaining antennas to innumerable people, I found there were areas that were common to misunderstandings.

This was the motivation for writing “*Antenna Physics, an Introduction*”.



YOUR COMPLETE GUIDE
TO ANTENNA THEORY
The second edition of Antenna Physics: An Introduction is thoroughly updated and includes new material to help you better understand the complexities of antenna theory.
World-recognized antenna technology expert Robert J. Zavrel, Jr., W7SX, is your guide to grasping a deeper understanding of how antenna systems function. In this book, he clearly communicates the theory and the mathematics that form the foundations upon which all antenna designs depend.
Although competence with mathematics is necessary to get the most from this book, Antenna Physics: An Introduction offers knowledge that will help anyone create their own antenna designs.
Topics include:
Antenna Physics
Development of Antenna Physics
Fundamentals
Radiation of Radio Waves
Transmission Lines
Antennas Using Multiple Sources
Applied Antenna Physics
Dielectric Effects Upon Radio Waves
Vertical Antennas
Yagi-Uda and Cubical Quad Antennas
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ANTENNA PHYSICS: AN INTRODUCTION
Zavrel
ANTENNA
PHYSICS:
AN INTRODUCTION
2ND EDITION
Antenna Axis
0°
30°
60°
90°
120°
150°
180°
210°
240°
270°
300°
330°
Max. Gain = 4.48 dBi
Freq. = 1.8 MHz
Elevation = 23.0 deg
Robert J. Zavrel, Jr., W7SX

Figure 2

This text is an attempt to bridge that gap. The book (now in the 2nd edition) is being used as an adjunct text to the more traditional engineering text books at several universities as well as advanced amateurs and practicing engineers

This seminar consists of selected sections from this book. Many of the complex equations used to describe antenna theory distill down to derivations of simple concepts well understood by engineers and technicians: for examples, Ohm's Law, and the Power Law. Therefore, within our limited time we will review some very basic concepts that are often confusing and misunderstood.

Of course, there is no replacement for the more advanced texts, but there *is* a need for an intermediate treatment.

In this seminar we will review

1. Antenna Aperture
2. Relating Gain to Aperture
3. Antenna Radiation Resistance
4. Antenna Radiation Mechanics
5. Basics of RF Power Related to Antennas

Some basic knowledge of RF/antennas is assumed, such as gain, the use of decibels, general types of antennas, etc.

Antenna Aperture

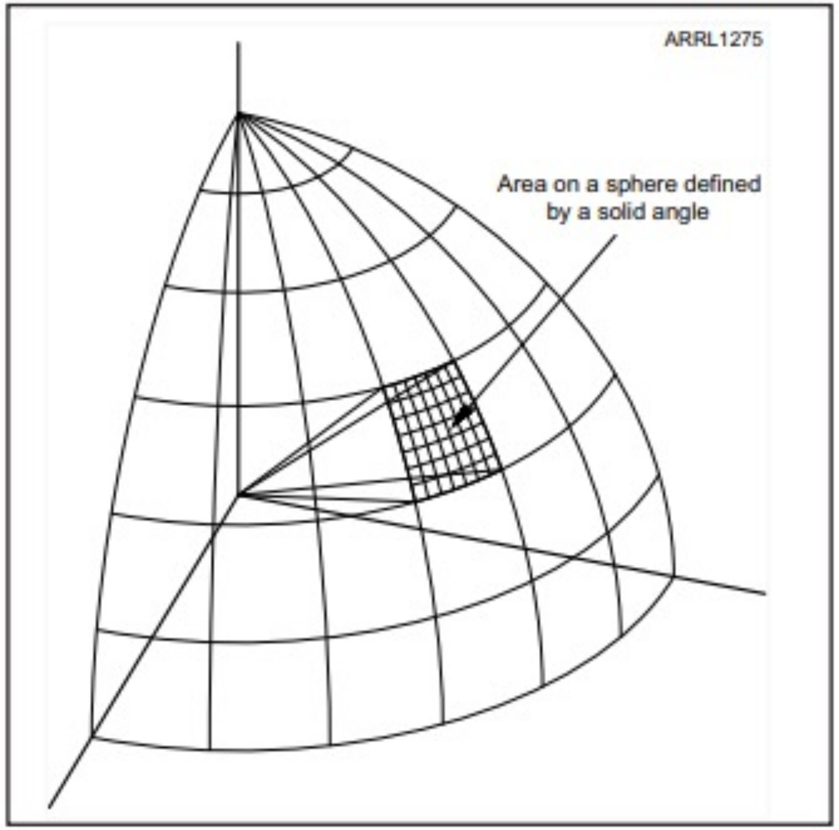

Figure 3

We begin with a 100 watt light bulb (since light is easy to "visualize") located at the center of an imaginary sphere. The light bulb is "isotropic" in that it emits light power equally in all directions (3D). Therefore, the total light power traveling through the sphere is 100 watts, evenly distributed over the sphere. The area of a sphere is $4\pi R^2$. We place a (100% efficient) solar cell on the sphere with an area *A.* If *A* is 1/100 the area of the sphere, we have recovered 1 watt

$$P_r = P_t \frac{A}{4\pi R^2} = 1\, watt$$

Aside: Since *R* is the distance to the solar cell, we can call it *D.* Separating *D* from the equation we get

$$P_r = P_t \frac{A}{4\pi} \frac{1}{D^2}$$

You may recognize $\frac{1}{D^2}$. It is the famous inverse-square law. Where the power received is inversely proportional to the distance from the source. If we place a second solar panel next to the first, we double the aperture and thus double the received power:

$$P_r = P_t \frac{2A}{4\pi R^2} = 2\, watts$$

The above discussion is valid for *all* (wavelengths) of EM waves including radio, but, why do we care?

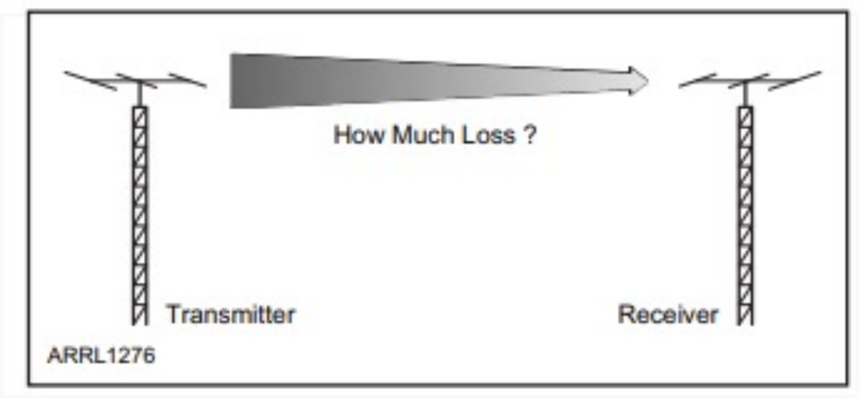

Figure 4

This simple diagram illustrates a critical question in radio engineering. The far more familiar terms of power and gain do not provide enough information to solve this simple yet very important problem.

- *Aperture must be used* to calculate the power loss and thus define the "link budget" of this configuration. Here, the distance between the antennas is the equivalent to the radius of the sphere, and if we assume an isotropic transmitter and a receiver with aperture *A* we can easily calculate the received power.
- But what if the transmitter uses an antenna other than isotropic? Some other gain? And, how do we (generally) relate gain to aperture? After all, gain not aperture is most often used for a key antenna specification.

Relating Gain to Aperture

We have hinted that aperture is related to gain, and that more gain implies greater aperture, but what is the relationship? We return to the isotropic antenna for our basic reference. An isotropic antenna has been standardized to a gain of 1, or 0dBi, so this is the obvious reference also for antenna aperture. So, what is the aperture of an isotropic antenna? THIS is the key trick question. This simple term relates these two fundamental antenna specifications:

$$A_{iso} = \frac{\lambda^2}{4\pi}$$

Where λ is the wavelength of operation in m^2 (or any measurement standard you want.)

We can now determine the path loss for a free space radio link between isotropic receive and transmit antenns:

$$\frac{A}{4\pi R^2} = \frac{\frac{\lambda^2}{4\pi}}{4\pi R^2} = \left(\frac{\lambda}{4\pi R}\right)^2 \quad \text{and} \qquad P_r = P_t \left(\frac{\lambda}{4\pi R}\right)^2$$

For example, assume a 1 meter wavelength (300 MHz) and a 10 km distance over a free space path:

$$\left(\frac{\lambda}{4\pi R}\right)^2 = 63.32\ x\ 10^{-12} = -102\ dB$$

So, for 100 watts of transmitter isotripoic power (+50 dBm) we receive

$6.32 \text{ x } 10^{-9\, watts}$ or -52 dBm

The numerical gain of a $\frac{1}{2}$λ dipole is 1.64 over an isotropic antenna, so the aperture of a standard $\frac{1}{2}$λ dipole will be $\frac{1.64\lambda^2}{4\pi}$.

If we substitute dipoles at each end, we increase gain by $1.64^2 = 2.69 = 4.3\ dBi$ where the broadside gain of a $\frac{1}{2}$λ dipole is 2.15 dBi.

Thus to adjust aperture for gain difference, we simply use the proper *numerical* coefficient for $\frac{\lambda^2}{4\pi}$. As implied in this discussion, transmitter EIRP (effective radiated power referenced to an isotropic source) is simply $P_{transmitter}\ x\ G_{i(tx)\ antenna}$.

For completeness, ERP (effective radiated power is referenced to a $\frac{1}{2}$λ dipole (0dBd) is *always* 2.15 dBi less than EIRP $(0dBd = 0dBi + 2.15)$, where EIRP is referenced to the isotropic .

Gain may also be defined by a steradian measure who's area contains more than twice the average power from the source, where: $G = \frac{4\pi(sr)}{antenna(sr)}$. For non-isotropic antennas, the aperture will be different in different directions from the antenna, much like the aperture will be different in different directions from a solar cell, and the same for gain.

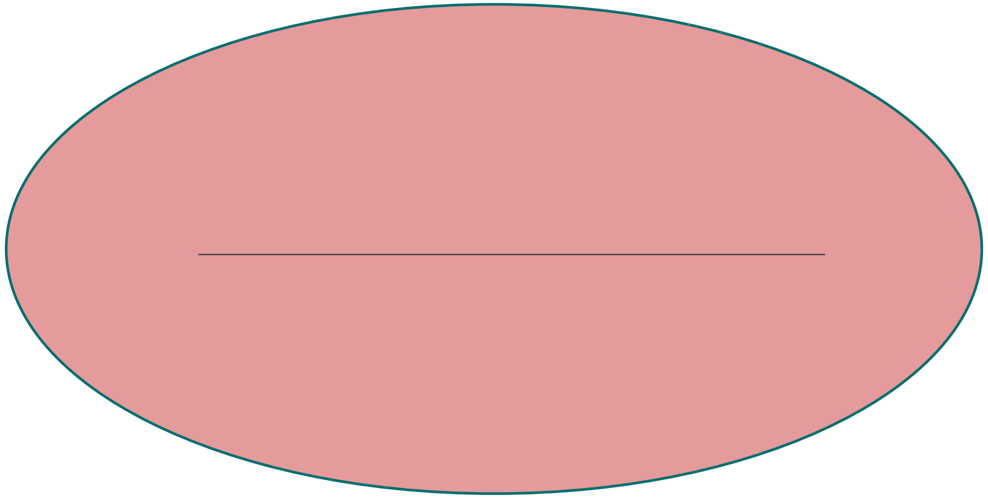

Figure 5

Here we show the approximate aperture of a ½ λ dipole antenna. The actual aperture boundary is not distinct like shown but rather “fuzzy” However, the effective aperture (the actual “collecting area”) IS well defined by $\frac{1.64\lambda^2}{4\pi}$

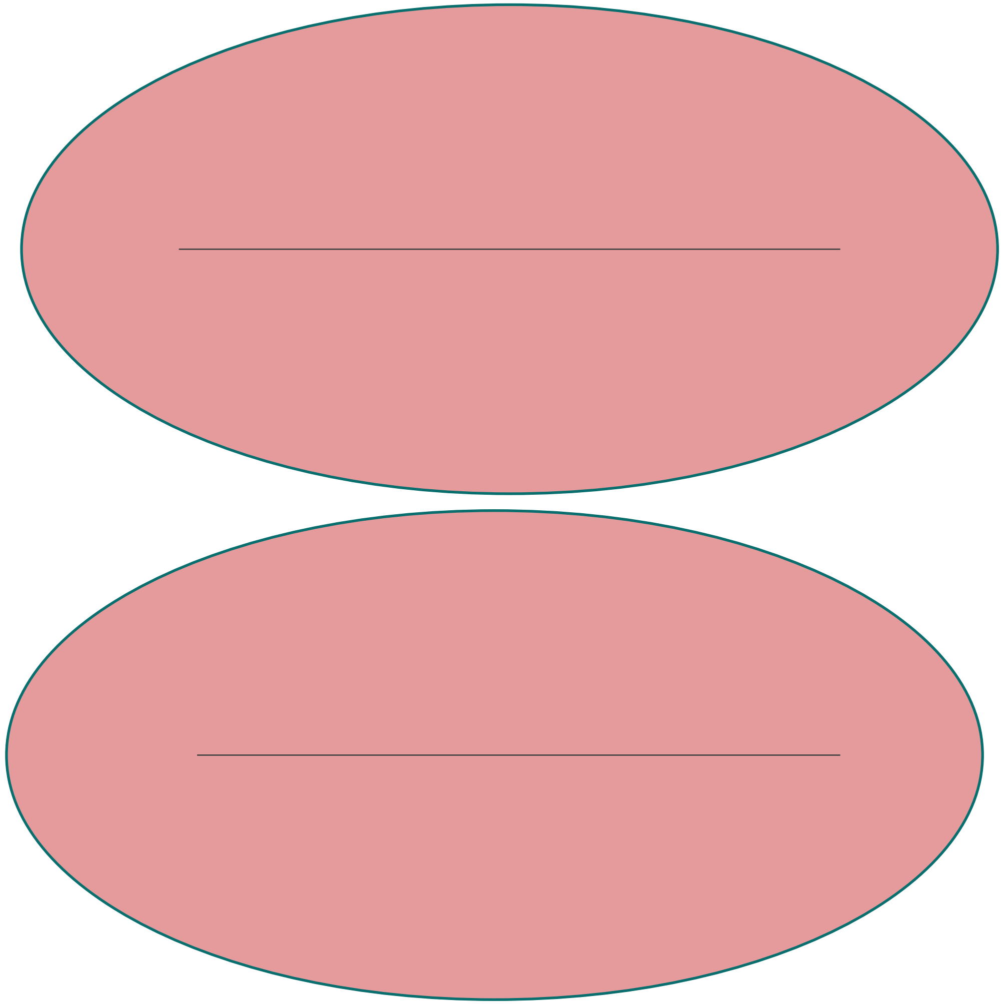

Figure 6

This leads to another key application of antenna aperture. If two or more antennas are to be “stacked” we can know how far the spacing(s) must be between the antennas. Here we see a proper spacing of two dipole antennas. The important goal is not to *duplicate* the *apertures* of the two antennas. This is analogous to “shading” one solar panel with another. For Yagi antennas, the aperture increases by adding additional elements, thus the required spacing increases.

Thus far we have only treated 100% efficient antennas. Here again, there is a simple relationship between antenna gain and aperture.

$$Gain = Directivity\ x\ efficiency\ x\ 100$$

The equivalency to aperture is:

$$A_e = A_{em}\ x\ \ efficiency\ x\ 100$$

Where A_e is effective aperture and A_{em} is the maximum effective aperture.

For example, a 100% efficient dipole will have a gain of 2.15 dBi (1.64), while a dipole with resistive loss of 50% will have a gain of -0.85 dBi (.82), but the two will have identical directivity, therefore the directivities are the same

To complete the algebra, we can derive a set of closed-form equations for antenna gain (related to aperture) and a final term:

Let us define gain as G. Again A_e is

$A_e = \frac{G\lambda^2}{4\pi}$ and thus the numerical gain is $G = \frac{4\pi A_e}{\lambda^2}$

By substituting the actual apertures for the transmit and receive antennas we now have all the terms necessary to compute the actual path loss in our original problem:

$$P_r = P_t \frac{A_{et}A_{er}}{r^2\lambda^2}$$

Thus we have derived the Friis Transmission Formula, where $A_{et}A_{er}$ is the product of the transmitter and receiver apertures.

Converting back to gain we find the closed equation which should now look familiar:

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi r}\right)^2$$

Where $G_t G_r$ is the product of the transmitter and receiver numerical gains.

These equations are applicable to applications ranging from garage door openers to Voyager-to-earth link budgets. Through algebra we can derive any term if we know the other terms: distance to a star, power of a source, brightness of a star, etc.

Figure 7

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Parabolic "dish" antennas are also called "aperture antennas" since the A_{em} is simply the cross-sectional area of the reflector. In this case the aperture is *fixed* and *independent of* λ*.* So, gain *increases* as the square of the frequency (the limit being the accuracy of the parabolic surface). This is easily defined by:

$$G = \frac{4\pi A_e}{\lambda^2}$$

The shorter the wavelength the higher the gain.

Radiation Mechanics

There are three fundamental types of electrical and magnetic fields: static, inductive and radiated. Static refers to the quite familiar types of electric static and magneto static fields. Inductive fields are the types most understood by the electric field inside a capacitor or the magnetic field around an inductor when an AC voltage is applied.

Radiated fields are *always* generated by an *accelerating* current traveling through space (usually on a conductor). A sine wave is an example of an accelerating current and most often used in radio communications. The accelerating current must have enough “space” for the resulting fields to detach themselves from the current source, otherwise they remain inductive fields.

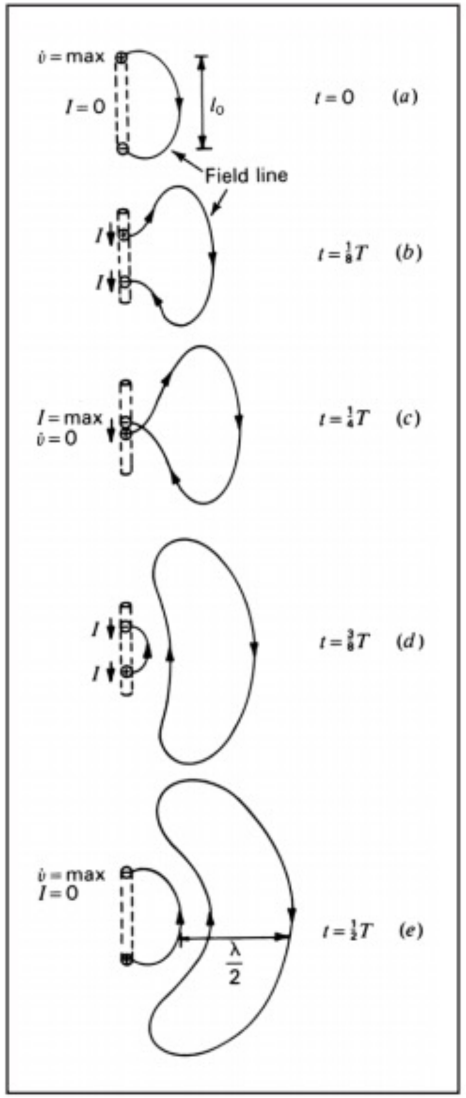

Figure 8

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On a dipole antenna the oscillating charges (+ and -) move from one end of the dipole to the other at the RF frequency in opposite directions. This creates a strong oscillating electric field with its E field vector *in line* with the antenna element.

The magnetic field consists of circular field vector lines around the element. The direction (polarity) of the magnetic field also oscillates and reverses its vector direction at the RF rate and detaches itself in the same manner of the electric field.

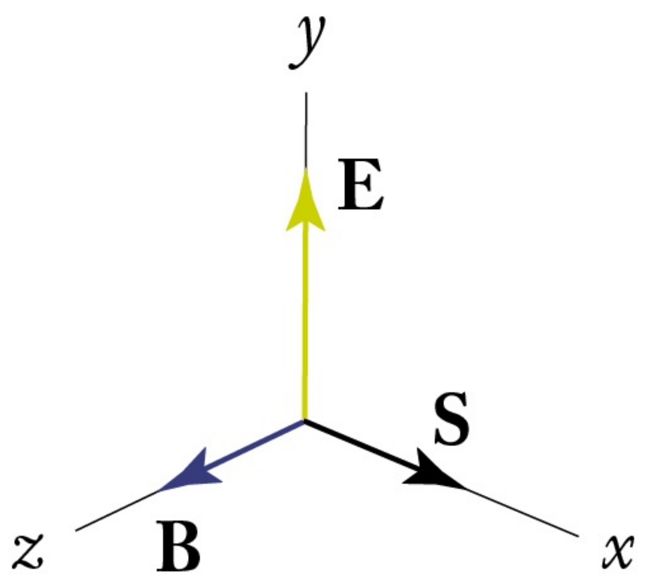

Figure 9

The Poynting vector (direction of propagation) therefor must be normal to the line of the dipole element.

The power of a plane wave is evenly distributed between **E** and **B**. **E** is measured in $\frac{V}{m}$and **B** in $\frac{A}{m}$ (field strength), the product being $\frac{Watts}{m^2}$ (power law and dimensional transformation), and the ratio $\frac{\frac{V}{m}}{\frac{A}{m}} = 377\Omega = impedance\ of\ free\ space$ (Ohm's Law).

Radiation Resistance

Aside from discussing antenna aperture, a widely misunderstood antenna specification is radiation resistance or R_r. Many of the commercial (marketing) requirements for “antennas” is to make them smaller, cheaper, and perform flawlessly. Of course, these requirements are all mutually exclusive. Here we will discuss some basics of R_r and then focus on the popular issue of small antennas. First, we’ll define R_r for a simple dipole antenna to get acquainted with the term.

We can define R_r as the resistance resulting from a circuit losing power to radiation (which is what a transmit antenna is supposed to do). In other words, a transmit antenna's R_r is simply a *load resistance*. By reciprocity, the receive antenna's (most often the same as the transmit antenna) R_r is the *source resistance* with the receiver front end as the load.

A simple description is "the larger the antenna (compared to the wavelength)" the "easier" it is for power to be created in the form of the radiated wave. This results in a *higher* R_r.

The easiest type of antenna to quantify is a one-dimensional structure like a ½ λ dipole antenna. This is the equation defining R_r on a linear antenna element.

$$R_r = \frac{h_e^2 Z_0}{4A_e}$$

h_e is the effective height or also called the effective length of a linear antenna, Z_0 is the impedance of free space (about 377Ω), and we already know what A_e is.

$$h_e = \frac{I_{av} h_p}{I_{max}}$$

I_{av} is the average current value on the antenna

I_{max} is the maximum current on the antenna

h_p is the physical height of the antenna, where the height is normalized to λ=1. We will also normalize the maximum current to 1 amp and thus the average current to .637

Example: calculation of Rr for a ½ wave dipole in free space

For half a sine wave the average current is .637 of the maximum current.

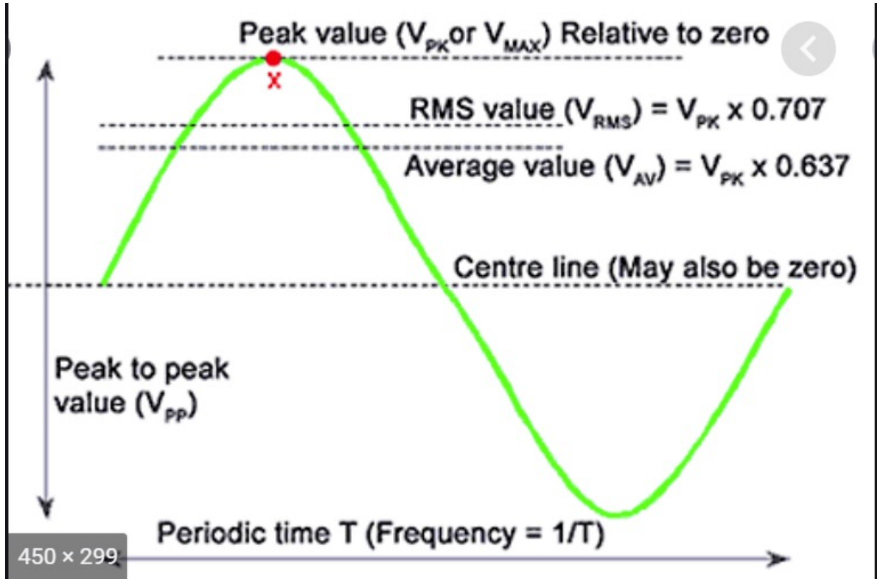

Figure 10

For a ½ wave dipole h_p is .5, therefore

$$h_e^2 = \frac{(.637\ x\ .5)^2}{1} = .101m^2$$

and $A_e = \frac{1.64\lambda^2}{4\pi}$

The value for λ is normalized in both the numerator and denominator terms.

Therefore: $R_r = \frac{h_e^2 Z_0}{4A_e} = \frac{.101m^2\ x\ 377\Omega}{4\frac{1.64\lambda^2}{4\pi}} = \frac{.101\ x377\Omega\ x\ \pi}{1.64} = 72.94\Omega$

Where λ is always 1 for effective height

73 Ω is the R_r *and* the feedpoint impedance at the center of a 1/2λ dipole. This coincidence is not always true.

There are many instances where the resistive part of a feedpoint impedance is *not* the same as R_r.

Notice the heavy dependence upon the physical height of the antenna. Note: for 2 and 3D antennas the same holds true, the smaller the antenna, the lower R_r will be.

A typical example of a very small antenna's complex impedance is 2 - j2740Ω. Here 2 is the part of the impedance that represents the real part while -2740 is the capacitive reactive part. If there is loss in the antenna, and its associated circuitry, the loss resistance will simply add to the real R_r. So, if there is 1Ω loss, the measured impedance will be 3Ω real.

Conclusion 1: small antennas have low R_r so they are prone to losses and thus inefficiencies. Antenna efficiency is defined as $R_r = \frac{R_r}{R_r + R_{loss}}$.

Conclusion 2. Small antennas exhibit very high capacitive reactances that must be tuned out by inductor(s). This creates a resonant circuit comprised of the antenna feedpoint and the external tuning circuit. In turn, this results in a narrow bandwidth for the circuit where

$Q = \frac{X}{R}$. From this elementary equation we can easily see that for higher R_r , efficiency and bandwidth increase.

Basics of RF Power Related to Antennas

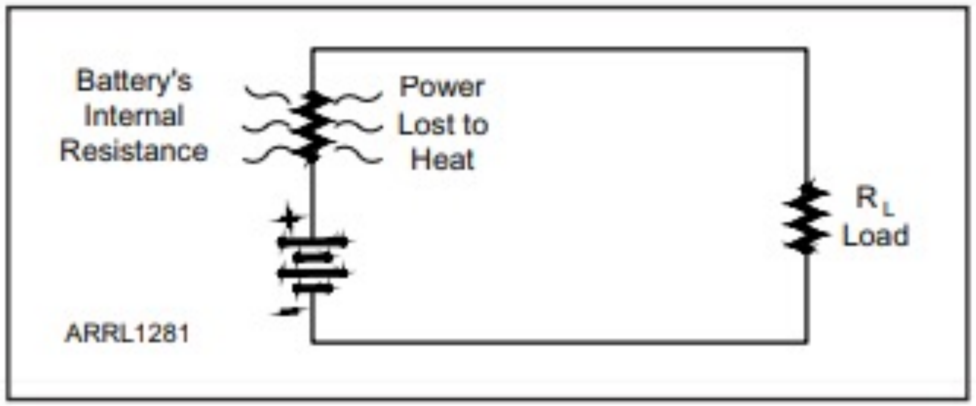

Figure 11

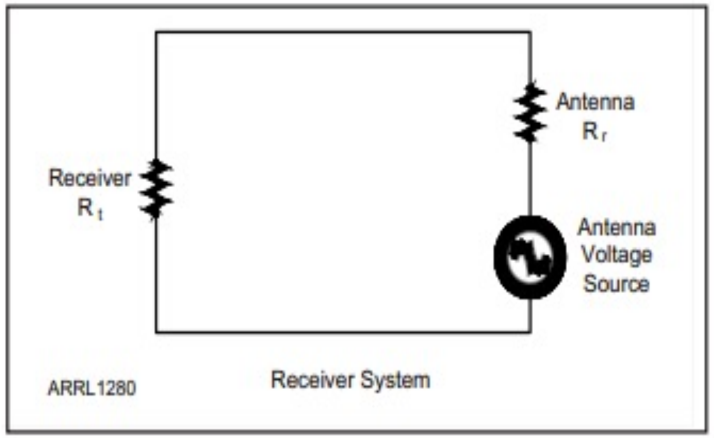

Figure 12

Here we use a very simple analogy to a battery, (the elementary maximum power transfer function) and a simplified circuit diagram of the receive case. All voltage sources exhibit a source resistance (in these examples we ignore reactances, as we are only interested in real power). Maximum power is transferred to the load when the source resistance is equal to the load resistance. When reactance (or without) such a condition is called a *conjugate match.*

In receive systems there is a relatively small trade-off between receiver noise figure and maximum power transfer. However, here we will assume a conjugate match.

In the battery example when a conjugate match is achieved, ½ of the power is delivered to load and ½ the power is dissipated as heat since the internal resistance is just that, a resistor. However, in the RF receiver case, the source resistance is R_r. The result is that ½ of the received power is re-radiated back into space since R_r does not dissipate heat! Indeed, this is the *best* power transfer possible with a receive antenna. This ½ of lost power is taken into account for gain and aperture calculations, so don't get thrown off. In most cases, a near-conjugate match is ideal for the receive condition.

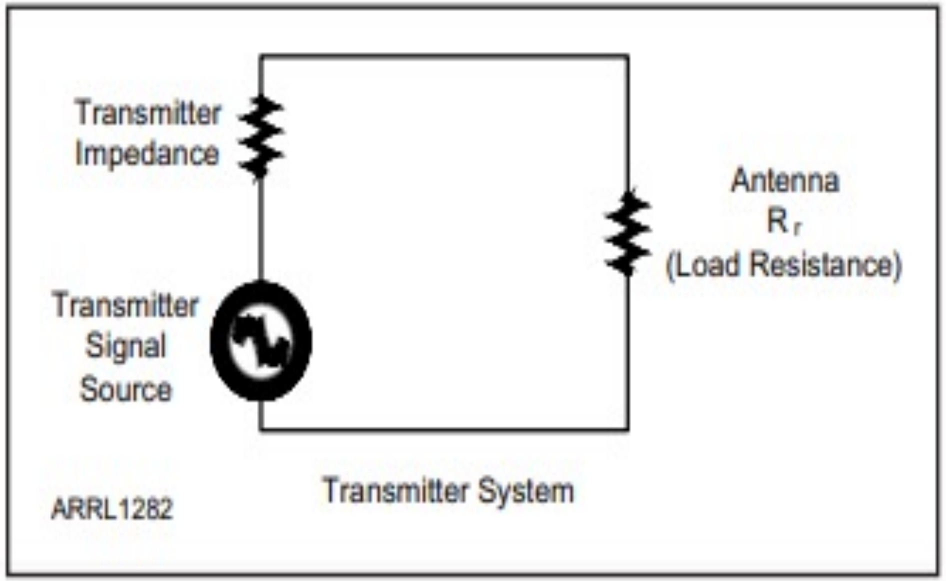

Figure 13

The transmit condition is different. If we assume a conjugate match, then the transmit system will be less than 50% efficient, and usually closer to 30—40% which would be unacceptable. For transmit conditions, the transmit source impedance is typically tuned to a *lower* load impedance than the actual load impedance (usually 50 Ohms). This provides for a much higher *efficiency* at the expense of maximum power transfer.

The actual optimum output impedance is a function of several variables (usually a partial differential equation) including the device (transistor or tube) characteristics and the output matching circuit. For details on this consult a textbook on RF power circuit design. When a transmitter is specified as 50 Ohms output, what they are really saying is that the transmitter is tuned for maximum efficiency assuming a 50 Ohm load.