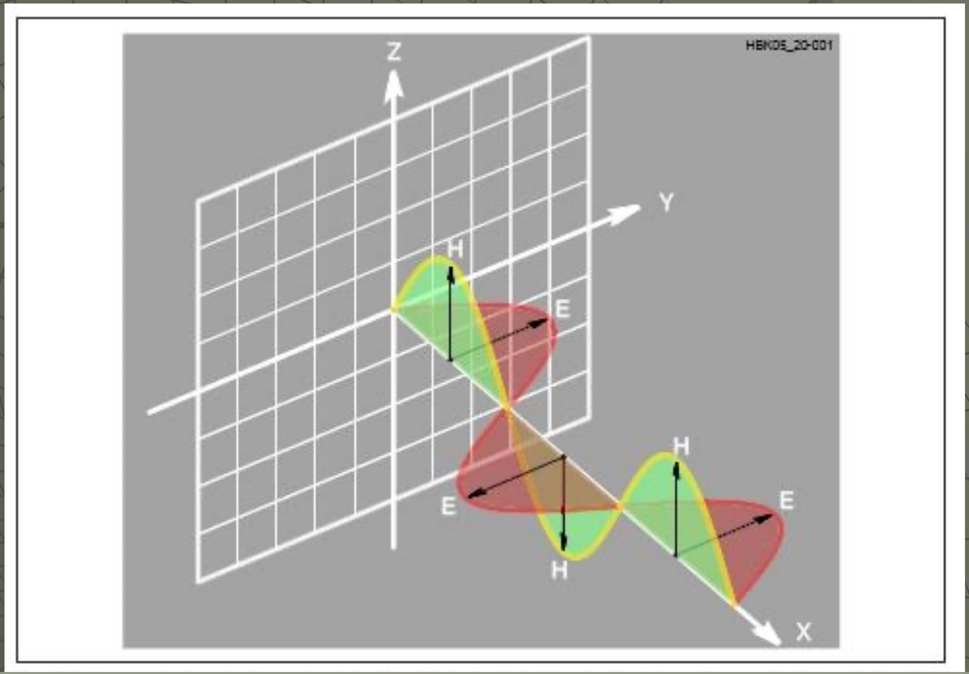
Radio Propagation And Antennas

Steve Cerwin
San Antonio Digital Radio Club
steve@cerwinconsulting.com
210-861-8060

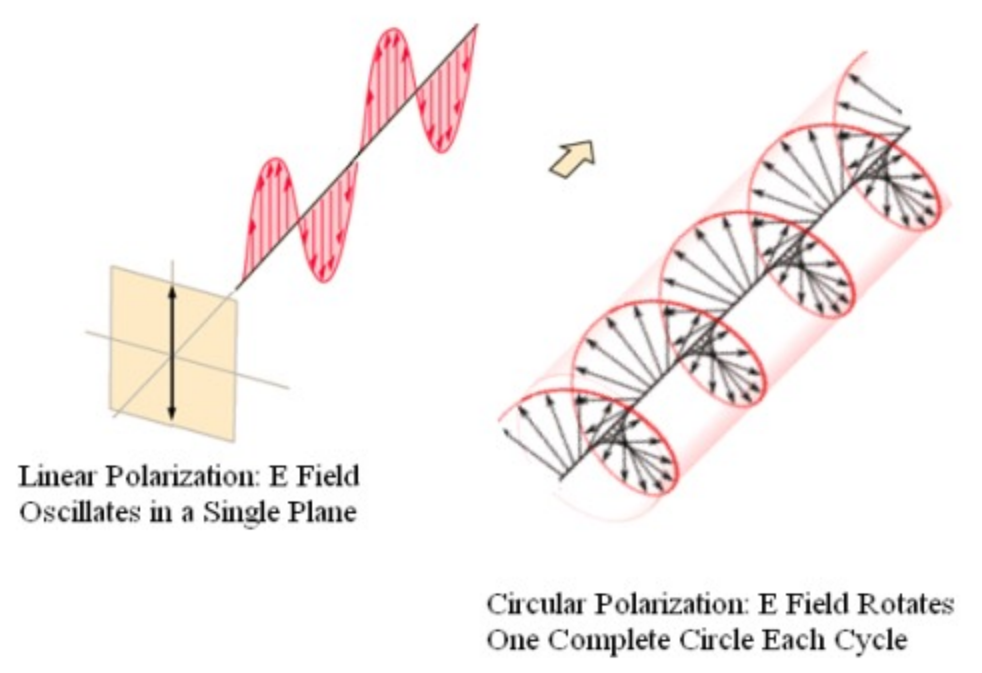
A Propagating Radio Wave Consists of Orthogonal Electric and Magnetic Fields Oscillating in a Plane Perpendicular to the Direction of Propagation



The fields are in-phase and oscillate sinusoidally at the characteristic frequency of the signal. The wave propagates at the speed of light, 300×10^6 m/sec or 186,000 miles/sec.

The electric and magnetic fields curl around each other in a self-reinforcing symbiosis to create a propagating electromagnetic wave capable of transferring energy from one antenna to another. In the absence of an absorber the wave could propagate forever. Example: 13-billion-year-old light now entering James Webb Telescope.

Polarization



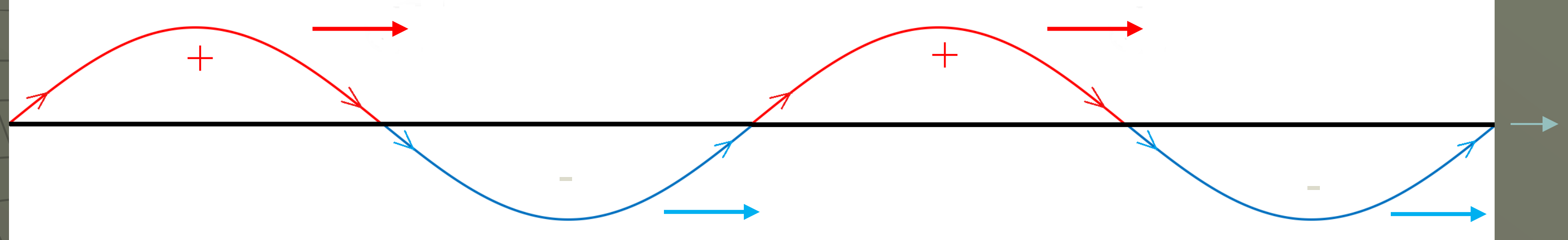
The radio wave has a polarization that is set by the disposition of the plane containing the E-field vector. If the E-field oscillates in only one plane, the wave is linearly polarized. Circular polarization occurs when the plane of the E-field vector rotates with each cycle of the wave. Both right and left hand circular polarization is possible.

Dipole Antennas

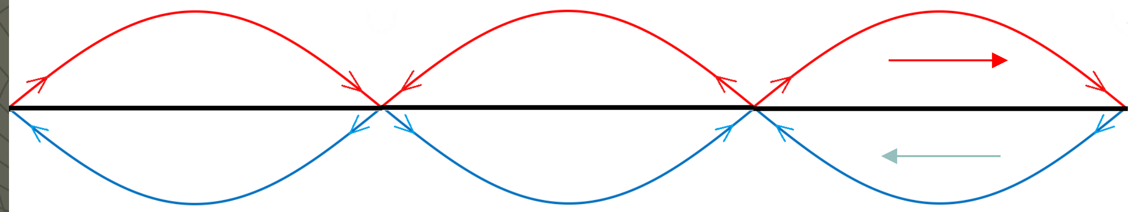
- The half-wave dipole is the fundamental antenna element and is the simplest antenna to construct.
- It has a nearly omnidirectional radiation pattern.
- The dipole can be fed from the center, the end, or anywhere along its length.
- It has a center-fed radiation resistance of 73 ohms in free space and matching schemes exist to obtain a match to almost any impedance in almost any environment.

Half Wave Dipole Formed by End Reflections

1. Traveling Wave of RF Current Moving Left-Right on a Long Wire

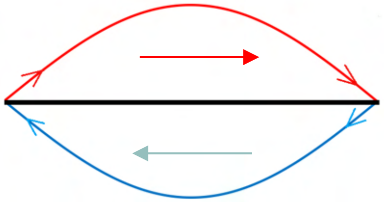


2. Counter Propagating Waves Created by Terminating Wire on One End



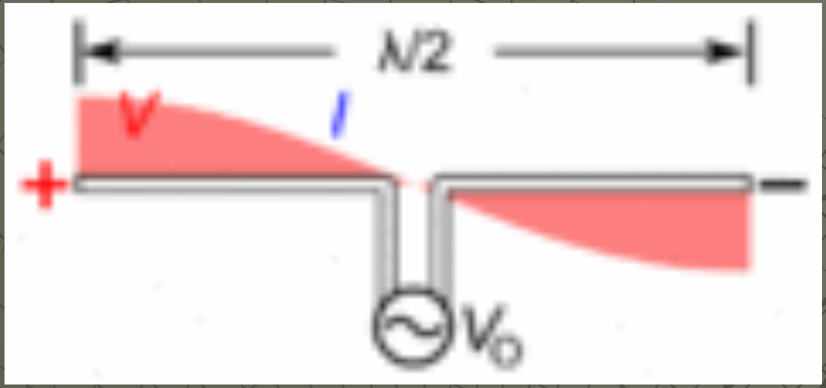
3. End Reflection Sends Wave Back Towards Source

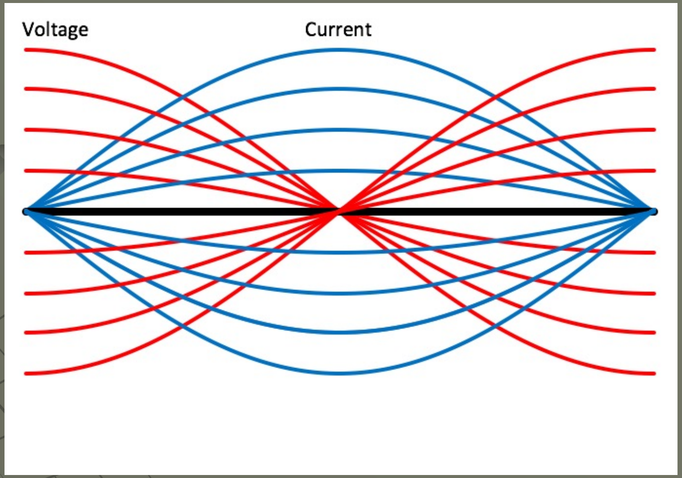
4. Terminating Both Ends to Trap Exactly One-Half Wavelength of Current Forms the Fundamental Half-Wave Dipole



5. Resulting Standing Wave where Current is always Maximum in the Middle and Zero on the Ends.

Standing Wave Current and Voltage Distributions on a Dipole Antenna



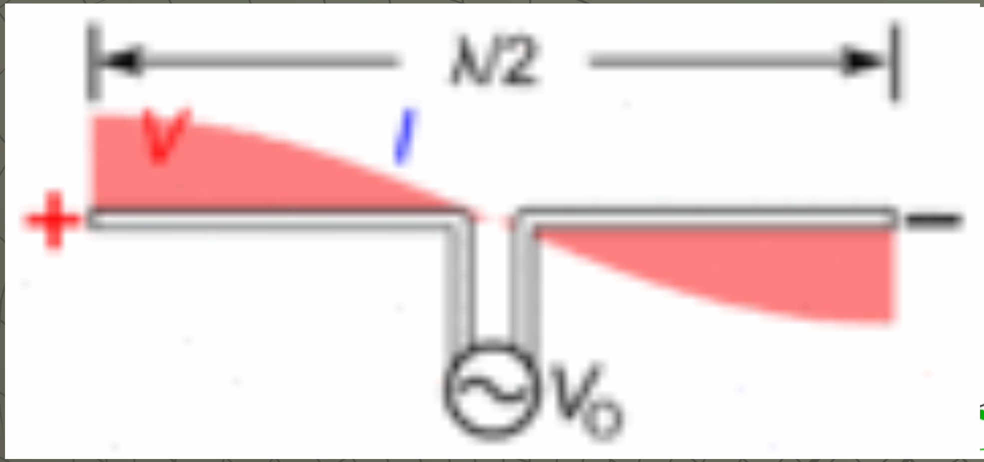


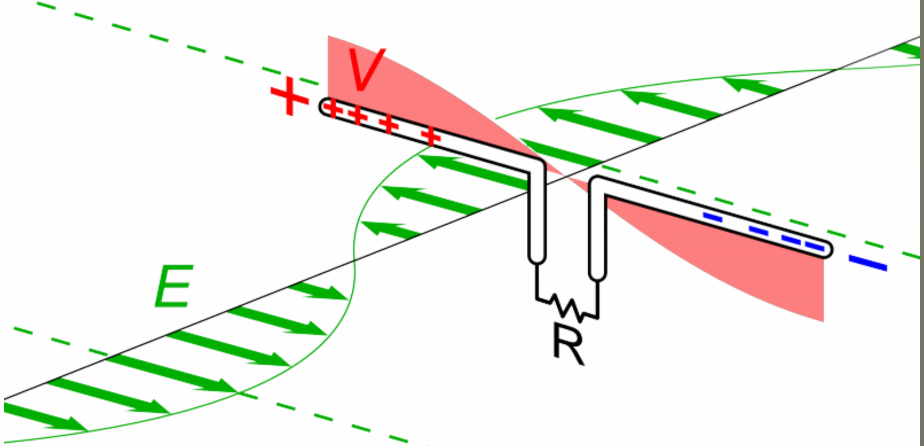
Current and Voltage are AC signals, so they alternate polarity sinusoidally from positive to negative. However, they form a standing wave in that the locations of the maximum and minimum values are at fixed positions on the wire.

Current is always maximum in the center and zero on the ends. A common feed method is to break the dipole here and feed with low impedance coaxial cable.

Voltage is always maximum on the ends and zero in the middle.

Dipole: The Fundamental Antenna





A dipole is a wire long enough to hold exactly one-half wavelength of voltage and current. It is a dynamic resonant structure. The end reflections cause the current and voltage distributions to congruently lie exactly on top of one another to build large amplitudes.
Transmit: back-and-forth oscillations accelerate electric charge which causes radiation of an electromagnetic wave.
Receive: a passing radio wave induces oscillating charges on the dipole that transfer power to a connected receiver.

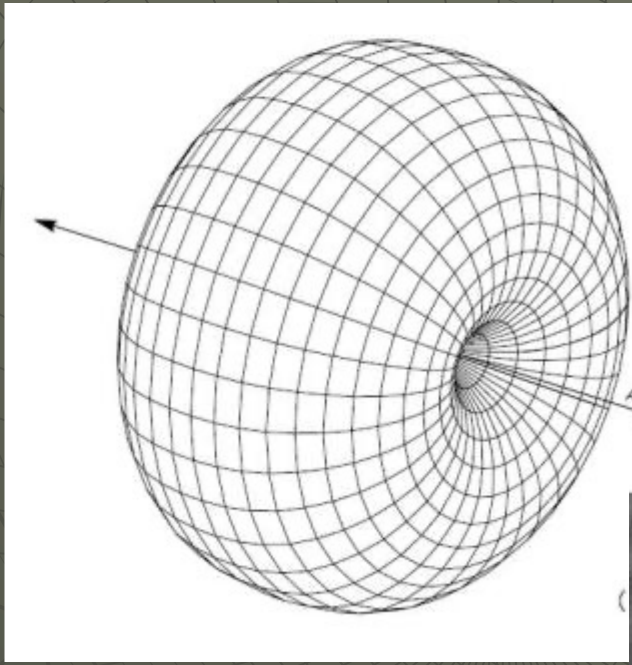
Current is always maximum in the center and zero on the ends. A common feed method is to break the dipole here and feed it with low impedance coaxial cable.

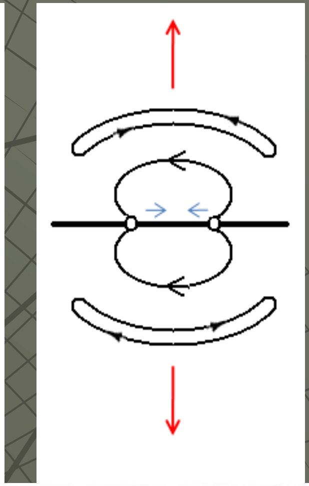
Voltage is always maximum on the ends and zero in the middle.

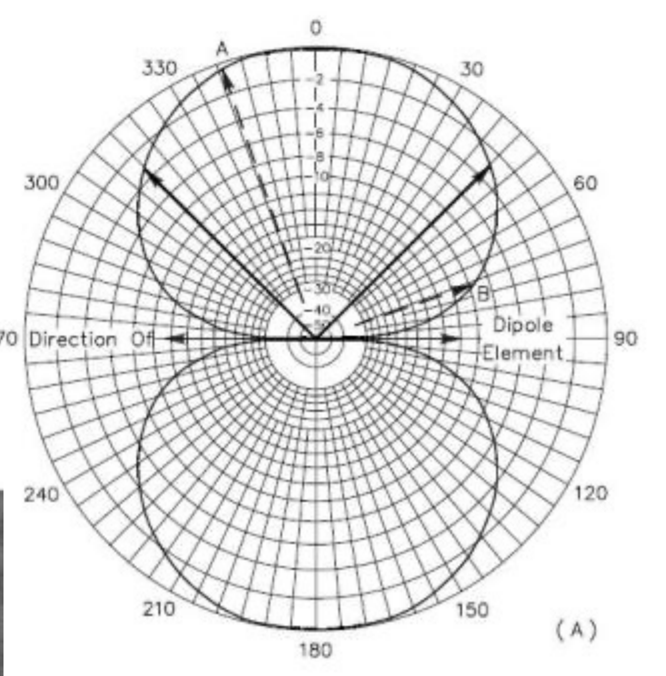
Dipole Radiation Pattern

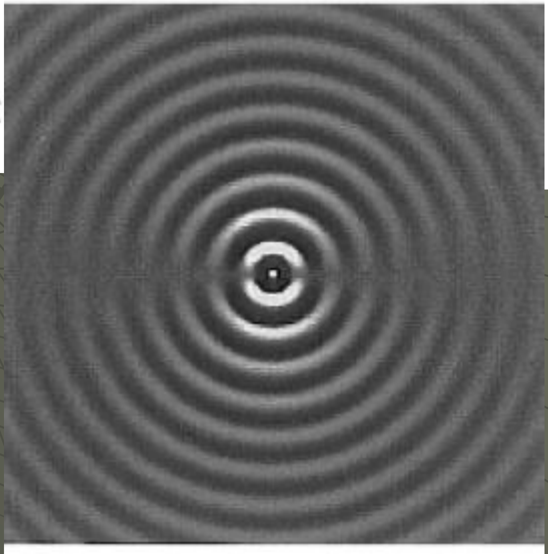
a) 3-dimensional pattern

b) Azimuth Slice







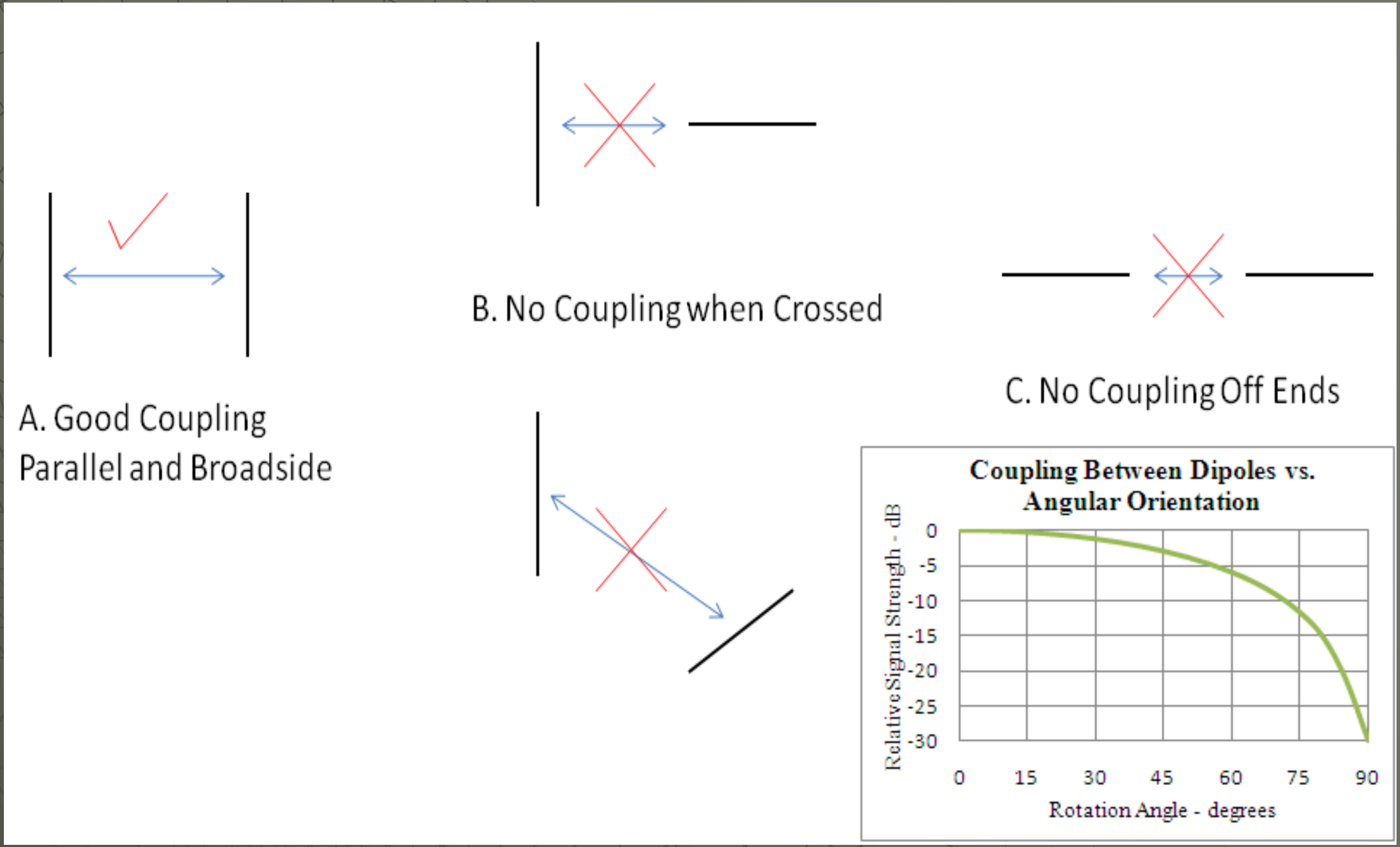


c) Farfield Visualization

Orientation:

A dipole radiates broadside, or radially to the dipole axis and has no radiation off the ends.

Dipole Orientation and Coupling

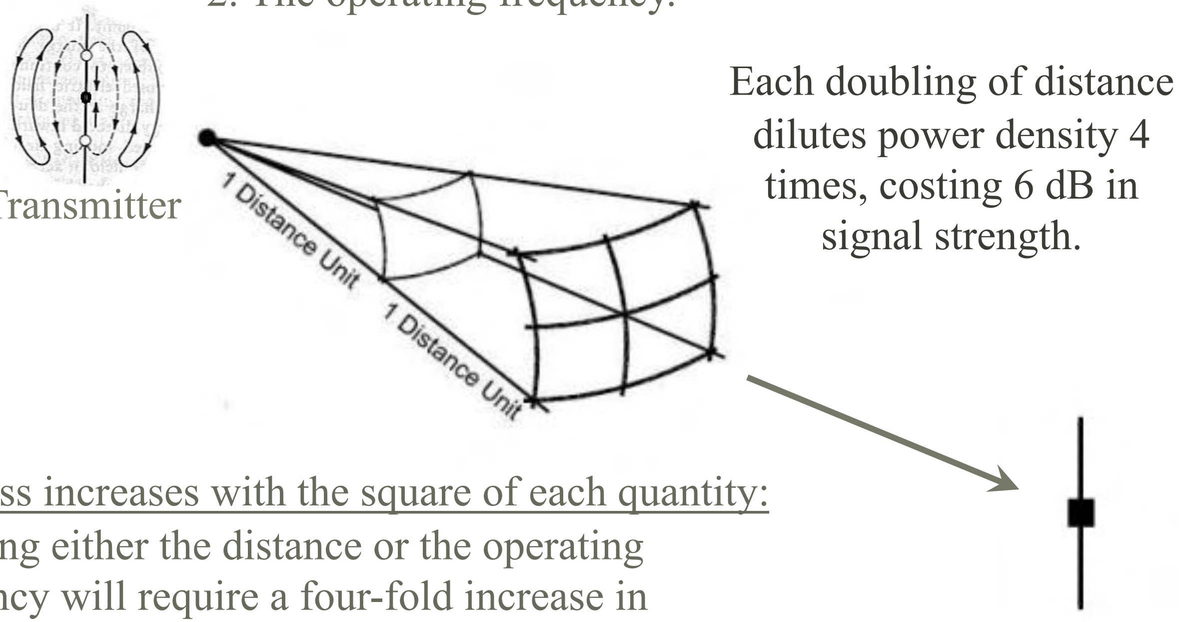


Dipole-dipole coupling demonstration

Line-of-sight Path Losses Between a Transmitter and Receiver

Two factors determine free space path loss:

1. The distance between the transmitter and receiver, and
2. The operating frequency.

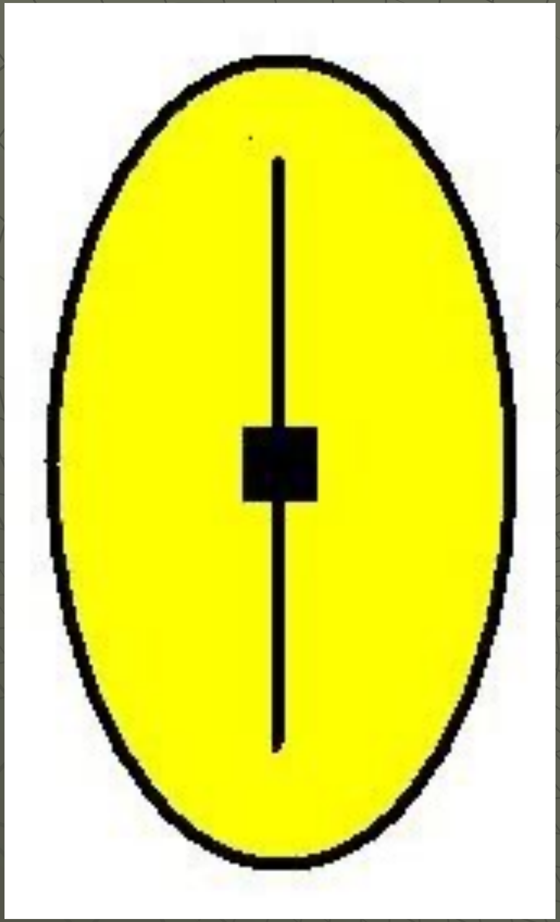


Each doubling of distance dilutes power density 4 times, costing 6 dB in signal strength.

Path loss increases with the square of each quantity:

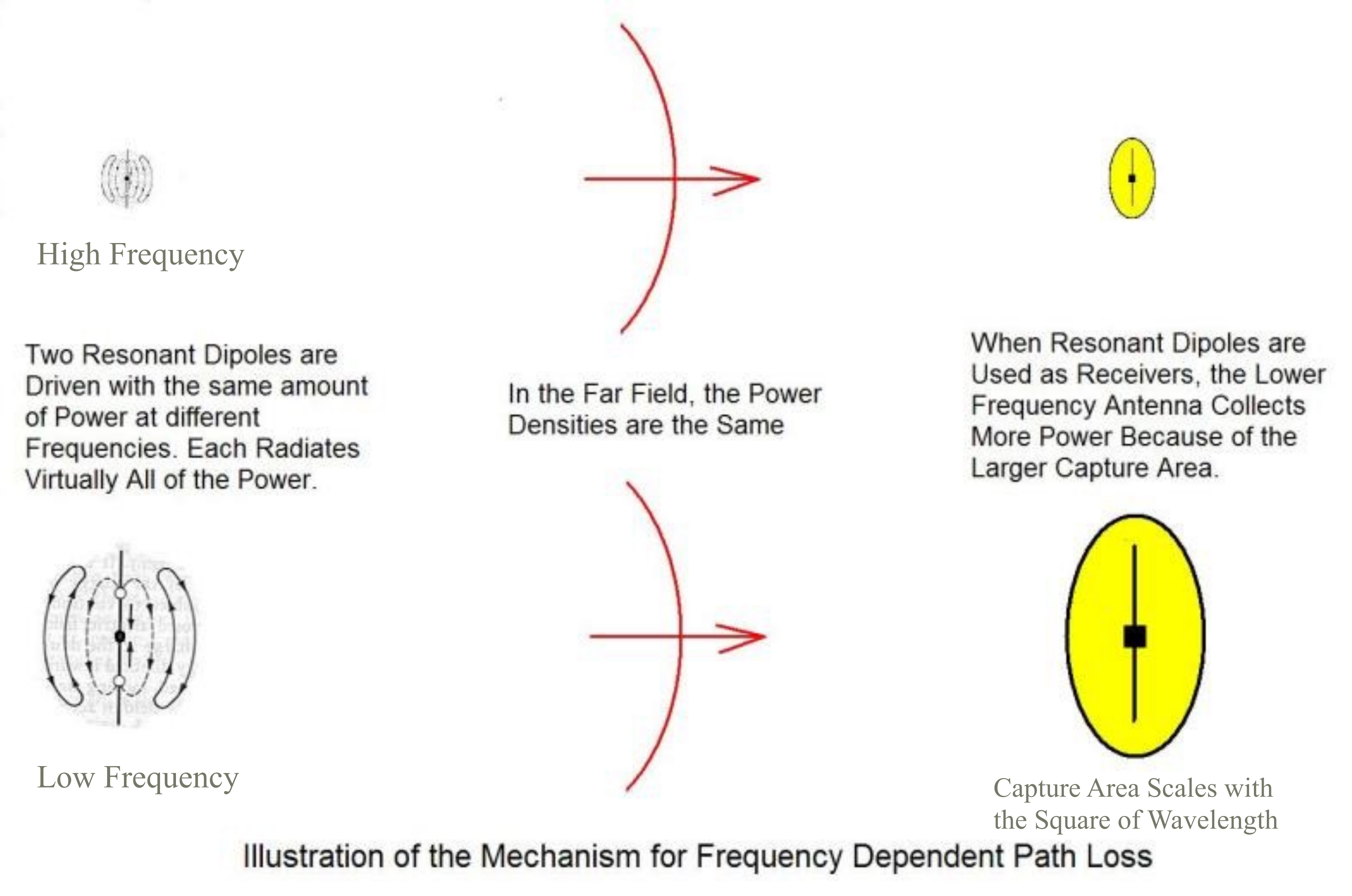
Doubling either the distance or the operating frequency will require a four-fold increase in transmitted power to maintain the same signal strength at the receiver.

The 20log(f) Term Arises from the Capture Area of the Dipole Used as Receive Antenna



- The Capture Area of a Dipole Antenna is an ellipse approximately ¾ wavelengths long by ¼ wavelength wide. Thus, the capture area scales directly with the square of wavelength or inversely with the square of frequency.
- Lower frequency antennas capture more power from the passing radio wave.

The 20 log(f) Path Loss Term from Frequency Effects Happens at the Receive End



High Frequency

Two Resonant Dipoles are Driven with the same amount of Power at different Frequencies. Each Radiates Virtually All of the Power.

Low Frequency

In the Far Field, the Power Densities are the Same

When Resonant Dipoles are Used as Receivers, the Lower Frequency Antenna Collects More Power Because of the Larger Capture Area.

Capture Area Scales with the Square of Wavelength

Illustration of the Mechanism for Frequency Dependent Path Loss

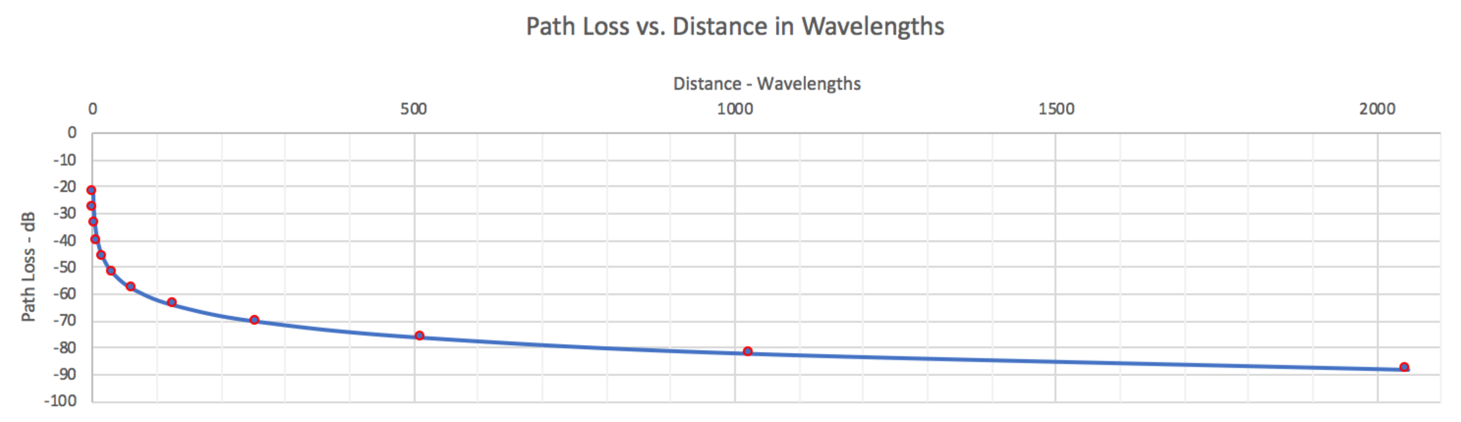
Demonstrate frequency-dependent signal strength

Simplified Path Loss Calculation For Line-of-Sight Links

Rule of thumb:
The signal drops off 22dB in the first wavelength from the antenna, then 6dB more every time the distance doubles.

λ: 22dB
2λ: 28
4λ: 34
8λ: 40
16λ: 46
32λ: 52
64λ: 58
128λ: 64

256λ: 70dB
512λ: 76
1024λ: 82
2048λ: 88
4096λ: 94
8192λ: 100
16384λ: 106
32768λ: 112



As transmitter and receiver get farther apart the 6 dB per distance doubling adds up FAST at first. But then those factors of two in distance start getting long. Example: once you go ¼ million miles to the moon, its only 6 dB to go another ¼ million miles.

Diffraction Can Allow Propagation Beyond Mountains and Buildings

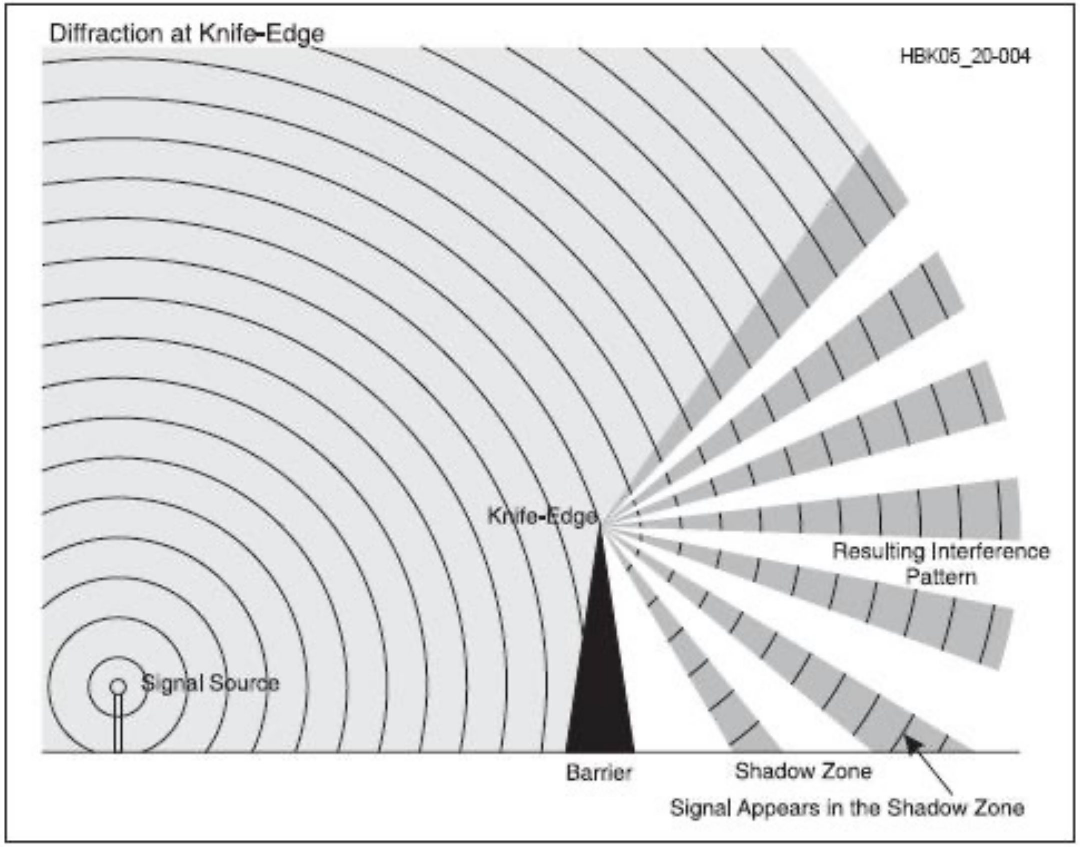
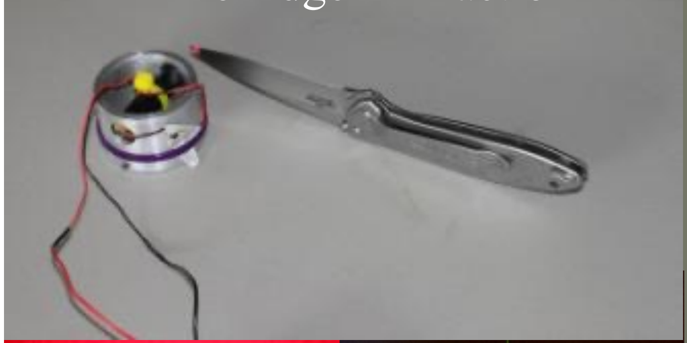
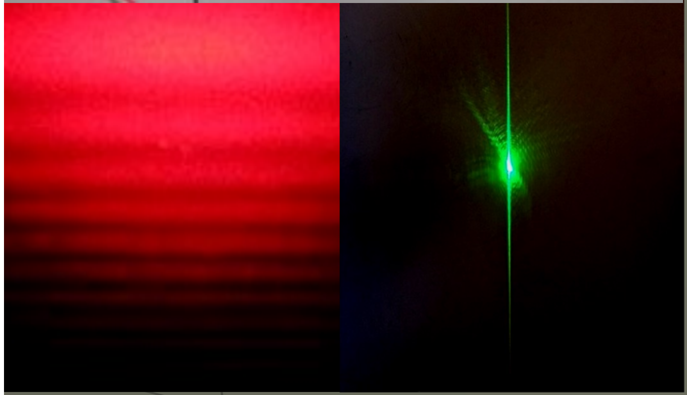


Fig 20.4—Radio, light and other waves are diffracted around the sharp edge of a solid object that is large in terms of wavelengths. Diffraction results from interference between waves right at the knife-edge and those that are passing above it. Some signals appear behind the knife-edge as a consequence of the interference pattern. Hills or mountains can serve as natural knife-edges at radio frequencies.

Setup to Demonstrate Optical Knife-Edge Diffraction

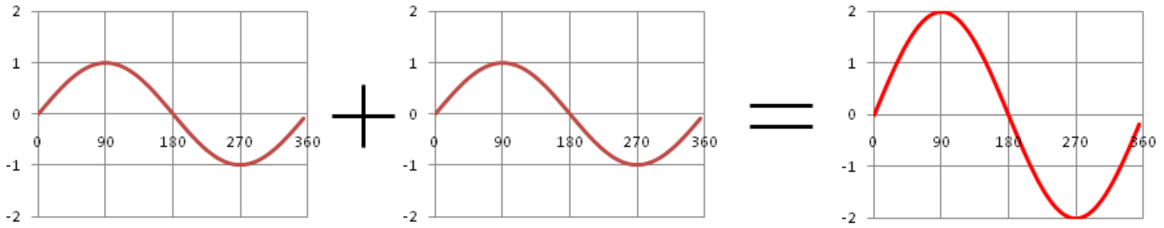




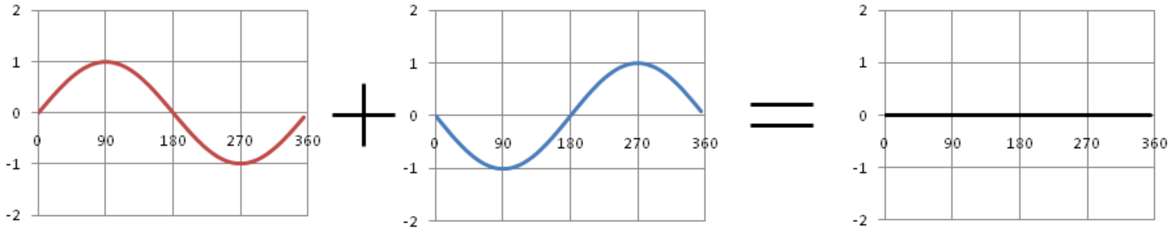
Optical Knife-Edge Diffraction Patterns

Demonstrate knife edge diffraction with laser and razor blade

Multipath Interference in Cluttered Environments Distributes Signal Energy into Complex Patterns



A. Two Equal Amplitude Waves Arriving In-Phase sum to Twice Amplitude

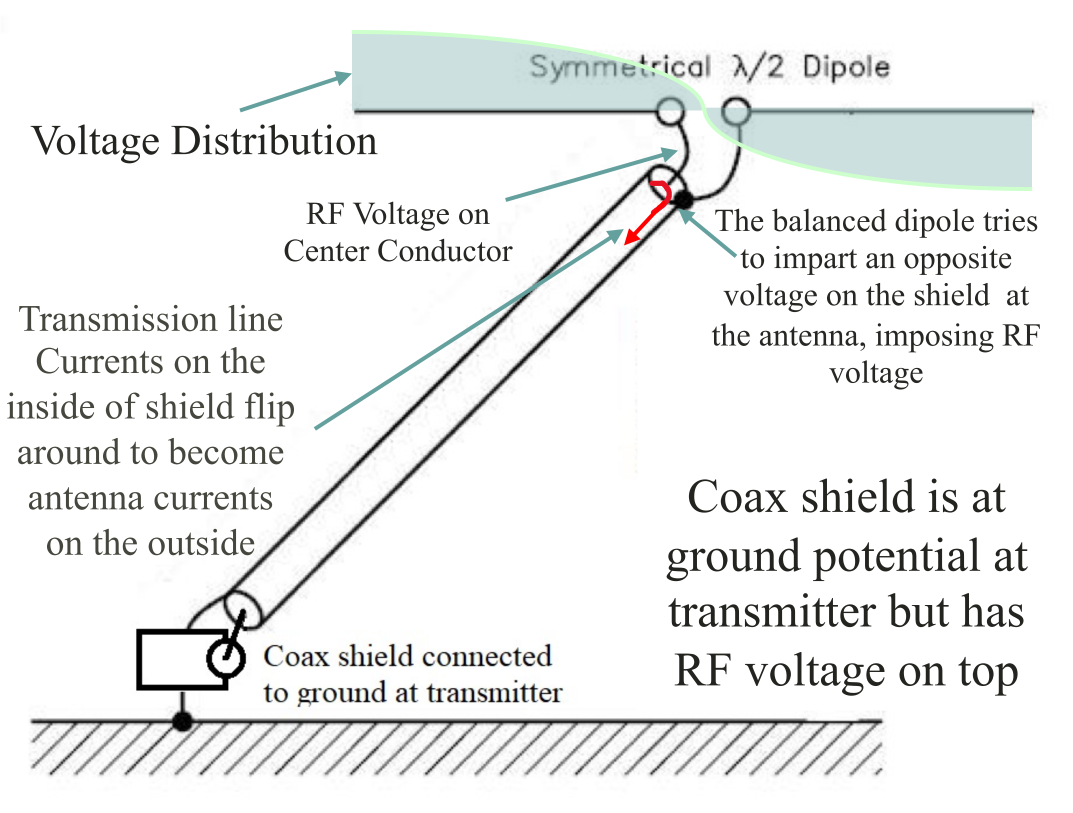


B. Two Equal Amplitude Waves Arriving Out-of-Phase sum to Zero

Optical Multipath Interference Analogy

Demonstrate Optical Interference Pattern

The Simplest Feed Method: Break the Dipole in the Center and Feed Directly with Coax. But what's Wrong with this Picture?



Transmission line Currents on the inside of shield flip around to become antenna currents on the outside

The balanced dipole tries to impart an opposite voltage on the shield at the antenna, imposing RF voltage

Coax shield connected to ground at transmitter

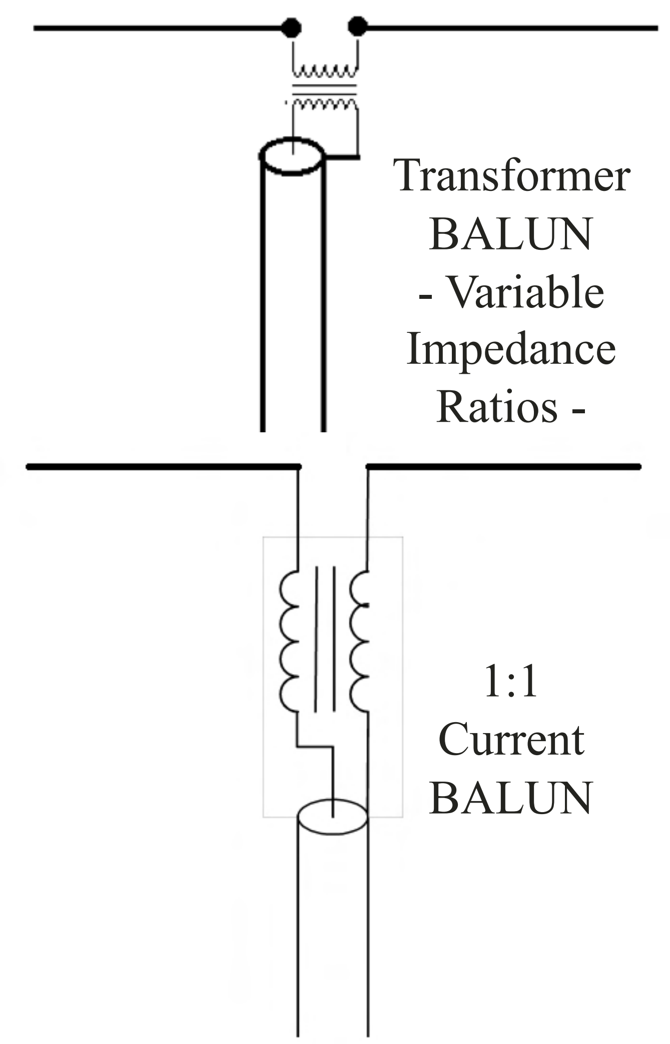
Coax shield is at ground potential at transmitter but has RF voltage on top

This feed method will work most of the time but makes the outside of the shield part of the antenna. This can cause problems with unwanted radiation to and from the feedline.

BALUNS: BALanced to UNbalanced Conversions

- BALUN is a contrived word consisting of the first letters of “BALanced” and “UNbalanced”.
- It is used in antennas to strip antenna currents from the outside of coax feed lines.
- It converts an unbalanced circuit having one grounded and one hot side to a balanced circuit having equal and opposite hot sides.
- BALUNs may be made to perform impedance transformations as well.
- BALUNs can operate on current or voltage and can be resonant or broadband.

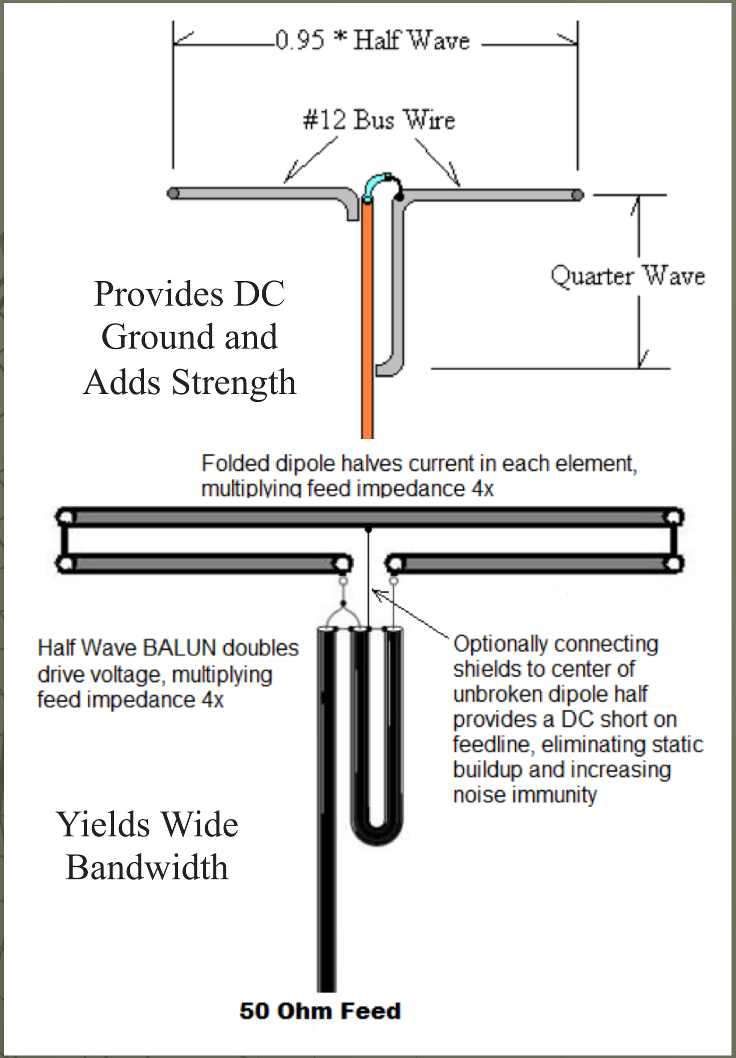
Common BALUN Topologies



Transformer BALUN - Variable Impedance Ratios -

1:1 Current BALUN

Available as Surface Mount Parts



Provides DC Ground and Adds Strength

Folded dipole halves current in each element, multiplying feed impedance 4x

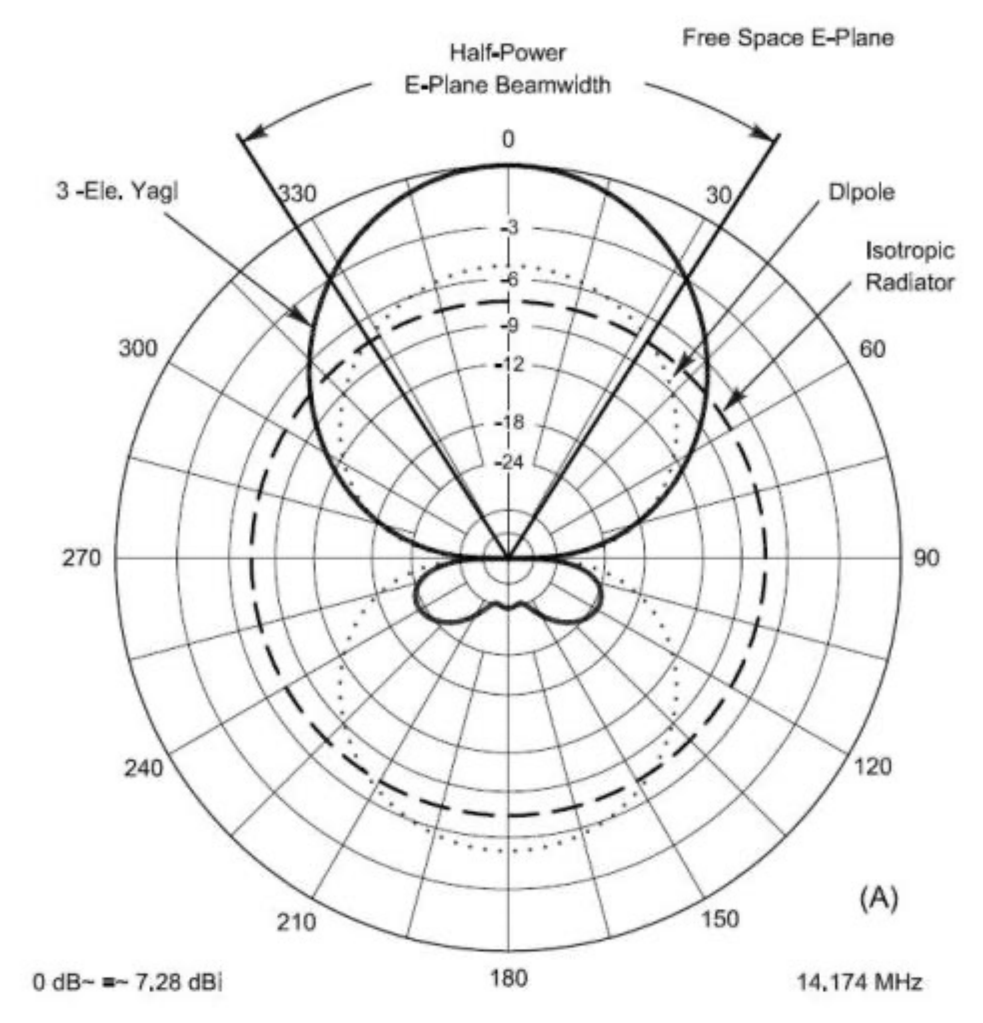
Half Wave BALUN doubles drive voltage, multiplying feed impedance 4x

Optionally connecting shields to center of unbroken dipole half provides a DC short on feedline, eliminating static buildup and increasing noise immunity

Yields Wide Bandwidth

Transmission Line BALUNs

The Isotropic Radiator and the Concept of Gain

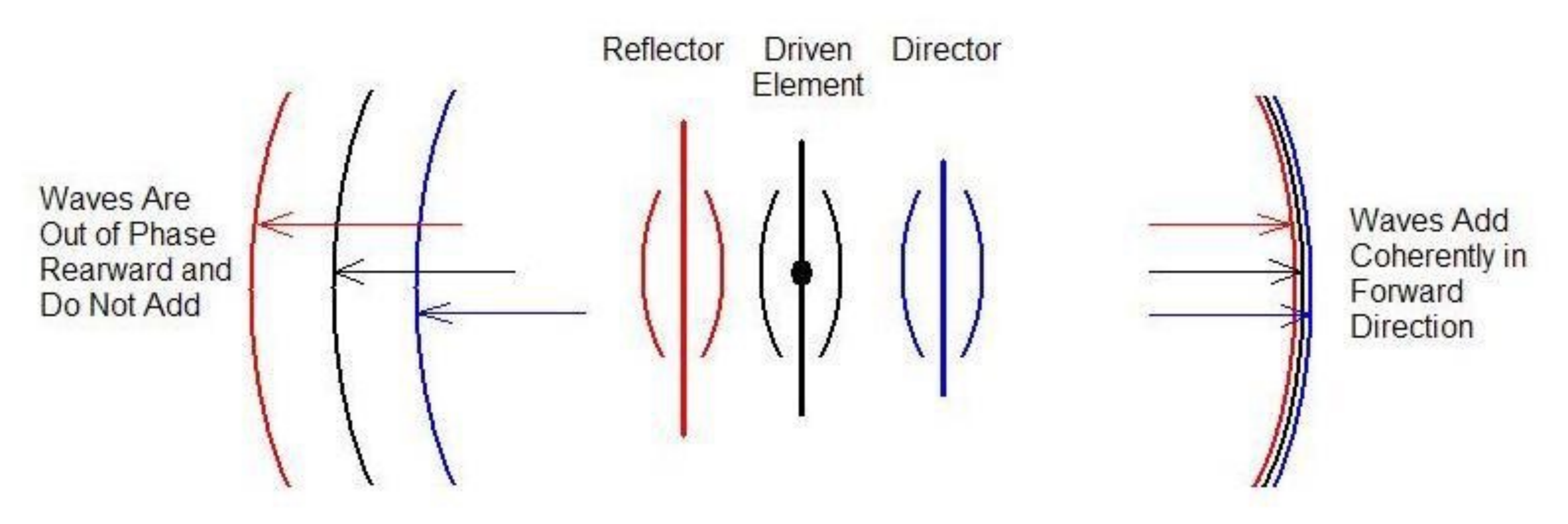


An antenna cannot radiate more power than is applied to it, but it can concentrate power in one direction at the expense of others. This is called directivity and is what makes gain. Shown here are the radiation patterns of an isotropic radiator, a dipole, and a gain-producing Yagi.

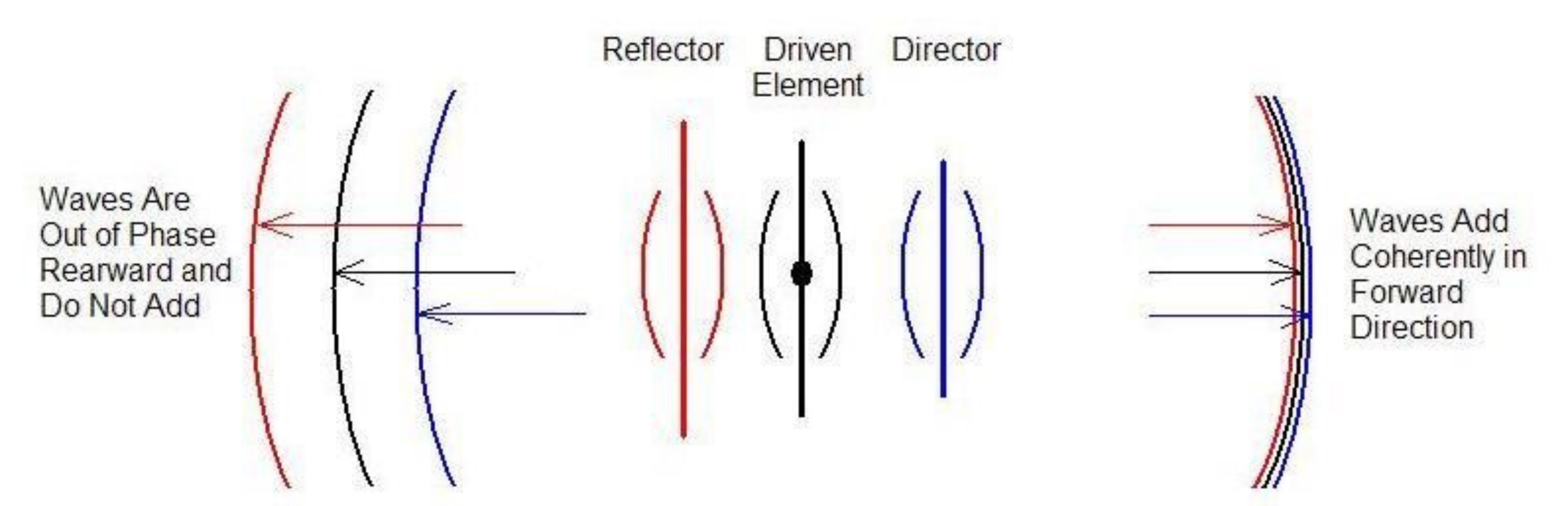
An Isotropic Radiator is a notional concept for an infinitely small radiator that radiates equally well in all directions – i.e., in a perfect sphere. None exist in the real world, but the concept serves as a valuable common point of reference.

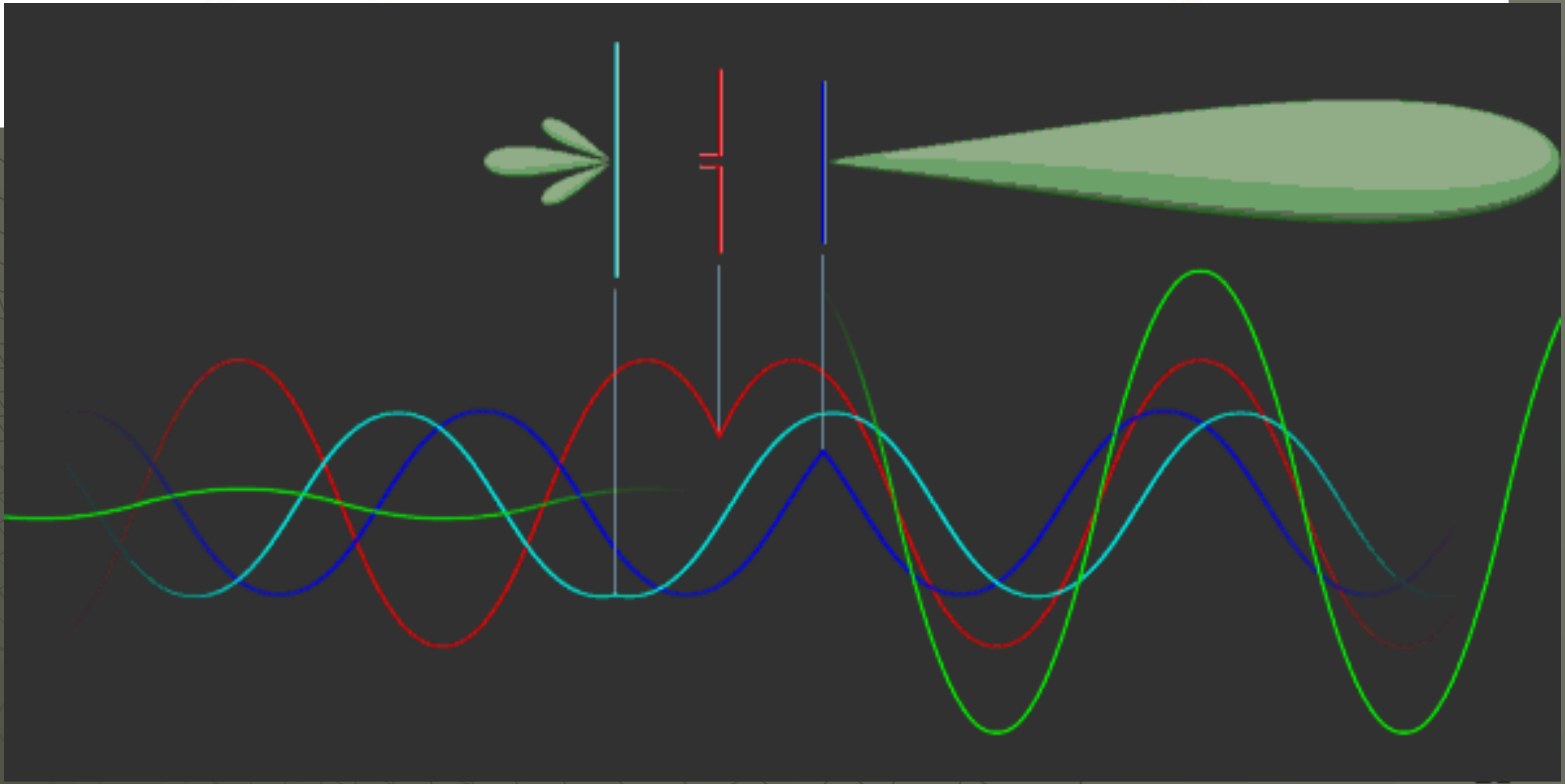
Mag Light Demonstration

Operating Principle of a Yagi Beam Antenna

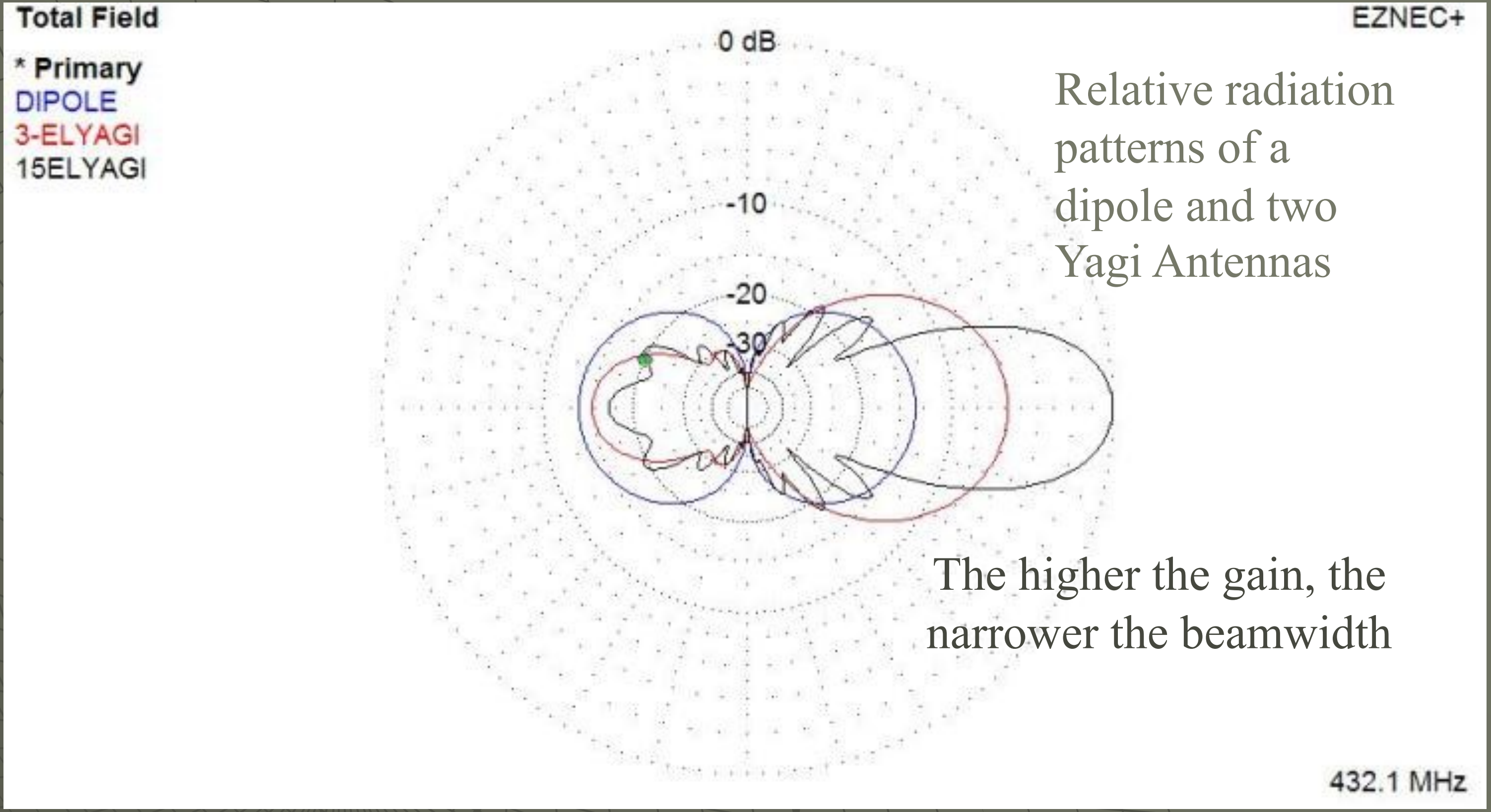


1. The resonant driven element radiates an electromagnetic wave in all directions.
2. The Reflector and Director parasitic elements absorb and reradiate energy in all directions with high efficiency.
3. The Reflector is longer than the resonant length causing it to have inductive reactance. This induces a phase lead in the reradiation, allowing it to “catch up” to the wave from the Driven Element in the forward direction.
4. The Director is shorter than the resonant length causing it to have capacitive reactance. This induces a phase lag in the reradiation, retarding the reradiation to align with the wave from the Driven Element in the forward direction.
5. Wavefront reinforcement occurs only in one direction, giving the antenna directivity and gain.


Reflector
Driven Element
Director
Waves Are Out of Phase Rearward and Do Not Add
Waves Add Coherently in Forward Direction



Gain and Directivity



Relative radiation patterns of a dipole and two Yagi Antennas

The higher the gain, the narrower the beamwidth

Gain cannot be produced without directivity. The more gain an antenna has, the narrower the beamwidth must become. High gain antennas have narrow beamwidths and require accurate pointing. Unfortunately, the converse is not true and losses in the antenna structure and feedline can result in directivity without gain.

Yagi Gain Is a Function of Boom Length

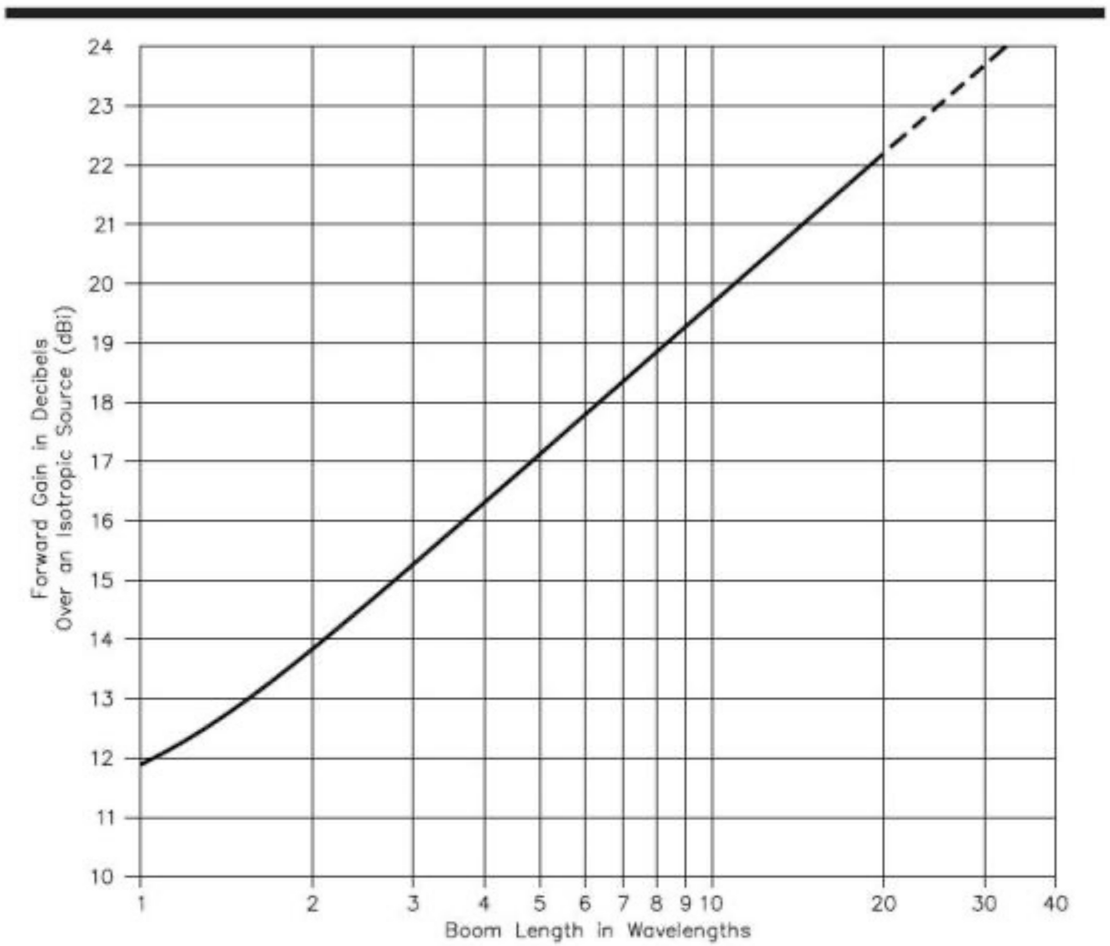
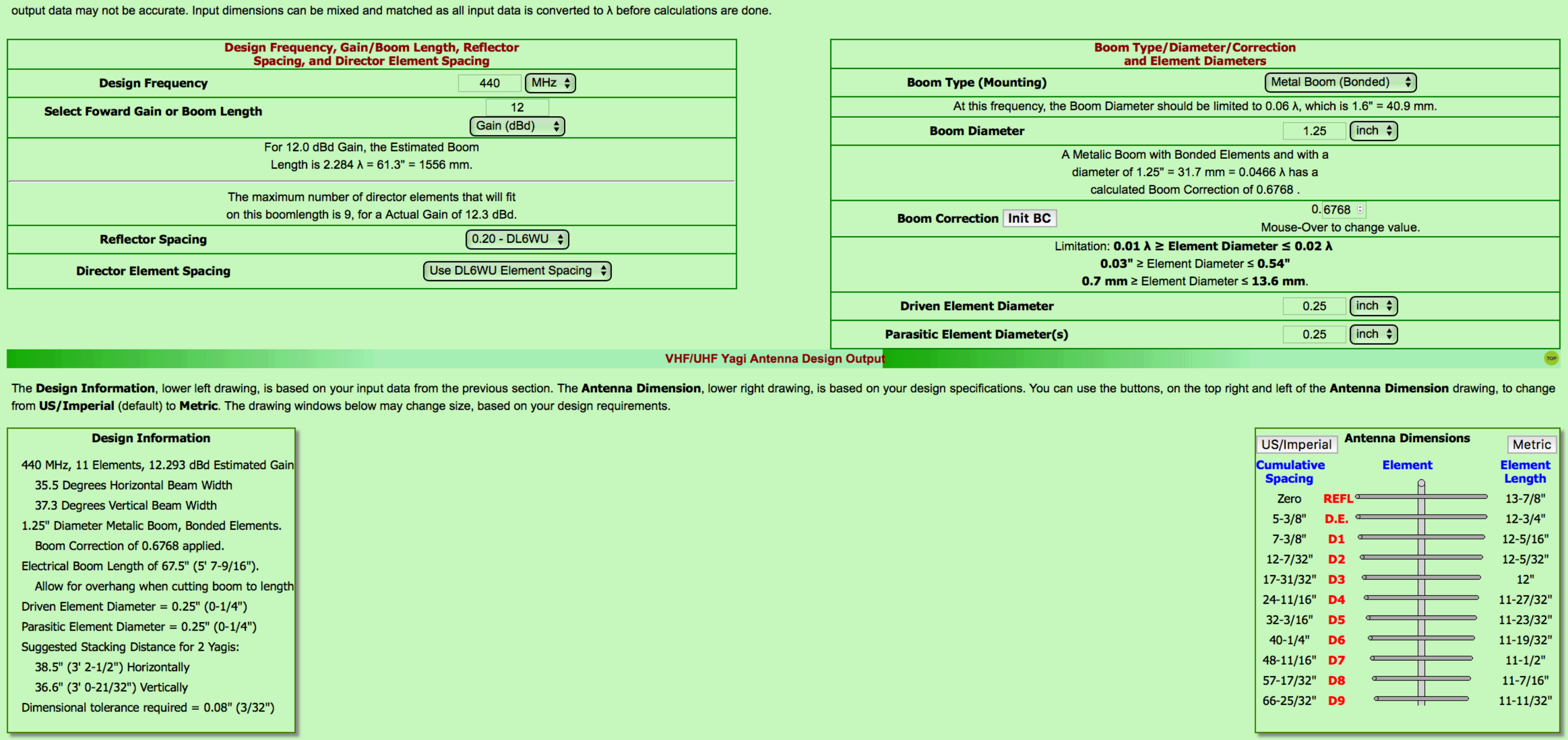


Fig 37—This chart shows maximum gain per boom length for optimally designed long Yagi antennas.

Careful design and tuning can yield Yagi antennas with gains approaching 20dB. Gain increases 2-3 dB each time Boom Length Doubles.

K7MEM Online Yagi Calculator



VHF/UHF Yagi Antenna Design Input

Use the following entry areas to define your antenna requirements. Specifying a Gain > 21.6 dBd or a Boom Length > 39 λ will limit the design to 21.6 dBd Gain and Boom Length to 39 λ. The page will operate below the lower limits, 11.8 dBd of gain and and 2.2 λ Boom Length, but the output data may not be accurate. Input dimensions can be mixed and matched as all input data is converted to λ before calculations are done.

Design Frequency, Gain/Boom Length, Reflector Spacing, and Director Element Spacing

Design Frequency 440 MHz

Select Foward Gain or Boom Length 12 Gain (dBd)

For 12.0 dBd Gain, the Estimated Boom Length is 2.284 λ = 61.3" = 1556 mm.

The maximum number of director elements that will fit on this boomlength is 9, for a Actual Gain of 12.3 dBd.

Reflector Spacing 0.20 - DL6WU

Director Element Spacing Use DL6WU Element Spacing

Boom Type/Diameter/Correction and Element Diameters

Boom Type (Mounting) Metal Boom (Bonded)

At this frequency, the Boom Diameter should be limited to 0.06 λ, which is 1.6" = 40.9 mm.

Boom Diameter 1.25 inch

A Metalic Boom with Bonded Elements and with a diameter of 1.25" = 31.7 mm = 0.0466 λ has a calculated Boom Correction of 0.6768 .

Boom Correction Init BC 0.6768 Mouse-Over to change value.

Limitation: **0.01 λ ≥ Element Diameter ≤ 0.02 λ**
0.03" ≥ Element Diameter ≤ **0.54"**
0.7 mm ≥ Element Diameter ≤ **13.6 mm**.

Driven Element Diameter 0.25 inch

Parasitic Element Diameter(s) 0.25 inch

VHF/UHF Yagi Antenna Design Output

The **Design Information**, lower left drawing, is based on your input data from the previous section. The **Antenna Dimension**, lower right drawing, is based on your design specifications. You can use the buttons, on the top right and left of the **Antenna Dimension** drawing, to change from **US/Imperial** (default) to **Metric**. The drawing windows below may change size, based on your design requirements.

Design Information

440 MHz, 11 Elements, 12.293 dBd Estimated Gain
35.5 Degrees Horizontal Beam Width
37.3 Degrees Vertical Beam Width
1.25" Diameter Metalic Boom, Bonded Elements.
Boom Correction of 0.6768 applied.
Electrical Boom Length of 67.5" (5' 7-9/16").
Allow for overhang when cutting boom to length
Driven Element Diameter = 0.25" (0-1/4")
Parasitic Element Diameter = 0.25" (0-1/4")
Suggested Stacking Distance for 2 Yagis:
38.5" (3' 2-1/2") Horizontally
36.6" (3' 0-21/32") Vertically
Dimensional tolerance required = 0.08" (3/32")

Antenna Dimensions

Cumulative Spacing	Element	Element Length
Zero	REFL	13-7/8"
5-3/8"	D.E.	12-3/4"
7-3/8"	D1	12-5/16"
12-7/32"	D2	12-5/32"
17-31/32"	D3	12"
24-11/16"	D4	11-27/32"
32-3/16"	D5	11-23/32"
40-1/4"	D6	11-19/32"
48-11/16"	D7	11-1/2"
57-17/32"	D8	11-7/16"
66-25/32"	D9	11-11/32"

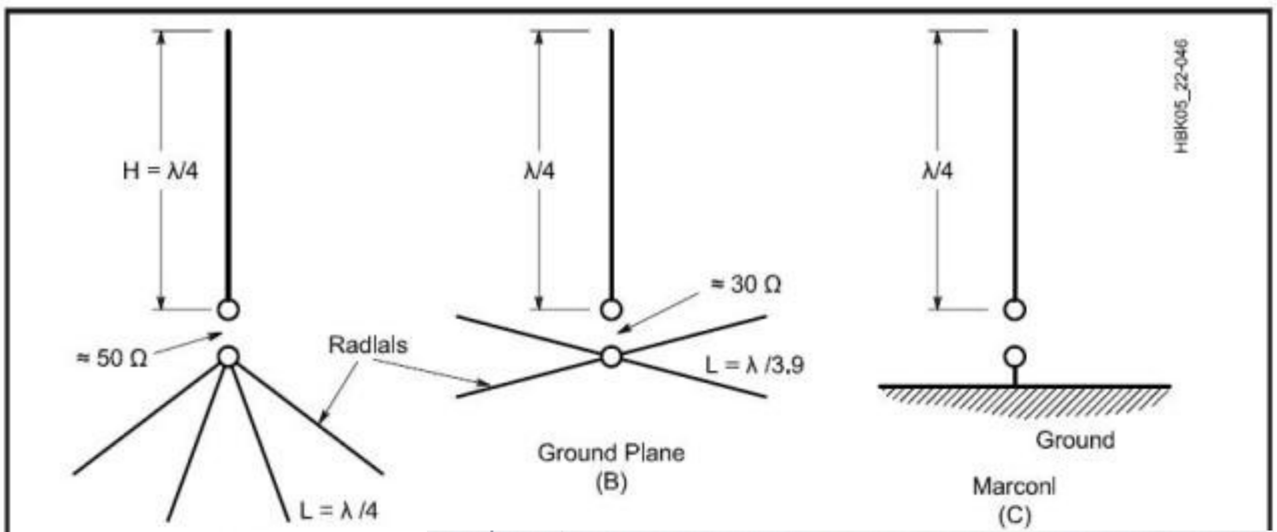
Yagis Aren’t Just for 2 meters!

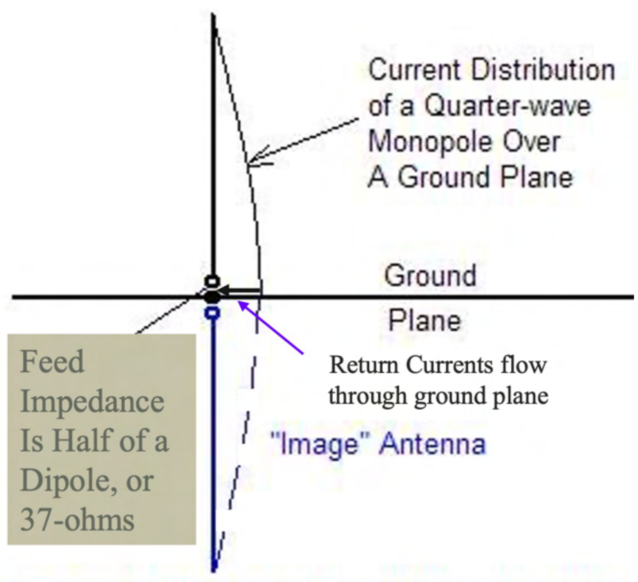
HIROSHIMA JAPAN

3.5/3.8MHz FULL SIZE 5EL
1.9MHz 1/2 λ DP 60mH
(Length of the boom 42m)

7J4AAL

Monopole Antennas Consist of a Quarter Wave Radiator and a Counterpoise





Feed Impedance Is Half of a Dipole, or 37-ohms

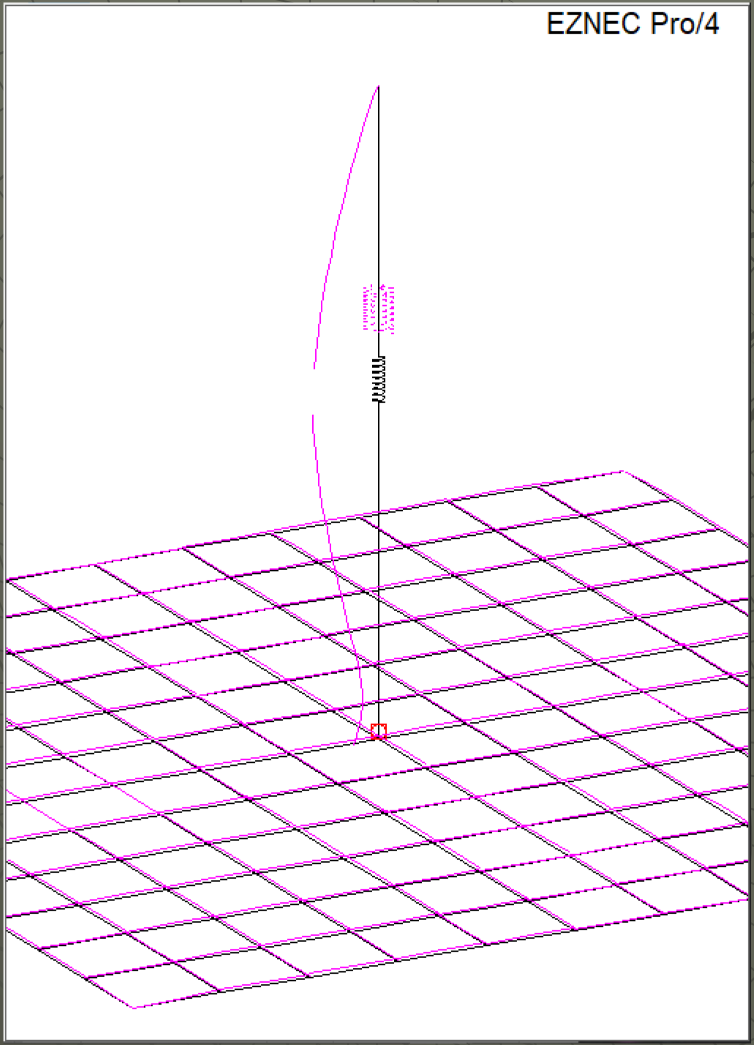
Vehicle Counterpoise for HF, VHF, and UHF

Gain Producing Dual Banders

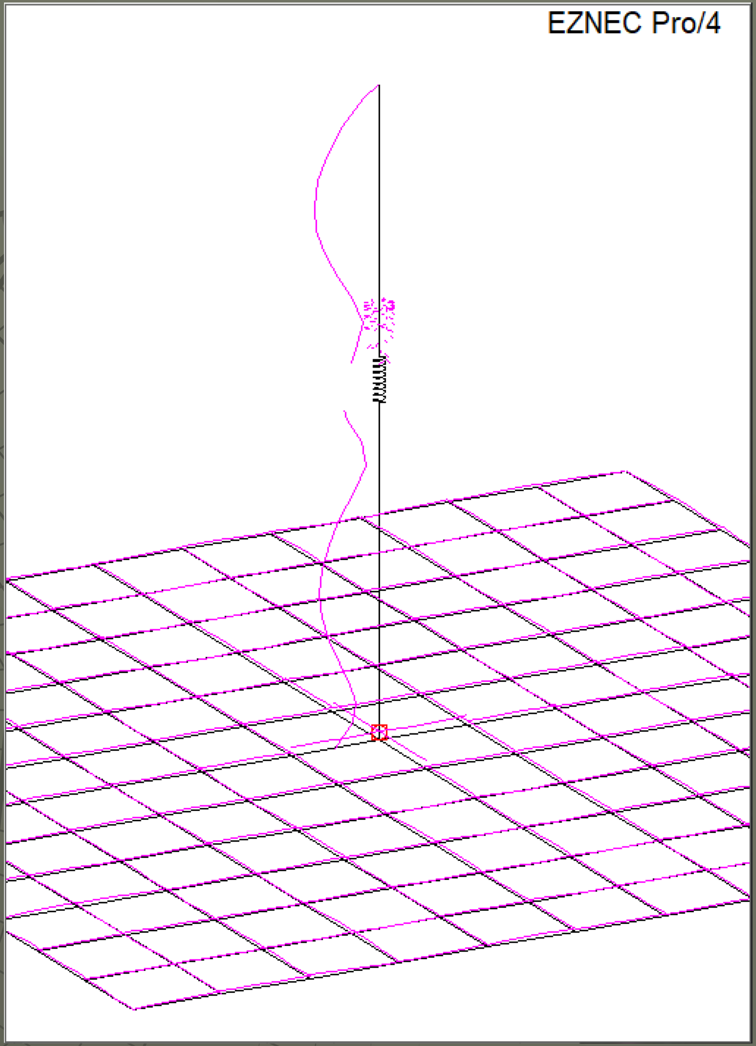
Diamond SG-7500A

Larsen NMO 2/70

Dual Modes and Bands with Center Loading Coil

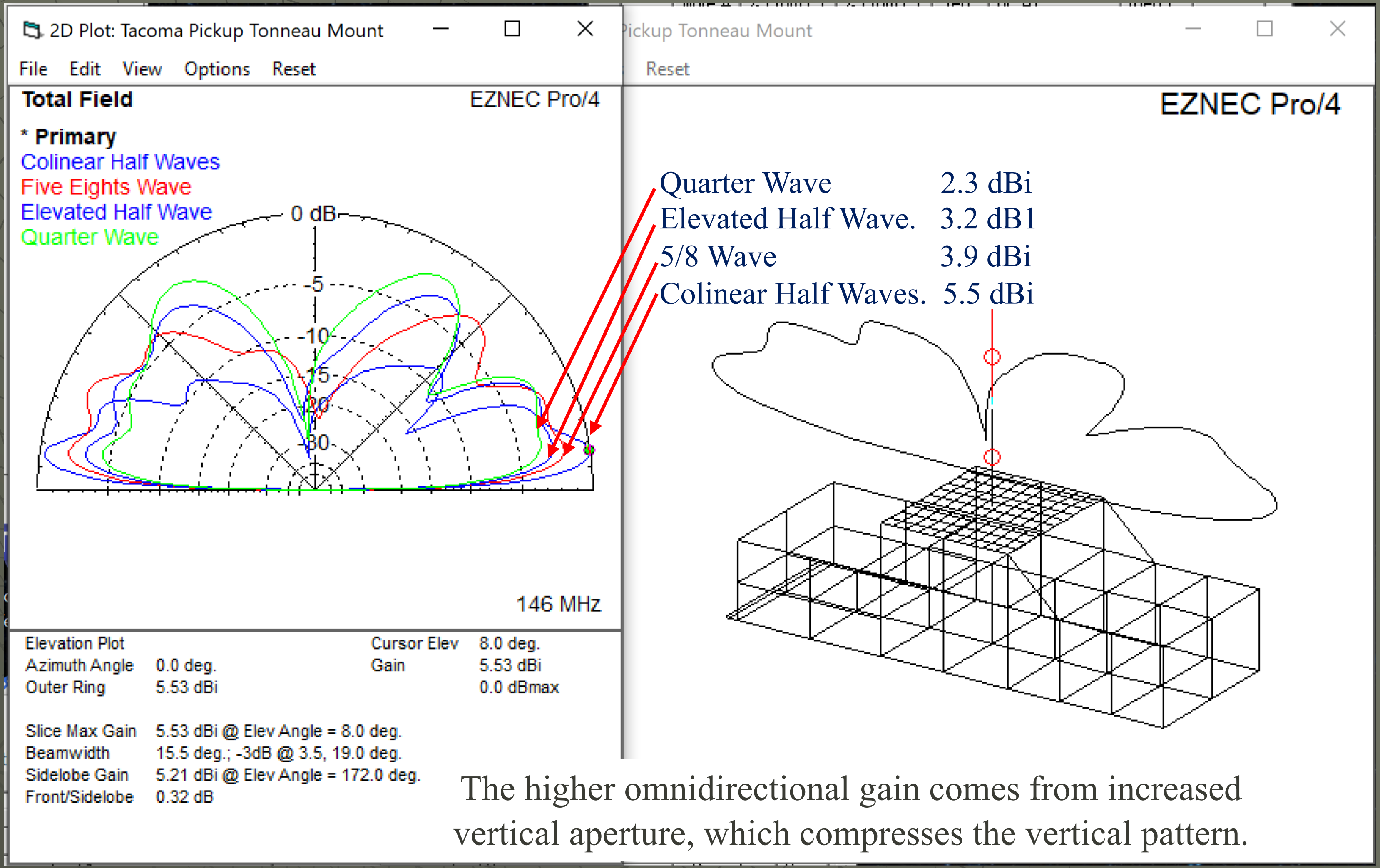


2m: Elevated End-Fed half Wave



70 cm: Two 5/8-Wave In-Phase

Elevation Patterns of Various Roof Mounted Antennas



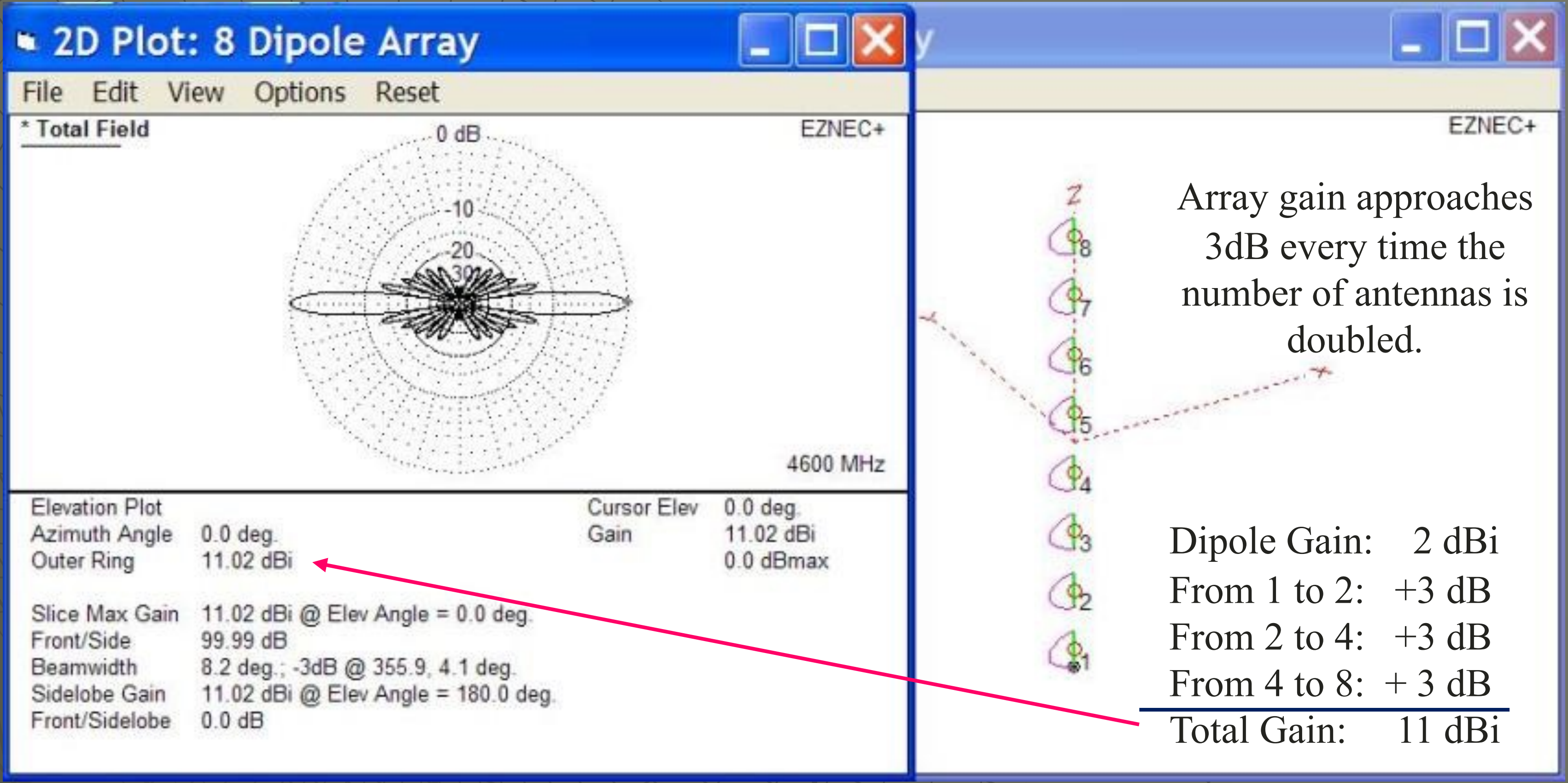
```
Elevation Plot                          Cursor Elev    8.0 deg.
Azimuth Angle     0.0 deg.              Gain           5.53 dBi
Outer Ring        5.53 dBi                             0.0 dBmax

Slice Max Gain    5.53 dBi @ Elev Angle = 8.0 deg.
Beamwidth         15.5 deg.; -3dB @ 3.5, 19.0 deg.
Sidelobe Gain     5.21 dBi @ Elev Angle = 172.0 deg.
Front/Sidelobe    0.32 dB
```

Quarter Wave	2.3 dBi
Elevated Half Wave.	3.2 dB1
5/8 Wave	3.9 dBi
Colinear Half Waves.	5.5 dBi

The higher omnidirectional gain comes from increased vertical aperture, which compresses the vertical pattern.

Stacking Radiating Elements Vertically Compresses the Vertical Pattern and Giving Significant Omnidirectional Gain in Azimuth



```
Elevation Plot                                   Cursor Elev   0.0 deg.
Azimuth Angle    0.0 deg.                        Gain          11.02 dBi
Outer Ring       11.02 dBi                                     0.0 dBmax

Slice Max Gain   11.02 dBi @ Elev Angle = 0.0 deg.
Front/Side       99.99 dB
Beamwidth        8.2 deg.; -3dB @ 355.9, 4.1 deg.
Sidelobe Gain    11.02 dBi @ Elev Angle = 180.0 deg.
Front/Sidelobe   0.0 dB
```

Array gain approaches 3dB every time the number of antennas is doubled.

Dipole Gain: 2 dBi
From 1 to 2: +3 dB
From 2 to 4: +3 dB
From 4 to 8: + 3 dB

Total Gain: 11 dBi

These antennas are common for police, fire, EMS, etc., base stations where high gain omnidirectional operation is required. Most FM and TV broadcast stations use a combination of transmitter power and antenna gain to achieve their large EIRP

Attenuation Rates for CommonTransmission Lines

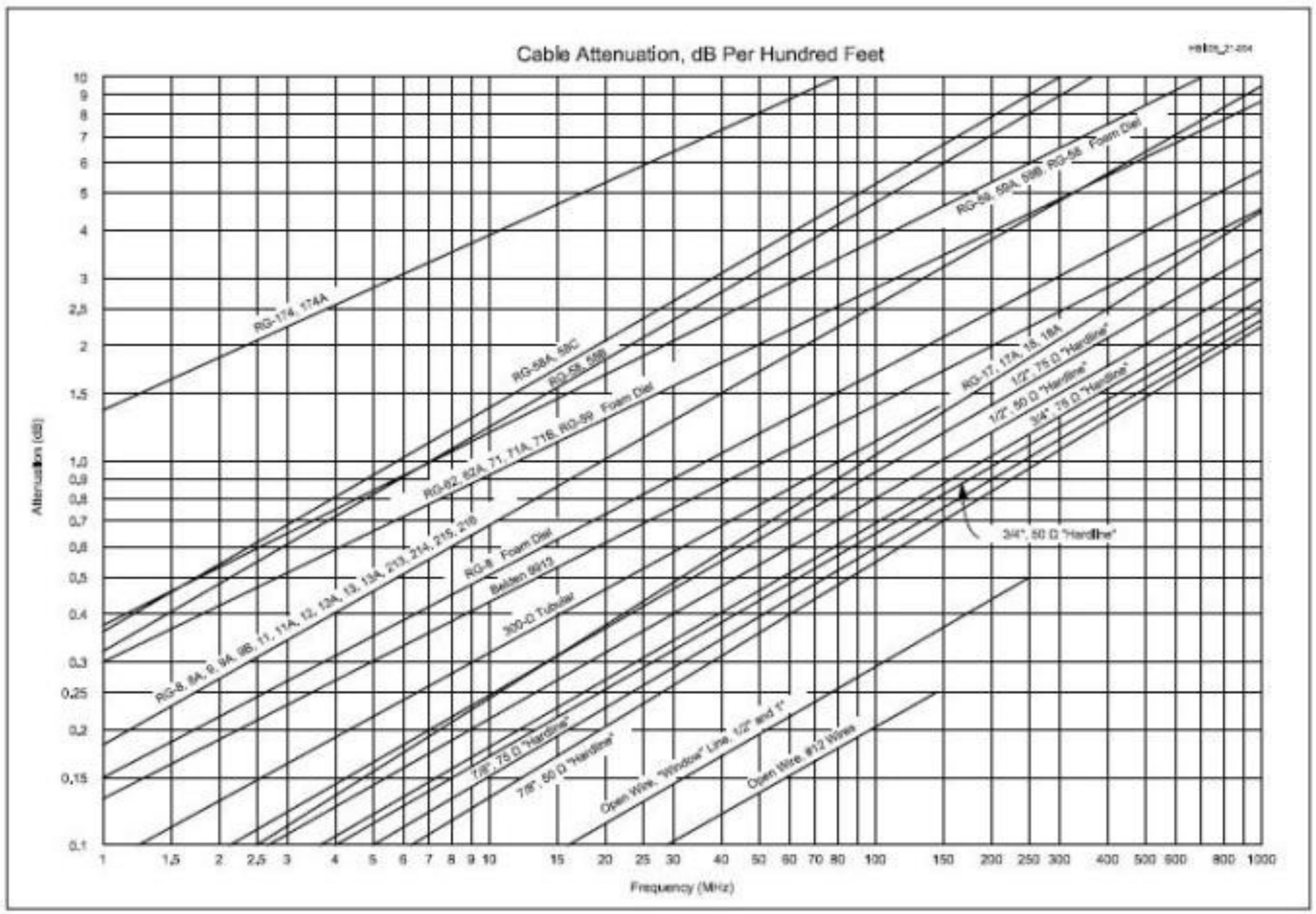
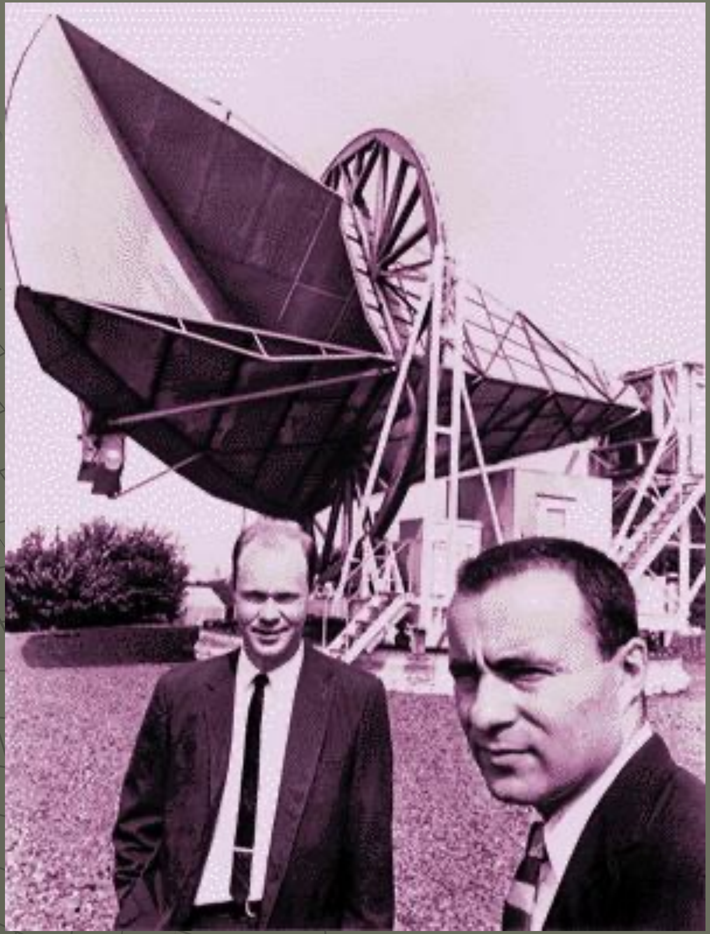


Fig 21.4—This graph displays the matched-line attenuation in decibels per 100 ft for many popular transmission lines. The vertical axis represents attenuation and the horizontal axis frequency. Note that these loss figures are only accurate for properly matched transmission lines.

Transmission line loss can seriously deteriorate station performance. A goal would be to lose no more than 10% range, which would require no more than 1 dB of transmission line loss. If the loss were 3 dB, only half the transmitter power would make it to the antenna.

Coax Cable Loss Demonstration

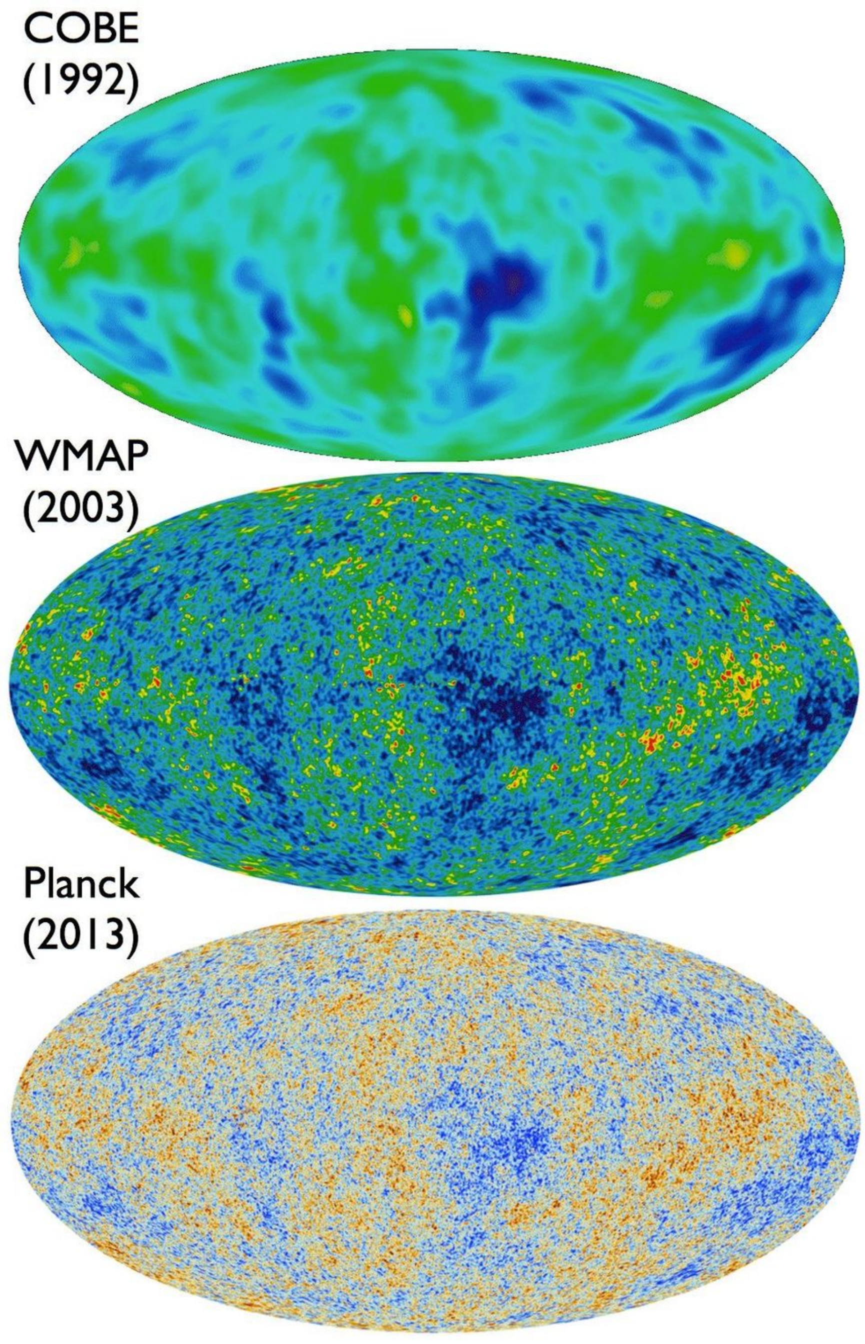
Big Things Can Come from Big Antennas



This is the horn antenna used by Wilson and Penzias to discover the cosmic background radiation.

The discovery confirmed the big bang theory, changed forever our understanding of the universe, and won them a Nobel Prize.

Successively Finer Resolution CMB Images Provided by Satellite Radiometers



1. Cosmic Background Explorer
2. Wilkinson Microwave Anisotropy Probe
3. Planck Satellite

Annoying Things Can Come from Big Antennas Too: The Duga OTH Radar Antenna

Antenna of the Infamous Russian Woodpecker
150m High x 700m Long (492 x 2296 ft.)