F. Basic Antenna Designs

There are **many, many, many** different antenna designs, each with different **attributes** (e.g., cost, size, gain, bandwidth, profile, etc.).

We will investigate a handful of the most **popular** and useful of these antenna designs.

A **wire antenna** provides a wide beamwidth in a small package with low cost. As a result, they are **very** popular!

HO: The Wire Antenna

The most popular of the wire antennas is the **half-wave dipole**. It has some very **special properties**!

HO: The Half-Wave Dipole

Another important type of antenna is the **aperture antenna**.

HO: The Aperture Antenna

Satellite communication requires a **very** high gain antenna. This is perhaps most easily accomplished by using a **reflector antenna**.

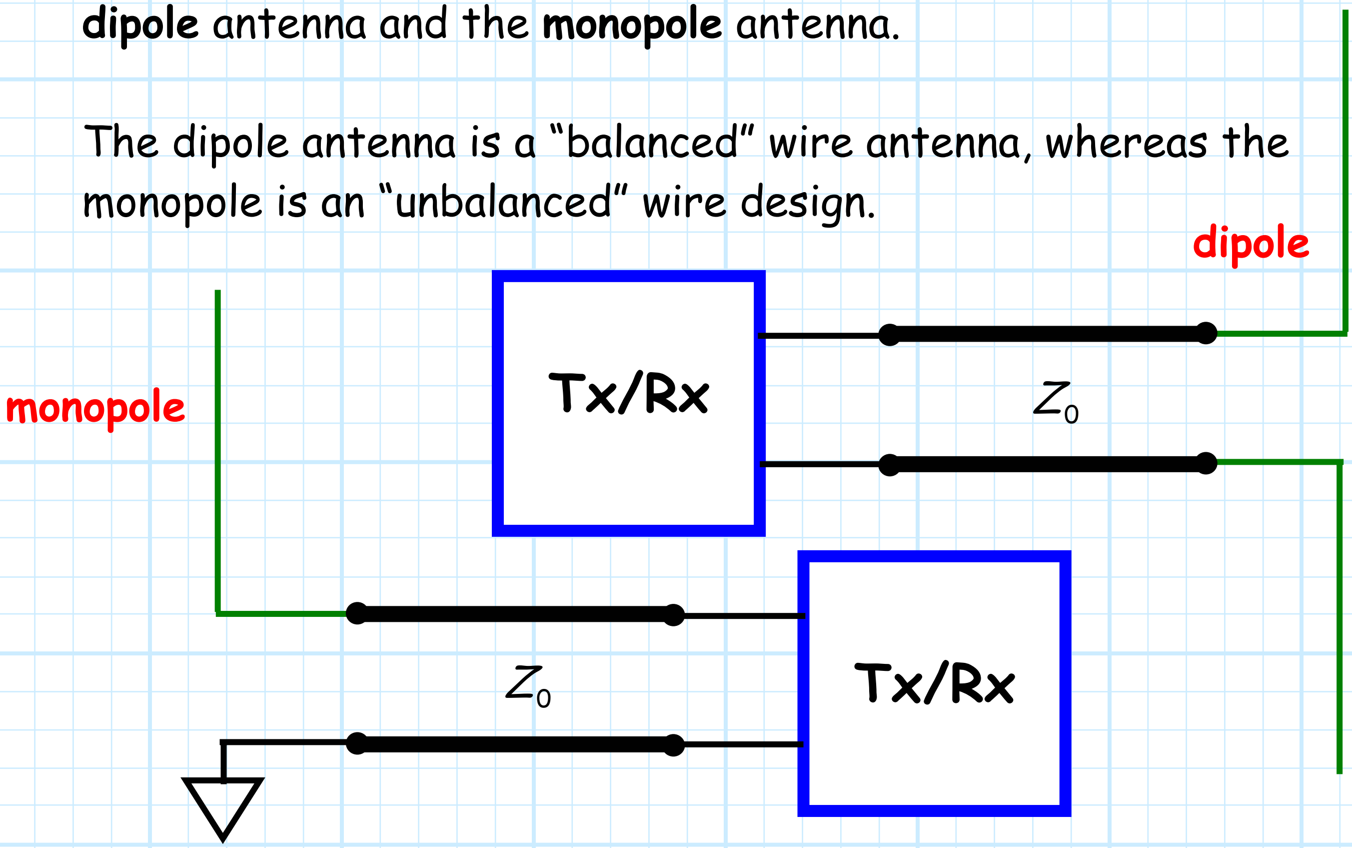
HO: The Reflector Antenna

The Wire Antenna

The simplest and perhaps most popular and prevalent antenna is the **wire antenna**.

The wire antenna comes in two prevalent "flavors", namely the **dipole** antenna and the **monopole** antenna.

The dipole antenna is a "balanced" wire antenna, whereas the monopole is an "unbalanced" wire design.



Q: ***Why*** *are wire antennas so popular?*

A: **Two** reasons!

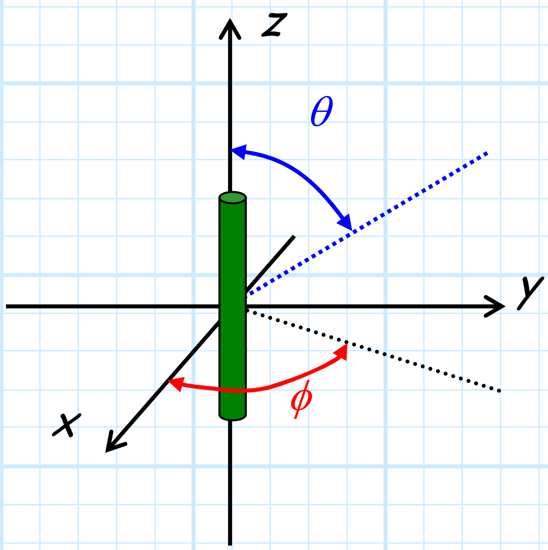
Reason #1: A wire antenna is really **cheap**!

A **wire** antenna is simply a straight piece of—um—**wire**. As a result, it is **inexpensive to manufacture**, a fact that makes it very popular for a plethora of consumer products such as **mobile phones** and **car radios**.

Reason #2: It is **azimuthally symmetric**!

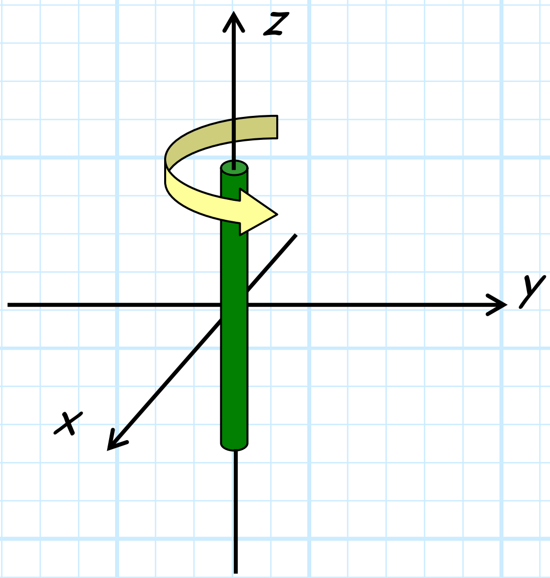
Q: *Huh??*

A: Say we orient our wire antenna **along the *z*-axis**.



Now let's consider the **gain pattern of** this antenna, "cut" by the ***x-y* plane** (i.e., $G(\theta = 90^\circ, \phi)$). We call this an "**azimuth cut**" of the antenna pattern provides antenna gain as a function of "azimuth" angle ϕ.

The **form** of this azimuth cut $G(\theta = 90^\circ, \phi)$ should be readily apparent! Consider **carefully** what happens if we were to **rotate** the wire around the z-axis:



→ **Nothing** happens!

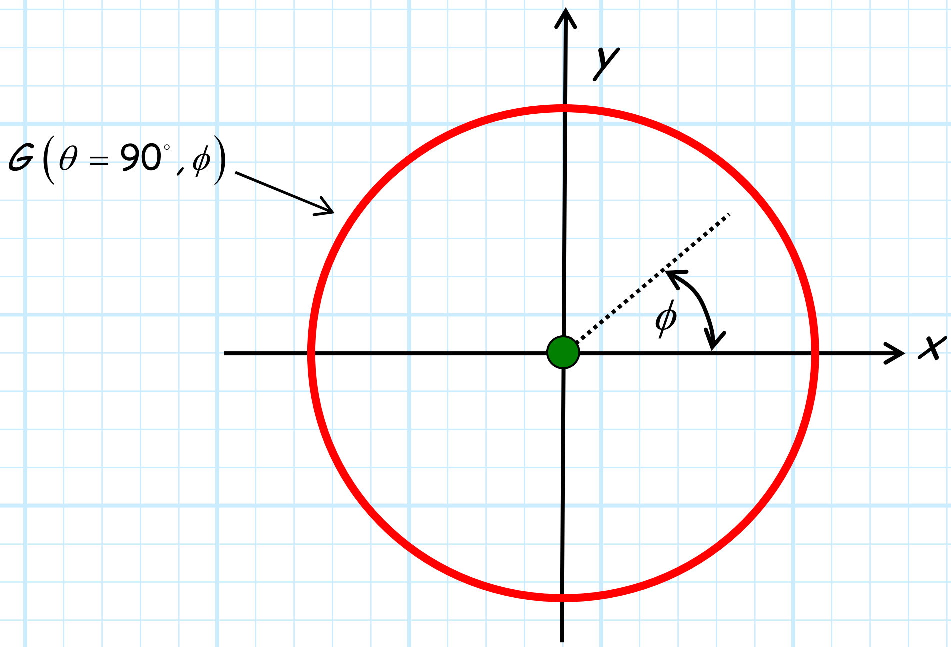
The wire is a **circular** cylinder, and as such possesses **cylindrical symmetry**. Rotating this cylinder in azimuth does **not** change the structure of the antenna **one whit**.

The wire cylinder has no **preferred** or **unique** direction with respect to ϕ—every direction is the **same**!

Q: ***Why*** *is this important?*

A: Since the antenna is **symmetric** with respect to ϕ—since every azimuthal direction is the **same**—the **gain pattern** produced by this antenna will likewise be **azimuthally symmetric**; the **gain** in every direction ϕ will be the same!

Thus, the gain pattern of an azimuthal cut (i.e., $G(\theta = 90^\circ, \phi)$) will be a **perfect circle**!

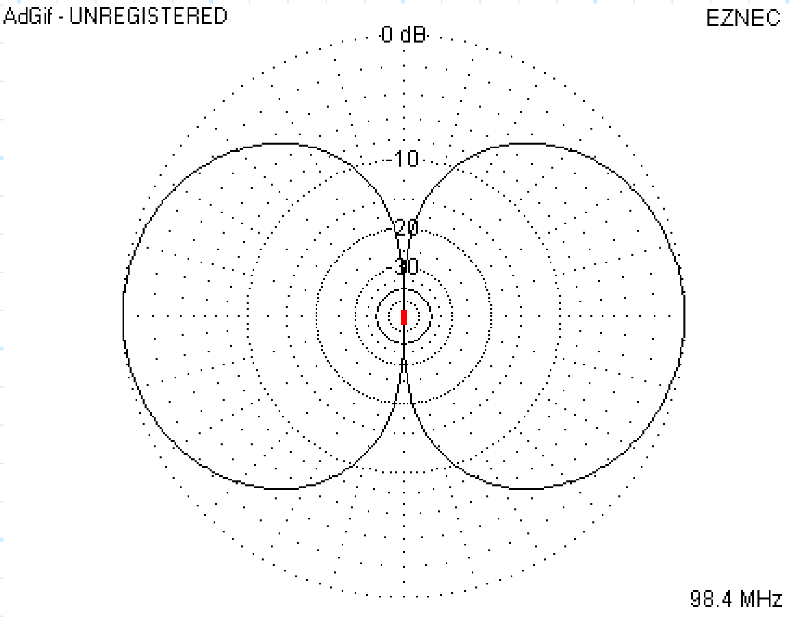


In other words, a **wire antenna** will radiate **equally** in all **azimuth** directions ϕ.

Q: *Wait a second! Radiates **equally** in all directions?? That sounds like an **isotropic** radiator, but you said an isotropic radiator is **impossible**!*

A: An isotropic radiator **is** impossible—meaning a wire antenna is of course **not** an isotropic radiator. Note that we found that a wire antenna radiates equally in all **azimuth** directions ϕ—it most definitely does **not** radiate uniformly in **elevation** direction θ.

In other words, if we take an "**elevation cut**" of a wire antenna by plotting its gain on the *x-z* plane (i.e., $G(\theta, \phi = 0)$), we will find that it is definitely not uniform!



Elevation cut of dipole antenna ($G(\theta, \phi = 0)$).

Q: *You say that this azimuthal symmetry is one reason while wire antennas are* ***popular****. Why is azimuthal symmetry a* ***desirable*** *trait?*

A: For **broadcasting** and **mobile** applications, we do not know where the **receivers are** located (if we are transmitting), and we do not know where the **transmitter is** (if we are receiving).

As a result, we need to transmit (i.e., radiate) across **all** azimuthal directions, or receive equally well from any and **all** directions. Otherwise we might **miss something**!

The Half-Wave Dipole

With most microwave or electromagnetic devices (e.g., μ–wave circuits, antennas), the important structural characteristic is not its size—rather it is its size **with respect to signal wavelength** λ.

Instead of measuring the size of an antenna (for example) with respect to **one meter** (e.g., 1.5 meters or 0.6 meters) we measure its size with respect to **one wavelength** λ (e.g., 0.3 λ or 1.1 λ).

Thus, our electromagnetic **"ruler"** is one which **varies** with signal frequency ω!

For **example**, we find that for a signal with an oscillating frequency of 300 MHz, its **wavelength** in "free-space" is:

$$\lambda = \frac{c}{f} = \frac{3\times 10^8}{3\times 10^8} = 1.0 \; meter$$

Whereas:

$$f = 600 \; MHz \quad \Rightarrow \quad \lambda = 0.5 \; meters$$
$$f = 1.2 \; GHz \quad \Rightarrow \quad \lambda = 0.25 \; meters$$
$$f = 3 \; GHz \quad \Rightarrow \quad \lambda = 0.1 \; meters$$
$$f = 6 \; GHz \quad \Rightarrow \quad \lambda = 5 \; cm$$
$$f = 12 \; GHz \quad \Rightarrow \quad \lambda = 2.5 \; cm$$

Note then, as **frequency increases**, the value of one **wavelength decreases**.

So now, let's consider again **wire antennas**.

The size of a wire antenna is completely defined by its **length** ℓ. We can express this length in terms of:

1. **meters** (e.g., $\ell = 0.6\ m$). We call this value the antenna's **physical length**.

2. **wavelengths** (e.g., $\ell = 0.2\ \lambda$). We call this value the antenna's **electrical length**.

Of course the **electrical** length of the wire antenna depends on **both** its physical length and the **frequency** (wavelength) of the propagating wave it is transmitting/receiving.

For **example**, say an antenna with a **physical** length of $\ell = 0.5\ m$ is transmitting a signal with **wavelength** $\lambda = 0.25\ m$. It is obvious (is it obvious to **you**?) that the **electrical length** of this antenna is $\ell = 2.0\ \lambda$.

But, if the frequency of the signal is **decreased**, such that its wavelength becomes $\lambda = 0.7\ m$, that **same** antenna with physical length $\ell = 0.5\ m$ will now have a **shorter electrical length** of $\ell = 1.4\ \lambda$

With respect to **wire antenna** (both dipoles and monopoles), the important length with respect to fundamental antenna parameters (e.g., directivity, impedance) is its **electrical length**!

The most **popular** of all dipole antenna is one with an electrical length of **one-half** wavelength (i.e., $\ell = \lambda/2$). We call this antenna the **half-wave dipole**.

The monopole equivalent of the half-wave dipole is the **quarter-wave monopole** (i.e., $\ell = 0.25\,\lambda$).

Q: *What makes the half-wave dipole so popular?*

A: One reason is that a half-wave dipole (or quarter-wave monopole) is relatively **small**. For **example**, at a frequency of 1 GHz, a half-wave dipole has a physical length of **15 cm**. A small antenna has many **obvious** advantages (e.g., low weight, cost, and size).

Q: *Well then, why don't we simply make the antenna* ***really*** *small? Say an electrical length of* $\ell = 0.05\,\lambda$ *or* $\ell = 0.00005\,\lambda$ *??*

A: The problem with making a dipole **extremely short** is its **impedance**.

As the electrical length of a dipole or monopole antenna **shortens**, **two** things happen to impedance Z_A:

1. Its **reactive** component X_A becomes very **large** and **negative** (i.e., capacitive).

2. Its **radiation resistance** becomes **very small**.

In other words, a dipole with **very** small electrical length "looks" like a **capacitor**, and capacitors make **bad** antennas.

→ It is exceedingly **difficult to match** an very electrically short dipole to either a transmitter or receiver!

However, as we begin to **increase the electrical length** of an electrically short dipole, we find that its radiation resistance **increases** and its reactive component **diminishes** (becomes less negative).

If we increase the electrical length enough, we find that the reactive component will drop to **zero** ($X_A = 0$), and its radiation resistance will have increased to a **desirable** $R_r = 73\,\Omega$.

Q: *At **what** electrical length does this happen?*

A: As you might have expected, this occurs **only** if the electrical length of the antenna is equal to $\ell = \lambda/2$—a **half-wave dipole**!

Thus, we find:

$$Z_A \approx 73\,\Omega \quad \text{for } \ell = \lambda/2$$

→ A half-wave dipole is the **shortest** dipole that can be easily **matched** to!

In fact, half-wave dipoles do **not** (necessarily) require any sort of **matching network**, provided that **characteristic impedance** of the transmission line is also numerically equal to 73 Ω (i.e., $Z_0 = 73\,\Omega$).

Generally speaking, a transmission line of $Z_0 = 75\,\Omega$ is used for this purpose (its **close enough**!).

Q: *So does a half-wave dipole a have a **wide** operating bandwidth?*

A: Of **course** not!

Remember, as the signal frequency **changes**, the wavelength **changes**, and thus the electrical length **changes**.

→ A half-wave dipole has an electrical length of $\ell = \lambda/2$ at **precisely one** (and **only** one!) frequency.

The **"design"** or "operating" frequency of a half-wave dipole can be found from its physical length as:

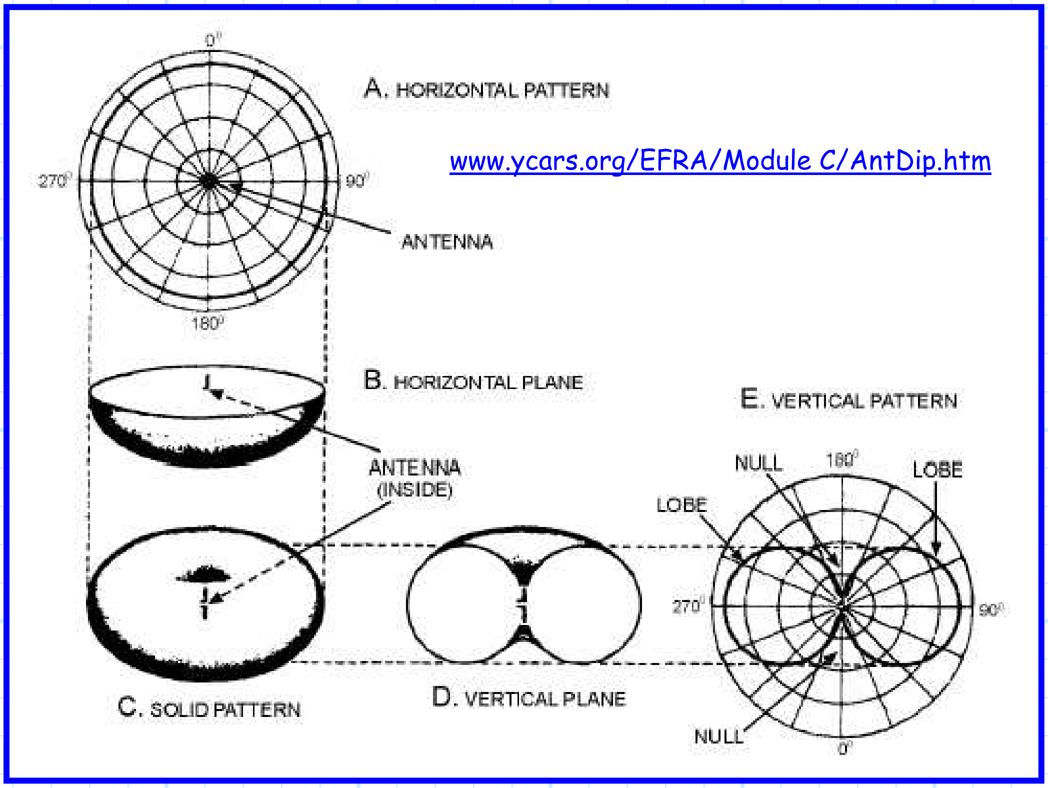
$$f_o = \frac{c}{2\,\ell}$$

If the signal frequency f is **slightly** greater or **slightly** less than the design frequency f_o, then the antenna impedance will still **approximately** be $Z_A \approx 73\ \Omega$, and a "good" match will be maintained.

→ A half-wave dipole antenna is an inherently **narrowband** device!

Q: *What about all the **other** important parameters of an antenna? What are these for a **half-wave** dipole.*

A: We know of course that a half-wave dipole is **azimuthally symmetric**, and thus so is the resulting antenna pattern (i.e., $\beta_\phi = 2\pi$.



In the elevation plane, we find that the beam pattern is likewise fairly **wide**, but with "nulls" occurring at $\theta = 0$ (straight above the dipole) and at $\theta = \pi$.

Thus, the antenna pattern produced by a half-wave dipole (or any electrically short dipole for that matter) has a classic **"doughnut"** shape.

→ In other words, a half-wave dipole has one **gigantic** mainlobe and **no** sidelobes.

This doughnut shape is about as **close** as antenna can physically get to **isotropic**, and thus we find the directivity of the half-wave dipole is only **slightly greater** than one:

$$D_0 = 1.643 \qquad D_0(dB) = 2.16 \qquad \text{for } \lambda/2 \text{ dipole}$$

Note that:

1. This value of maximum directivity occurs in the direction $\theta = \pi/2$ and for **any** and **all** azimuthal directions ϕ.

2. This value D_0 is **independent of design frequency**—this directivity value is valid for any and **all** half-wave dipoles, regardless of their **design** frequency f_0.

Since we know the directivity of a half-wave dipole, we can now determine its **effective aperture**:

$$A_{em} = \frac{\lambda^2}{4\pi} D_0 = \frac{\lambda^2}{4\pi} 1.643 \approx 0.13\lambda^2 \qquad \text{for } \lambda/2 \text{ dipole}$$

Note that this value **does** change with design frequency!

As the **wavelength increases** (i.e., the frequency decreases), the **effective aperture** of a half-wave dipole will **increase**.

→ **Lower** design frequencies mean a **larger** effective collecting aperture for a half-wave dipole!

Q: ***Why*** *is that?*

A: Recall that as we lower the design frequency (i.e., increase the signal wavelength λ), the **physical** length of the antenna must **increase**.

* For **example**, a half-wave dipole for a signal with $\lambda = 0.2\ m$ must have a physical length of $\ell = 0.1\ m$.

* Whereas, a half-wave dipole for a signal with $\lambda = 2.0\ m$ must have a physical length of $\ell = 1.0\ m$.

→ Remember, antennas that are **physically larger** generally have **larger effective apertures**—and the size of half-wave dipoles must increase as design frequency decreases.

Q: *What about the **quarter-wave monopole**?*

A: We find that the **impedance** of a quarter-wave monopole is **half** that of a half-wave dipole:

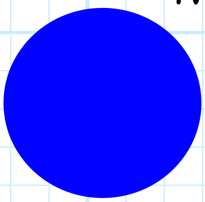
$$Z_A \approx 36.5\,\Omega \quad \text{for } \ell = \lambda/4 \text{ monopole}$$

But the directivity is **doubled**:

$$D_0 = 3.29 \qquad D_0(dB) = 5.16 \qquad \text{for } \lambda/4 \text{ monopole}$$

The Aperture Antenna

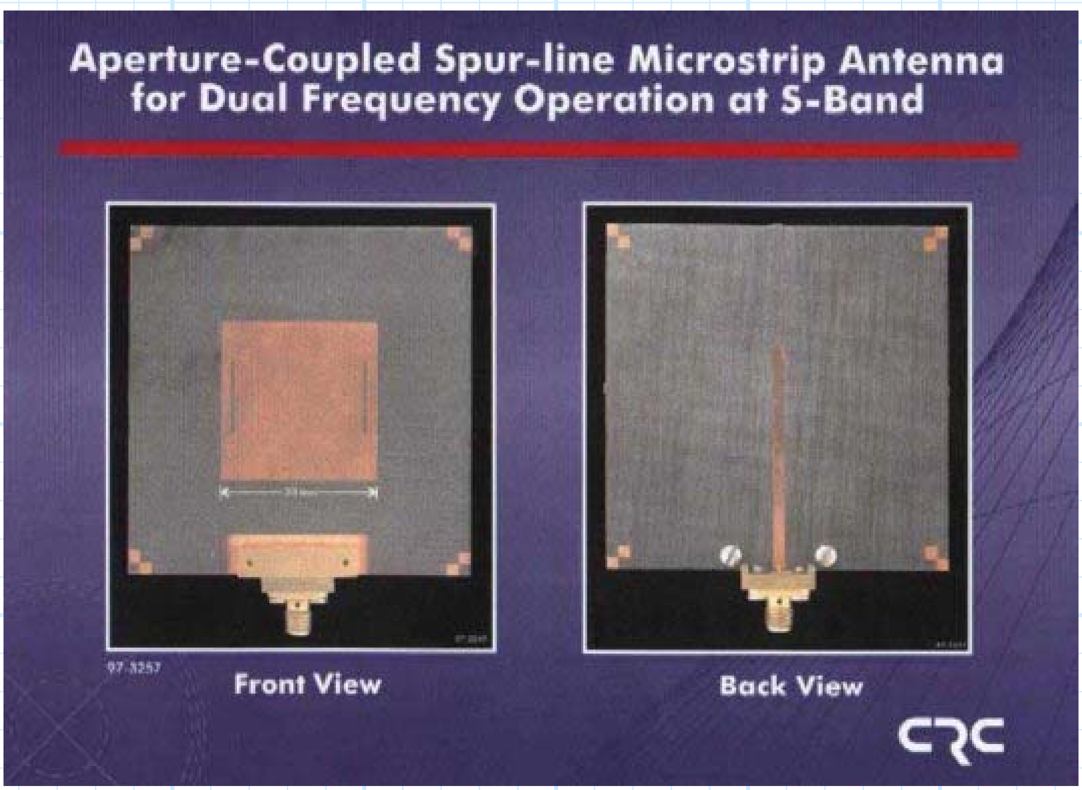
An **aperture** antenna has a well defined aperture—a shape in two-dimensions that essentially forms a **physical** aperture.



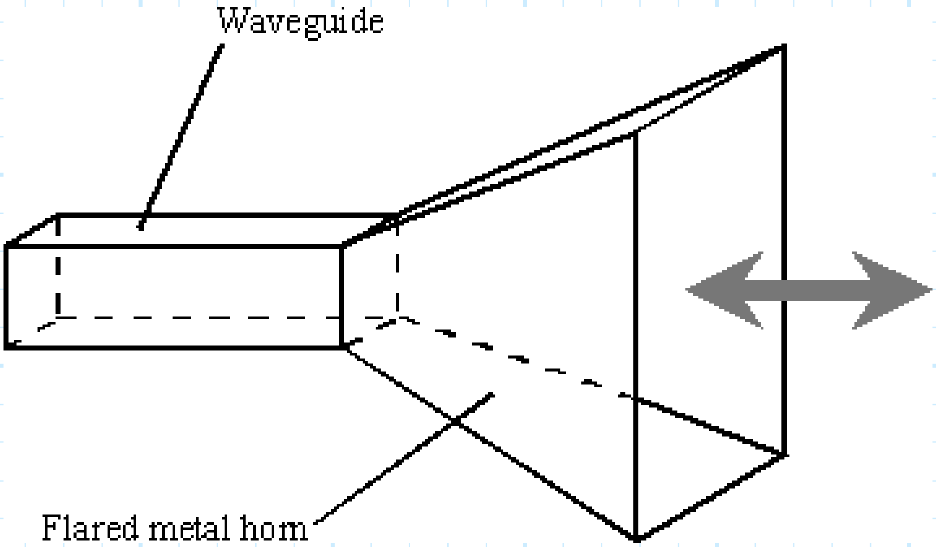
The shape of these aperture antennas are most commonly a **circle** and **rectangle**.

Three common forms of aperture antennas are:

1. **The microstirp antenna** - A microstrip antenna is simply a conducting **rectangle** etched onto a microstrip substrate. It is particularly useful for **conformal** antenna designs, such as the surface of an aircraft.

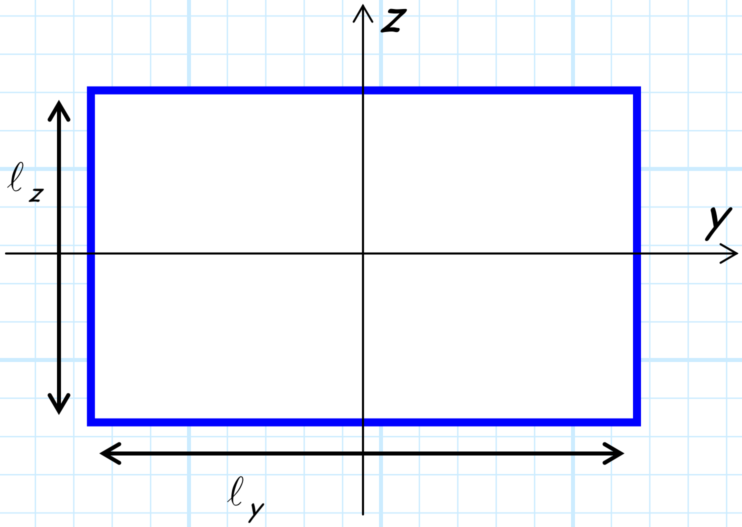


2. The horn antenna - A horn antenna is hollow metallic structure that is shaped like—um—a **horn**! Essentially, a **horn** antenna is an open-ended **waveguide**, with a taper that efficiently **"launches"** the guided wave into free-space. The aperture is the open end of the horn.



3. The reflector antenna - We will learn about the reflector antenna **later**!

In either case, the dimensions of the antenna aperture (ℓ_y and ℓ_z) pretty much determines **all** the important antenna parameters.



Note that from the **aperture dimensions**, we can determine the aperture area—the **physical aperture size** A_p:

$$A_p = \ell_y \ell_z$$

Q: *But the **physical** size of the antenna aperture is **not** important. Don't we need to determine its **effective** aperture A_{em}??*

A: **True** enough! But for aperture antenna we find that the physical aperture size **is** (approximately) the effective aperture:

$$A_{em} \approx A_p = \ell_y \, \ell_z$$

Note that the effective aperture of an aperture antenna is thus **independent of frequency**.

From this result we can determine the **gain** of an aperture antenna:

$$G_0 = \frac{4\pi}{\lambda^2} A_{em} \approx \frac{4\pi}{\lambda^2} A_p = \frac{4\pi}{\lambda^2} \left(\ell_y \ell_z \right)$$

Note then that the **gain increases** as the signal **wavelength decreases**.

→ In other words, **increasing** the signal **frequency** will likewise **increase** the **gain** of the aperture antenna!

Q: *If the **gain** changes with frequency, doesn't that mean that the **antenna pattern** must change with frequency?*

A: That's exactly correct!

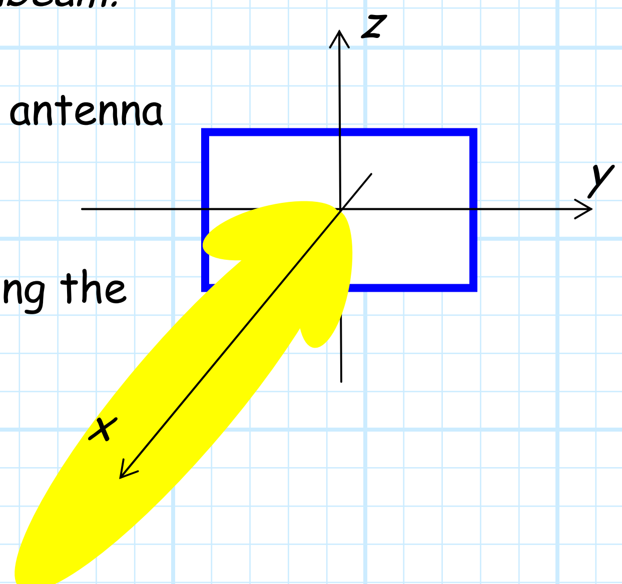
Aperture antennas are generally **very efficient**, such that $G_0 \approx D_0$. Since we know that:

$$D_0 \, \Omega_A \approx 4\pi$$

We know that as the **gain** of an aperture antenna **increases** with frequency, the **beamwidth** of the mainlobe must proportionately **decrease** with frequency.

Q: *In what **direction** is this mainbeam?*

A: The mainbeam of an aperture antenna is directed **perpendicular** to the aperture surface (using our notation, the mainbeam points along the x-axis).



Q: *What is the* ***size*** *of the mainbeam?*

A: To answer this question, we first must make an additional **approximation**.

Recall that we can define the mainbeam in terms of its **solid angle** Ω_A (in steradians) **or** in terms of two angles β_ϕ and β_θ (in radians) corresponding to the **azimuth** and **elevation** "cuts".

If the beamwidth Ω_A in steradians is **small** (i.e., $\Omega_A < 0.2\pi$) we find the relationship between Ω_A and angles β_ϕ and β_θ (in **radians!**) is **approximately**:

$$\Omega_A \approx \beta_\phi \, \beta_\theta$$

And since we **also** know that $D_0 \, \Omega_A \approx 4\pi$, and $D_0 \approx G_0$ we can conclude:

$$G_0 \, \beta_\phi \, \beta_\theta \approx 4\pi$$

Combining this with our newly acquired knowledge that:

$$G_0 = \frac{4\pi}{\lambda^2}\left(\ell_y \ell_z\right)$$

We find:

$$\beta_\phi \, \beta_\theta = \frac{\lambda^2}{\ell_y \, \ell_z}$$

And from this we correctly **infer** that:

$$\beta_\phi \approx \frac{\lambda}{\ell_y} \qquad \beta_\theta \approx \frac{\lambda}{\ell_z} \qquad [radians]$$

To more clearly see what these expressions **mean**, we might rewrite them as:

$$\frac{1}{\beta_\phi} \approx \frac{\ell_y}{\lambda} \qquad \frac{1}{\beta_\theta} \approx \frac{\ell_z}{\lambda}$$

Note the value ℓ_y/λ is the **electrical width** of the aperture (i.e., the aperture width in wavelengths), while ℓ_z/λ is the **electrical height** of the aperture.

Thus, the **azimuthal** beamwidth β_ϕ is **inversely** proportional to the **electrical width** of the aperture, and **elevation** beamwidth β_θ is **inversely** proportional to the **electrical height** of the aperture.

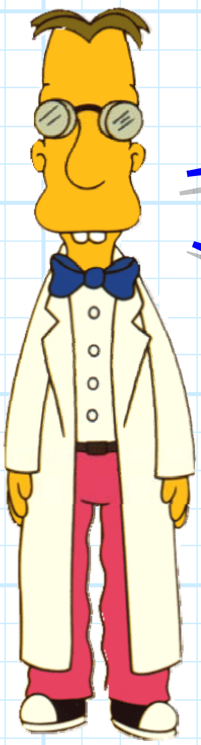
Q: *What about the **bandwidth** of an aperture antenna?*

A: It depends. **Microstrip** antenna are fairly **narrowband**, very much like dipole antenna. On the other hand, the bandwidth of **horn** antenna is similar to the bandwidth of a wave guide (i.e., a **moderately** wide bandwidth).

The Reflector Antenna

A reflector antenna is a great way to achieve **very** high gain—and therefore **very** high effective aperture and **very** narrow beamwidth.

The first component of a reflector antenna is (typically) a **horn** antenna.



Q: *Surely you jest! A* ***very*** *high gain* ***horn*** *antenna would be* ***huge!*** *I.E.,* ***very*** *large and* ***very*** *heavy.*

A: Relax! The horn used in a reflector antenna is generally **very small**.

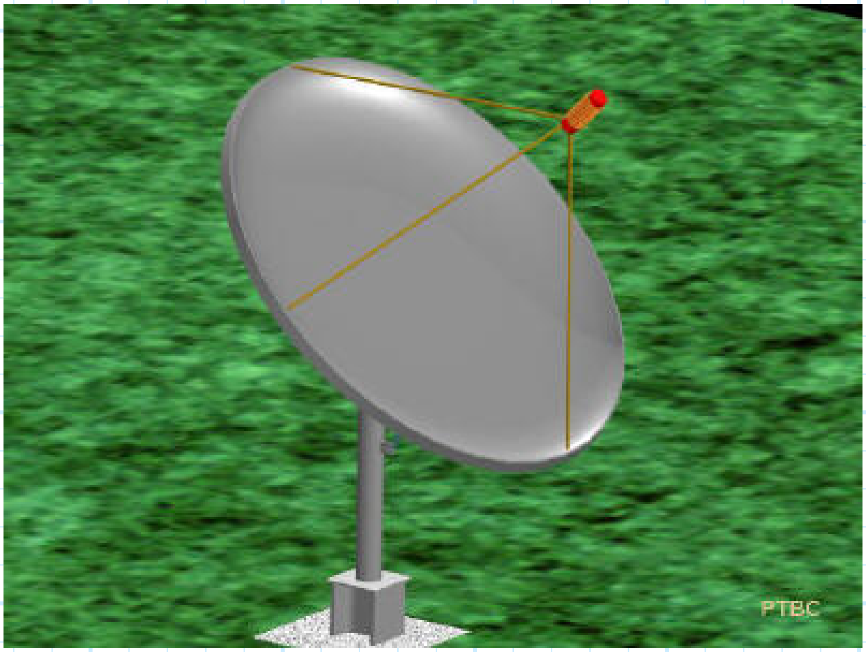
Q: *Huh? A* ***small*** *horn means* ***small*** *gain.*

A: True, but the horn is **not** the only element of a reflector antenna.

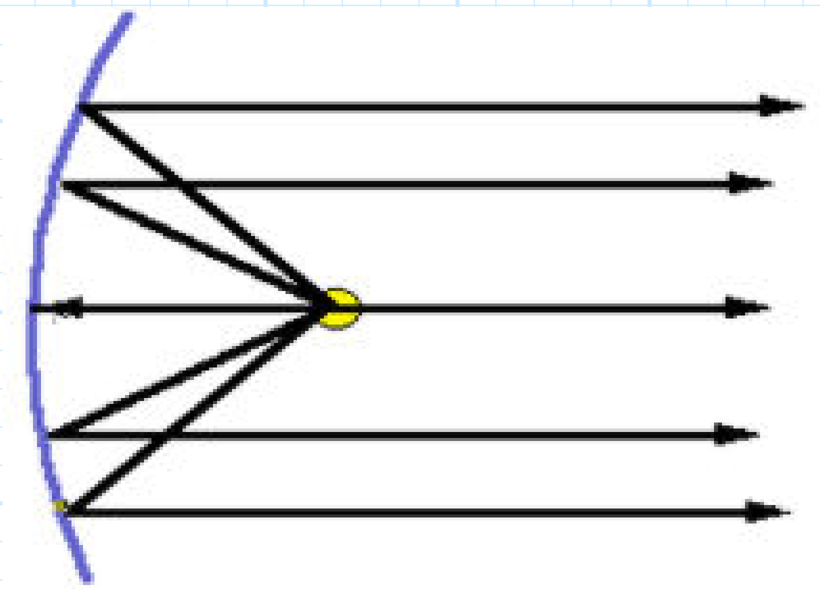
This small horn antenna is called a feed horn; we combine this feed horn with a **very** large **reflector**.

→ The **reflector** size determines the gain/beamwidth of the reflector antenna.

For **example**, the most common reflector is the **parabola**.



A parabola **reflects** the spherical feed horn wave into **one** primary direction!



The **diameter** (*d*) of the parabolic reflector specifies the performance of the antenna (e.g., an 10 meter "dish").

* The **physical** "area" (A_p) of the parabolic reflector is:

$$A_p = \pi \left(\frac{d}{2} \right)^2$$

* For an **efficient** parabolic reflector antenna, we find that the **effective** aperture is approximately equal to the this **physical** aperture:

$$A_{em} \approx A_p = \pi \left(\frac{d}{2} \right)^2$$

Just like an aperture antenna!

The **gain** of a parabolic reflector antenna is therefore:

$$G_0 = \frac{4\pi}{\lambda^2} A_{em} \approx \frac{4\pi}{\lambda^2} A_p = \frac{4\pi^2}{\lambda^2} \left(\frac{d}{2} \right)^2 = \left(\pi \frac{d}{\lambda} \right)^2$$

Since the **gain** of a large reflector antenna is **very** large, the resulting **beamwidth** is **very** small. Thus, we can use the approximation:

$$G_0 = \frac{4\pi}{\Omega_A} \approx \frac{4\pi}{\beta_\phi \beta_\theta}$$

But, since the parabolic reflector antenna is **circular**, the two beamwidths are **equal**:

$$\beta_\phi = \beta_\theta \doteq \beta$$

Therefore:

$$G_0 \approx \frac{4\pi}{\beta^2}$$

And now **equating** the two results above:

$$G_0 = \left(\pi \frac{d}{\lambda}\right)^2 = \frac{4\pi}{\beta^2}$$

And then **solving** for beamwidth β:

$$\beta = \frac{1}{\sqrt{\pi}} \frac{2\lambda}{d} \approx 1.13 \frac{\lambda}{d} \approx \frac{\lambda}{d} \quad [radians]$$

Advantages of Reflector Antennas

* A large gain can be created with a relatively **small volume**.

* Antenna bandwidth is the **same** as the feed horn (i.e., moderately wide).

Disadvantages of Reflector Antennas

* The design is somewhat **complex**.

* A reflector can exhibit a large "**wind load**".

* Works **only** if $d \gg \lambda$!!