Amateur Radio Antenna Systems

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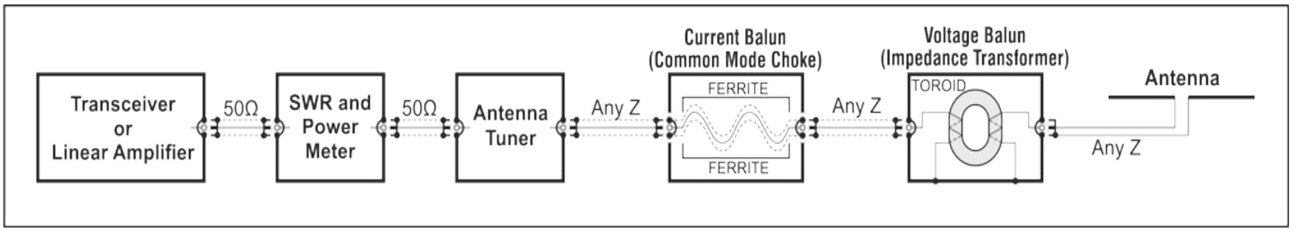


Example of an Antenna System

A. General

To clear things up right from the start: I have been a radio amateur for over 50 years and professionally I'm an electronics designer. Got my degree in radio and TV systems in 1970. There is more info about my current ham situation on qrz.com page: https://www.qrz.com/db/sv9rmu .

By an "antenna system" I mean everything between transceiver's or linear amplifier's antenna connector and the antenna, including SWR/power meter, feed line, antenna matching system (tuner), balun(s), the antenna itself and all connections between different equipment and parts. You may not have or need all the parts in the example drawing above. Or you may have some additional equipment.

I have tried to collect in this document practical information and personal experiences about antenna systems. I am also trying to clear up some common misunderstandings regarding antenna systems. I am not going too deep into the finer aspects of antenna design and try to keep the mathematics at its minimum and as simple as possible.

It seems that in some parts of ham radio community, misconceptions about antennas and antenna systems are abundant. For some reason a more or less functional antenna system of one station is taken as a universal rule. Most of the time those "rules" apply only to that particular station's antenna system. In general an antenna lay-out of one ham station cannot be directly copied to another station because of different surroundings, equipment, materials etc. *So, one **must always** apply the basic **scientifically proven technical facts** to one's own antenna system and then make adjustments as needed for that particular installation!*

There really is no mystery in antennas and antenna systems. They always work according to the laws of physics. One just has to know what those laws are. In this document I'm trying to explain some of the most important basics for antennas and antenna systems.

Please forget all the "suspicious information" available in internet or over the air and take the following explanations seriously. They are based on real (measured, when applicable) technical facts and supported by all ***reliable*** amateur radio and professional literature, like the RSGB and ARRL handbooks, and for instance ITT's "Reference Data for Radio Engineers" (published by Howard W. Sams & Co, USA). I have the 5th edition (1973) of that manual.

This document handles only HF, VHF and UHF antenna systems. The equipment, materials and construction techniques of microwave antenna systems differ significantly from the ones used on lower frequencies.

Note 1! All examples given in this document are in common use, but they DO NOT constitute a complete list of all possible solutions!

Note 2! As an electronics designer, I rely only on manufacturers' published specifications for all electronics, including everything related to antenna systems.

All photos and drawings in this document are just examples of different solutions. They are not the only ways to build or design those parts.

B. Antennas in general

B.1 First, some history

B.1.a Antennas

German physicist Heinrich Hertz built the first antennas in 1888 to prove the existence of waves, predicted in James Clerk Maxwell's electromagnetic theory from 1865. Hertz antennas were the first (non-resonant) dipoles or doublets. Hertz has been quoted of saying: "I do not think that the radio waves I have discovered will have any practical application". I think we all have a different opinion nowadays. From Hertz name comes the name ("hertz") and abbreviation ("Hz") for frequency. In English speaking countries "c/s" or "cycles-per-second" was used for frequency many decades ago, which is exactly the same as Hz. Also, until around 1960's wavelength was commonly used instead of frequency, especially in AM broadcast receivers.

From 1895 onwards Guglielmo Marconi started developing practical antennas for long-distance wireless telegraphy. His antennas were basically "monopoles" (sort of like modern verticals in the shape of "T") with multiple wires up in the air and real ground as counterpoise. Antenna theory has advanced considerably since the early days and modern antennas are not based on the early experiments.

B.1.b Transmitters

In the early days a spark gap across antenna terminals was used as transmitter. The high voltage arc generated a wide band of frequencies and the antenna itself determined (ie. "filtered") the "actual" transmit frequency. To make the spark electrodes last longer, rotary spark gaps were developed, which added modulation (single tone AM) to the transmitted signal. These had a rotating (motor driven) wheel of multiple spark electrodes and two stationary ones at opposite sides. Later various low Q L/C resonators were added to the circuit to determine the transmit frequency. The transmitted CW signals were very wide. -3 dB (half power) signal width was for instance ± 200 kHz from the centre frequency. Modern transmitters don't have anything to do with a spark gap transmitter.

The first sine wave (continuous carrier) transmitters were:
- 1910 Alexanderson Alternator: This is basically just an AC generator, which has a lot of poles to be able to output a VLF frequency. One of these transmitters is still now (2024) operational in Grimeton, Sweden, call sign SAQ. It was designed for 200 kW (!) output power. A few times each year the transmitter is switched on for sending special CW messages on 17.2 kHz. See https://alexander.n.se/en/ .
- 1920's vacuum valve transmitters: These were based in feedback oscillators using triode valves. They could be easily modulated to transmit audio signals (AM modulation).
- 1933 first license for an FM broadcasting station.
- Late 1930's first analogue B/W television stations on low VHF frequencies.

B.1.c Receivers

In the early days a "coherer" detector was used for receiving RF signals. It was based on the 1890 findings of Edouard Branly. The device consists of an insulator capsule (often glass) containing two electrodes with loose metal filings ("powder") in the space between. When an RF signal is applied to the device, the metal particles stick to each other or "cohere", reducing device's high initial resistance, so a much higher DC current can flow through it. The current would activate a bell or a paper tape recorder. Coherer's metal filings remained conductive after end of RF signal, so the device had to be "un-cohered" by mechanically tapping it. Coherers remained in widespread use until about 1907. Later more sensitive electrolytic or crystal detectors replaced the coherer detector. These early circuits were in a sense the original direct conversion receivers. Electronics and receiver technology have advanced immeasurably from the early systems and modern receivers don't have anything to do with those circuits.

B.1.d Some early milestones

January 1900: First ever practical radio link, established from Hogland island in the Gulf of Finland to Kuutsalo island near city of Kotka, Finland (distance about 40 km / 25 miles). Those days Finland was part of Russia. Both station equipment were built according to instructions of Russian physicist Alexander Popov. The transmitter was a spark gap one, of course.

Battleship "General-Admiral Apraksin" ran aground on Hogland island in November 1899. By the time the Apraksin was freed from the rocks by the end of April 1900, 440 official telegraph messages had been handled by the Hogland island wireless station. Besides the rescue of the Apraksin's crew, more than 50 Finnish fishermen, who were stranded on a piece of drift ice in the Gulf of Finland, were saved following distress messages sent by wireless telegraphy.

December 1901: First trans-Atlantic transmission by Guglielmo Marconi from Poldhu, Cornwall, England to Signal Hill, St. John's, Newfoundland, Canada.

April 1912: Sinking of ocean liner Titanic. The (spark gap) radio operators of Titanic were not at all interested in ice warnings sent by other ships (including the Carpathia and the Californian) and told them to "shut up". They were only handling paid messages from and to Titanic passengers. Those operators were working for the Marconi company, not for Titanic's owner, the Five Star Line.

December 11th, 1921: First trans-Atlantic ham radio transmission from 1BCG in Greenwich, Connecticut, USA to Ardrossan, Scotland. 1BGC used a transmitter with 990 W input power (probably around 450 W power output) on approximately 1.3 MHz (close to modern 160 m band).

April 11th, 1964: First fully successful trans-Atlantic 2-way amateur radio QSO via EME ("moon bounce", Earth-Moon-Earth) on 144 MHz (2 m band) between W6DNG, Long Beach, California, USA and OH1NL, Nakkila, Finland.

B.2 Some antenna system basics

Every radio operator (amateur and otherwise) needs an "antenna system" for converting the RF power generated by the transmitter to radiated RF energy, which can be received by other stations. Even a cell phone is a radio transceiver, but in that case the antenna is inside the handset. There are innumerable ways to build an antenna system and some of them are more efficient than others. In this case the efficiency means how much of transmitter's output power is actually radiated by the antenna. ***There are always some losses in the antenna system***:

- A good antenna system has an efficiency close to 100 % (usually around 98 %). So, for instance, from 100 W transmitter, 98 W is radiated by the antenna and only 2 W is lost, mostly as heat. In this case the antenna system losses are only -0.088 dB.
- A poor antenna system has much lower efficiency. For instance in a very bad case, from 100 W transmitter, 1 W is radiated by the antenna and 99 W is lost, mostly as heat. In this case the antenna system losses are very high at -20 dB.
- Note that the antenna system efficiency is the same in both directions, ie. for both receiving and transmitting.
- From the above one can see that antenna system's efficiency should always be as good as possible, but that depends on what you actually need. If you only want to contact some friends a few km or mi away and do not want to communicate with DX, it doesn't really matter how efficient your antenna system is.

Antenna system efficiency can be reduced by a lot of factors, including:

- Feed line's (often 50 ohm coaxial cable) inherent loss. This depends on cable type, cable length and operating frequency.
- Antenna system mis-match. If the antenna itself does not have 50 ohm resistive impedance (no reactance!), the antenna system must be matched so that the transmitter "sees" a 50 ohm resistive load. All the different matching circuits do have losses.
- Losses in the antenna itself. This can be caused for instance by poor quality or unsuitable materials, bad connections between different antenna parts, or even bad antenna design.
- Antenna's height above ground. If the antenna is less than say 1/4 wavelength above ground, the losses can be caused in two ways: 1) The "real" ground is always lossy, so some of the radiated RF power is lost as heat in the ground. 2) Antenna's maximum radiation is directed many degrees (say 15° ... 20°) above the horizon, which is not good at all for DX.
- Antenna's proximity to other conducting materials, like power and telephone lines, reinforcement steel embedded in concrete, metal roof, rain water gutter etc. Even tree branches are conductive, especially when wet. These will "suck in" some of antenna's radiated power.

- Although any of the separate losses above (and possibly others, too) may be quite low, when added together the total loss may be significant. For instance:
  - -1 dB total loss means that 20.6% (about 1/5) of the transmitter power is going somewhere else and is not radiated by the antenna.
  - -2 dB total loss means that 36.9% (over 1/3) of the transmitter power is going somewhere else and is not radiated by the antenna.
  - -3 dB total loss means that half (50%) of the transmitter power is going somewhere else and is not radiated by the antenna.

It seems to me that many radio amateurs have not grasped the basic principle for ***all*** antennas: For most efficient radiation of RF the ***antenna itself must be resonant***. For a ***resonant antenna the total length is always an <u>electrical</u> ½ wavelength***, or a multiple thereof. When an antenna is resonant, it does not have any reactance (±j = 0 ohm) at its feedpoint, and only impedance's resistive part (R ohms) is present. This is the most important factor for an efficiently radiating ***antenna***. The exact feedpoint resistance is not important. It can be from a few ohms to several 100's of ohms. Then, if needed, matching for instance to 50 ohm feed line can be easily done with an RF impedance transformer, often called a "balun" or "un-un". A couple of examples of resonant antennas:
- A centre fed dipole (or inverted V, as the case may be) must have exactly the same ***1/4 wave electrical length*** of wire (or other metal) to both sides from the feedpoint to make it resonant.
- A vertical antenna must be ***electrical 1/4 wave*** high and ***it must have*** four or more ***1/4 wave electrical length*** "radials" (= ***RF*** ground) from the feedpoint to form the other half of dipole and make it resonant.

The exact ***wavelength in free air or space*** can be calculated from the exact frequency as: **λ = v / f**, where:
- "λ" is the wavelength in meters.
- "v" is the propagation speed ("velocity") of RF in air and space. The speed is the speed of light, ie. 299'792'458 m/s (670'616'629.384 miles/hour). That is quite close to 300'000 km/s.
- "f" is the exact frequency in Hz (***not MHz!***).
- For antenna calculations the formula can be simplified to:
  - Wavelength in meters = **300 / MHz** with at least three (3) decimals
  - Wavelength in feet = **984 / MHz** with at least three (3) decimals
  - The resulting error is extremely small and has no significance for practical antenna design.
  - Note that the formulas above result in one full wavelength, so divide the result by 2 for instance for a dipole.

Electrical wavelength is not the same as RF signal's wavelength over the air! Every other medium, like antenna's wire, coaxial cable, ladder line etc. slows down the signal speed. The ***frequency*** remains always the same, which makes the wavelength shorter when measured in metres or feet. The difference between over-the-air wavelength and electrical wavelength is the medium's ***velocity factor*** and is expressed as a percentage or decimal number relative to the free air wavelength. The physical (= electrical) wavelength is needed for all kinds of antenna system calculations, like antenna element lengths, feedline lengths, tuning stub lengths and positions, feedline lengths for impedance matching sections etc. A couple of examples for some mediums:
- Free air and space: 100% or 1.00
- Dipole antenna's wire: approx. 95% or 0.95, but usually needs adjustment up or down.

As far as antennas themselves are concerned, in addition to the wavelength calculated from frequency, also many other factors affect the electrical length and position of their elements, like:
- Element thickness (in parts of wavelength).
- Proximity of other elements (reflector(s), director(s), elements for other bands) in multi-element antennas.
- Element installation method to boom (insulated, connected, through boom etc.).
- Proximity to ground (real and/or ground plane).
- Proximity to other conducting materials (electrical and telephone lines, mast or tower, metal roof, trough, drain, water pipe etc.). Even tree branches are considered to be conductive RF wise, especially when they are wet.
- Element tapering
- etc.

Designing a multi-element and especially a multi-band antenna is quite a job in itself. In years past antennas were designed using simple pen-and-paper calculations (or using a slide-rule, see photo above of my last one) and "cut-and-try" methods, which took a lot of time (months or even years). That did not always produce the best possible results, because at some point the designer had to decide that the antenna was "good enough". National Bureau of Standards of USA (NBS) performed a major experimental work to dimension yagi antennas. Their report was published in 1976 - see for instance:
https://nvlpubs.nist.gov/nistpubs/Legacy/TN/nbstechnicalnote688.pdf
Antennas based on that report are made even today (2024). Fortunately nowadays there are computer programs (antenna simulation software) available for this purpose, which simplifies (and speeds up) the design process a lot. In general the simulated results hold true very well in real life, too, as long as all settings in the software are made according to actual construction and installation situation of the antenna, like materials and their thicknesses, installation height, ground type/conductivity etc. I have designed a number of different antennas and antenna arrays for HF and VHF using the free MMANA-GAL software (available from http://gal-ana.de/basicmm/en/) and no modifications have been needed after building the antennas. There are also many other antenna simulation software available, like EZNEC, NEC-Win Pro, 4nec2 etc.

High quality commercial antennas can be quite expensive, because of the countless hours of design and testing work required and because of using high quality materials. ***You will get what you pay for!*** When I was still in school, my math teacher used to say: "a poor man can't afford to buy cheap". Be very wary about antennas sold at e-bay and other similar places. Make sure you understand what they are selling. And remember that there is no way to know, if the seller is telling everything about the antenna and what he/she says is actually true!

An antenna can normally be resonant only on one (1) frequency, so for instance a ***resonant*** dipole is a single band antenna, which is resonant more or less at the band centre, with some reactance (SWR) at band edges. Hopefully the reactances are low enough, so that antenna's SWR bandwidth (say 1.2:1 or 1.5:1 max.) covers the whole band. This applies to all frequencies from the bottom of 160 m to VHF, UHF and beyond. If one deviates from the electrical ½ wavelength dimension, the antenna is not resonant and has always some reactance (+ or - j ohms) at the feedpoint. In that case the wire antenna should not be called a "dipole", but a "doublet". Some kind of L/C matching circuit is then required to cancel the reactance and perform the matching to ***50 ohms resistive for transmitter***. The matching circuit could be a fixed one for a specific antenna or an "antenna tuner". ***Note that sometimes also these L/C matching circuits themselves are fairly narrow band and may not cover a whole HF ham radio band with the same settings***.

Antenna's reactance and resistance mis-match is shown by an **SWR meter** as increased SWR reading higher than 1.00:1. "SWR" means "Standing Wave Ratio".

If the SWR meter (or actually its ***measuring bridge***) is located for instance next to the transceiver or even inside it, as is often the case, and antenna is connected to it with a length of coaxial cable, the shown SWR in mis-match situation is almost never the SWR of antenna itself. This is because ***everything between the SWR meter and antenna, including the feedline, L/C matching circuit, balun, connectors etc., act as impedance transformers***. That is one of the reasons (in addition to increased feedline losses etc.), why the antenna's impedance as "seen" at antenna end of feedline (with possibly a balun between antenna and feedline) should always be the same as that of the feedline. Exceptions to this rule can be made with certain types of multi-band antennas, which are fed with high-impedance (and low-loss) feed lines, such as ladder line (window line) or open wire line. Note that a standard 50 ohm SWR meter cannot measure SWR in a high-impedance line. A special SWR meter must be built for that purpose.

On the other hand, as far as the transmitter is concerned, it should always "see" more or less a 50 ohm impedance. Most transmitters and transceivers can actually operate with full power into at least 1.5:1 or 2.0:1 SWR. This means that the impedance "seen" by the transmitter can be 33 ... 75 ohms (1.5 SWR) or 25 ... 100 ohms (2.0 SWR). In many cases the transmitting power is automatically reduced by transmitter's internal protection, if the SWR exceeds the value designed into that piece of equipment.

In general, the more elements an antenna (yagi, quad etc.) has, the narrower is its SWR bandwidth. This is because each antenna element is kind of a bandpass resonator and, of course, more resonators mean narrower "filter bandwidth". Just like in an L/C filter. However, it is possible to design beam antennas (yagis, quads etc.) so that their bandwidth is wide enough to cover the whole band with low enough reactance (= SWR) at band edges. This is done by adjusting the lengths and positions of parasitic elements (reflector, directors) to achieve the desired result. This resembles stagger tuning a multi-resonator bandpass L/C filter. From this follows, however, that for instance antenna gain cannot be quite as good as it would be with a singly resonant antenna. The gain reduction is usually only in the -0.1 ... -0.2 dB region, however, so the slightly lower gain is amply compensated by wider bandwidth.

Many different kinds of multiband antennas (with traps, parallel elements etc.) have been constructed for HF bands, but they are always compromises between different antenna parameters, like impedance and gain on different bands, power handling, mechanical strength etc. "Random length" wire antennas (dipole, doublet, OCF, end fed etc.) are also used a lot to cover many (or all) HF ham radio bands. These are usually fed with high impedance parallel lines and an antenna tuner is used for matching.

Be aware that the gain and SWR figures given by commercial antenna manufacturers may not hold true in real life, because for instance:

- There is no way of knowing how and in which kind of installation they have measured the antenna (including its radiation pattern).
- Have they actually done any real life measurements? Or are the published values copied from some antenna simulation software, where the settings were made for best possible antenna performance regardless of installation?

The fact is that ***laws of physics does limit the available power gain*** of any antenna of specific size and shape. ***There is no such thing as a "miracle antenna"!*** A couple of **bad** examples:

- Somebody sold antennas, which had 1.0:1 SWR from 1.5 MHz to 30 MHz. In reality those antennas did not radiate or receive much anything, because they were just dummy loads with a 50 ohm resistor across the feed point of an unreasonably short radiator.
- A beam antenna's gain was specified unreasonably high when installed at a specified (low) height above ground. Well, to a degree the stated gain could be true because of ground reflection, but what they failed to mention was that the max. radiation was some 12 to 15 degrees above horizon, which is not at all good for DX.

To have a single, reliable reference for comparison, all antenna specifications should only be given for "free space installation", because that is the only constant, which applies to all antennas. Unfortunately that is often not the case. A general statement applicable to every antenna ***installation*** should never be made. An antenna manufacturer can't guess the installation situation at any of their customers' stations. Innumerable factors affect any antenna's performance at the final installation site.

Many multiband beams have different number of elements for different bands, but they are often advertised only with the total number of elements. That does definitely give a wrong impression to potential buyers (more elements mean more gain, in theory). When estimating this kind of antenna's real gain, do not count the total number of elements, because they are not all used on all bands. Count only the elements used for each band separately. Also, a multiband antenna is always a compromise, because the elements of un-used bands do load/de-tune the used band's elements, so all element lengths and positions must have been adjusted accordingly during antenna's design phase. This almost always means that some antenna parameter (gain, F/B ratio, SWR, radiation pattern shape etc.) must be compromised to get the antenna working on all intended bands. In practice a multiband beam has usually less gain than a single band beam with the same number of (band) elements.

As a rule of thumb: A 2 element yagi gives roughly 3 dB power gain and a 2 element quad about 6 dB power gain, both over a resonant dipole ("dBd"). Every time you ***double the number of elements*** (regardless of shape), you get another 3 dB more gain. So, for 4 element yagi the gain would be about 6 dBd and for 4 element quad about 9 dBd. This is not very accurate and the real gain of these particular antennas is somewhat (1 - 2 dB) higher, but you'll get the estimated gain value close enough for comparison purposes.

In antennas with some gain (including even a wire dipole) the increased radiated power to one direction is always achieved by reducing the radiation to other directions, or "by moving the radiated power from other directions to the main direction". That is done by electrical phasing of antenna's elements, ie. by adjusting the lengths and positions of the elements.

To clear some possible confusions with the "dB" values, there is a simple rule of thumb:
- +3 dB (or simply "3 dB") means that the antenna's radiated power ***towards the maximum in radiation pattern*** is exactly 2 times the transmitter's output power.
- +6 dB (or simply "6 dB") means that the antenna's radiated power ***towards the maximum in radiation pattern*** is exactly 4 times the transmitter's output power.
- And so on. Every time another +3 dB is added to the gain, the radiated power ***towards the maximum in radiation pattern*** is doubled.
- As far as antennas are concerned the ***"dB" values are always power gain*** (or loss in case of negative dB, like "-3 dB"), not voltage or current gain. The formula to calculate the radiated power for other gain (dB) values is: $\mathbf{P2 = P1 \times 10^{(dB/10)}}$, where:
  - "P2" is antenna's radiated power towards the maximum in radiation pattern.
  - "P1" is transmitter's output power reaching the antenna (ie. minus feedline losses etc.).
  - "dB" is power gain (or loss) in dB.
- Note that for power increase (or decrease) calculations it does not matter how the dB values are specified:
  - "dB" = The manufacturer has not specified the reference for gain "measurement".
  - "dBd" = The gain is specified relative to the gain of a resonant ½ wave dipole.
  - "dBi" = The gain is specified relative to the gain of (imaginary) isotropic antenna.
  - The gain in "dBd" is ***always*** +2.14 dB higher than the gain in "dBi" ***towards the maximum in radiation pattern***. *If an antenna manufacturer claims something else, that statement cannot be true!*
- ***The "direction of maximum radiation" can, at least in theory, be to any direction from the centre of a sphere.*** It is not necessarily the desired direction towards horizon.
- Note also that the gain (or loss) values apply in both directions, ie. the antenna gain is the same to and from radiation pattern's maximum for both transmitting and receiving.

B.3 Height of an antenna

In general, a **horizontal antenna** (wire or directional) should be installed as high as possible to have low vertical angle for maximum radiation. The lower an antenna is, the higher is its vertical radiation angle above horizon. The antenna height should be at least 1/4 free air wavelengths above ground or any kind of metal (like a ground plane, concrete reinforcement steel etc.) below the antenna. It would be better to have the height at least 1/2 wavelengths for lower radiation angle and better DX.

Antenna height can represent practical problems, however, especially on lower HF bands (160 m - 30 m). 1/4 wavelength for 160 m band is about 40 metres and 1/2 wavelength about 80 metres! For 80 m band 1/4 wavelength is about 20 metres and 1/2 wavelength 40 metres! For higher HF bands (20 m - 10 m), antennas can usually be installed high enough using pipe masts or towers. At VHF and UHF bands the antenna height is generally not a problem, because they can be easily installed several wavelengths high. For instance on 2 m band 5 wavelengths is about 10 metres and on 70 cm band 10 wavelengths is about 7 metres.

Basically the ground reflection for an antenna installed at "low" height (in wavelengths) increases the vertical angle of maximum radiation many degrees (say 10° - 15°) above horizon, which is not all that good for DX. It may also increase antenna's radiation gain towards the maximum of radiation. That depends a lot on ground type, including its conductivity. The vertical angle of maximum radiation should be held as low as possible (ideally towards horizon) for DX contacts. The ionosphere reflection (for HF) or other ways of reflection (for VHF, UHF and above) are usually at their best, when the signal's arrival angle is as shallow as possible. Note that there is no point of trying to have the vertical radiation angle below horizon, because the earth will block the signal. Not for DX contacts anyway.

Vertical antennas are usually installed on the ground, or sometimes lifted at some height using a support mast. Because of the ground plane they require, the vertical radiation angle is fairly low, maximum usually around 3 - 5° above horizon.

The **height of your QTH** (above sea level) can have a significant effect on the distance to horizon. The further away the horizon is, the shallower is the arrival angle to the layer of reflection, which means significantly better signals to and from a DX station. For instance:
- 20 m high antenna at sea level: Horizon is about 16 km away.

- 20 m high antenna from ground at 100 m above sea level (my antenna height here in Crete): Horizon is about 39 km away.
- 20 m high antenna from ground at 200 m above sea level (my ham radio friend's antenna height here in Crete): Horizon is about 53 km away.

So as you can see from above, the higher your QTH is located, the further away is the horizon and the better signals for DX contacts you will have. This assumes, of course, that your antenna's maximum radiation is towards horizon and that there is nothing on the way to horizon (like buildings, hills or mountains) to block or reflect the signal. The distances above were calculated at https://www.ringbell.co.uk/info/hdist.htm.

In general the "skip distance" on HF bands is around 3000 ... 6000 km (1800 ... 4000 mi), depending on the reflection layer height at any particular direction and moment of time. The height varies constantly (150 ... 800 km, 95 ... 500 mi). The "skip distance" means a single hop of radio signal from TX station to the next point it hits the earth:
- Often the signal can hop several times between earth and ionosphere before reaching the receiving station, and each hop is within the distance mentioned above.
- If one cannot contact a station in a desired (distant) area, sometimes the DX contact can be made by turning the antenna to opposite direction. This is called "long path propagation", because the signals are going the longer way around the earth.
- In some (rare) cases the signal can even circulate the whole earth one or more times, in which case the transmitting station can receive its own delayed signal (especially in CW). These signals are called "long delayed echos".

Because of ionosphere reflection, on HF bands there is often a fairly big "dead zone" about half way of the skip distance (centre about 1500 ... 3000 km, 900 ... 1900 mi away). This is because the transmitted "ground wave" cannot reach that far and the "sky wave" hops over that area. So no contacts can be made there. The "dead zone" size and location varies a lot, depending on general RF signal propagation.

C. Selecting and locating an antenna

In general it does not matter what kind of antenna you have as long as you are able to feed RF power into it and can receive other stations with it. Every antenna is always bi-directional, ie. it works for both transmitting and receiving. More or less any matched antenna (even a small tuned loop) can radiate the transmitted power fairly efficiently, but for receiving a bigger (ie. normal) size antenna, like a wire or dipole, is often better because of its larger "capture area". For contest and serious DX work that may not be enough, though, and a directional, rotating gain antenna is needed.

For most of us the kind of antenna we can install and its installation location is mostly restricted by other factors than the antenna itself. For instance:

1. **Property size**. Usually one can't install an HF wire antenna, which is longer than the longest dimension of the plot. Often it must be even shorter than that because of obstructions (buildings etc.) and/or lack of support points (trees, for instance). Note that for instance an 80 m band resonant dipole is about 40 metres (131 ft) long and a 160 m band resonant dipole is about 80 metres (262 ft) long! If you have a friendly neighbour, it may be possible to extend the antenna to his/her side, but most of the time that is not the case.

2. **Antenna's mechanical size** in general. A multiband, high gain, full size HF beam is much bigger than some other types of antennas (like verticals), requiring a fair amount of real estate to install it (mast or tower + guy wires). The antenna size has also a direct effect on its support structure, because of weight and wind load caused by the worst storms in your area. In some places also snow and especially ice (= extra weight and higher wind load) may compromise the antenna itself, tower, rotator etc.

3. Possible **zoning restrictions**. Fortunately we don't have anything like that in Europe, but this may be an issue in some other countries. In Europe, as a licenced radio amateur, you are always legally permitted to install an antenna regardless of what other people may say, as long as it fulfils the local mechanical and electrical safety regulations.

4. **RF radiation levels** to public. On HF bands the RF radiation is generally not a problem (except possibly for ground mounted verticals), even when using a linear amplifier, but it may limit the transmitting power and/or antenna gain on VHF and especially UHF and higher frequencies.

   ICNIRP ("International Commission on Non-Ionizing Radiation Protection") screens and evaluates scientific knowledge and recent findings toward providing protection guidance on non-ionizing radiation, i.e. radio, microwave, UV and infrared. National authorities in more than 50 countries (including Greece) and multinational authorities such as the European Union have adopted the ICNIRP guidelines.

   There is free ham radio software available to calculate safe distances for RF radiation for general public. "ICNIRPCalc" by DL9KCE is one such software, downloadable from:
   https://www.iaru-r1.org/about-us/committees-and-working-groups/emc-committee-c7/links-to-emc-resources/ .

   ***Note! Greece has adopted stricter limits for RF radiation levels than other European Union countries**, so in ICNIRPCalc set the transmitter power 1.5 times (150%) of your actual transmitting power to get the correct safe distance in Greece.*

5. Your **immediate family**. In my case, for instance, the XYL said ***NO TOWER*** in capitals - HI. So at the moment I have a 3 meters (about 10 ft) tall rotating mast on the roof of our 2 storey house, which supports a 6 band HF Hexbeam, the feedpoint of a 16 + 29 = 45 meters (149 ft) long OCF doublet for HF and 2 x 4 element yagi array for 2 meters.

6. **Money**. How much cash one is able/prepared to spend for an antenna system, including the antenna itself, its support structure, feedline, possible rotator, balun(s), antenna tuner etc. Often antennas are cheaper to build at home, but that depends on the price and availability of needed materials, and the ability and/or tools of the radio amateur to actually construct the antenna.

7. **Interference to neighbours, own family etc**. In general radio and TV interference are not so much of a problem nowadays for HF band transmissions, because few people are listening to AM radio any more and all TV transmissions are digital and on UHF (at least in Europe). But, that depends a lot on the placement, antenna installation, internal shielding and filtering etc. of the radio (FM) or TV antenna system and receiver. ***So, please, ask your family and neighbours, if they are experiencing radio or TV interference when you are transmitting.*** And if they are, correct the situation, before the relationships get any worse:
   - I have seen a digital TV set to switch on and off and change channels in random just because a ham in the same household was transmitting SSB with 100 W on 40 meters. That TV set must have really poor shielding/filtering for out-of-band RF. This problem was solved by installing a different ham radio antenna in a different place.
   - I had a problem, too, because my WSPR transmissions with 5 W output on all HF bands overloaded the UHF TV and FM antenna mast top amplifier and caused the TV to go blank. These simple wideband antenna amplifiers have only mediocre filtering to separate the different broadcast bands and no attention has been given to out-of-band (like ham radio) signals. That was solved with home made L/C filters at antenna amplifier inputs, which attenuate all HF signals by well over -110 dB but pass through the FM radio and UHF TV frequencies with minimal attenuation.

8. **Internet interference**. ***A big problem for radiated RF***, especially on HF bands, can be the different networking equipment, like landline telephone cables, broadband DSL (Digital Subscriber Line) modems and routers, Ethernet (LAN) hubs, switches and cables etc., including their power supplies. Unfortunately that stuff is almost never shielded and filtered well enough to keep the external RF radiation out of their circuits. Depending on the locations/distances of ham radio antenna and network equipment, the result can be for instance lost internet connection during transmissions. It may take several minutes after end of HF transmission, before the network equipment have re-booted themselves and the internet connection is working again.

   In general, there are no easy solutions to this problem. One can try to install clip-on ferrite blocks on all cables in and out the affected equipment, but there is no guarantee for success. Ethernet cables are often not shielded (type UTP = Unshielded Twisted Pair), so it may help to replace all of them with shielded ones (type CAT5 or CAT6). In worst case one may have to replace the affected equipment with less susceptible ones.

Note that the wireless (RF) part of an internet connection (Wi-Fi etc.) does not usually have HF interference problems, because it is working on 2.4 GHz or 5 GHz band. The problems are always related to the physical networking equipment and their cabling.

9. **Interference for ham radio reception**. The biggest problem for ***receiving*** ham radio signals is nowadays the interference (QRM) caused by switching power supplies. The harmonics of these power supplies can cover all the HF ham bands, and interfere even VHF and UHF frequencies. Those equipment are almost never shielded and/or filtered well enough to keep the switching power supply harmonics inside the units. Even all energy saving lamps (fluorescent, LED) have switching power supplies, which chop the mains AC voltage directly to a lower (or higher) voltage. There are also many other kinds of noise sources, like bad (arcing) connections in power lines, electric (DC or AC) motors, electric welding equipment etc. Non-technical people may not even be aware of the noise, but it is a real problem for everybody using radio frequencies up to at least 1 GHz.

   An example: The switching power supply of my radio computer's monitor (made by Samsung) blocked all HF frequencies from 160 m to 10 m bands. I trashed that power supply and am now running the monitor from a linear 13.8 VDC power supply.

   Another interference source in some countries is PLC or Power Line Connection. This is a system, where internet is routed to customers through mains network power lines. Similar equipment are also used for extending network connections within the same household. It has been shown many times that this type of data transfer is a major interference source for amateur radio reception (and for radio networks of various authorities) and can have an effect several kilometres (or miles) from the actual power line. The main reason is that the mains networks are built ***only*** for transferring 50 Hz (or 60 Hz) AC power to households etc. It is not at all suitable for any "high frequency" (say 2 ... 30 MHz) transfer and will radiate those frequencies without restriction. Because of the interference, this type of networking has been legally prohibited in many countries. Not in Greece, though, as far as I know.

   Often vertical antennas pick up more noise than horizontal ones, but that depends. Most of the time balanced horizontal antennas (like resonant dipoles or inverted Vs) pick up the least amount of man-made noise.

   Basically, ***the interference should always be stopped at its source***. There is no reliable way to stop it anywhere else, because after exiting the interfering piece of equipment, the noise is propagated in many different ways and routes. It is relatively easy to find the interfering equipment in your own ham shack or residence, just switch different pieces of equipment off one at a time to see when the noise disappears. But when everyone in a city, town or village has those equipment, the noise just adds up to a continuous "hiss", which can be strong enough to prevent receiving anything, except the loudest ham radio signals. The noise is propagated by RF radiation, but also conducted through power and telephone lines etc., which can also radiate the noise on radio frequencies.

   In a ham radio station the ***interference is always picked up by the antenna***. It cannot go through your transceiver's power supply or other power supplies in the station. In some cases it is possible to reduce the noise by installing clip-on ferrite blocks in your feed line, but very often those do not help.

   There are also noise cancelling equipment available (like MFJ 1026, Timewave ANC-4, DX Engineering NCC-2, Wimo QRM-Eliminator, X-Phase QRM Eliminator and others). These units are basically diversity receivers using two antennas, a "noise" antenna and the actual ham radio antenna. The RF noise from one antenna is inverted and there are several settings to achieve the wanted result. Next RF signals from the two antennas are combined and the result (at least in theory) is no noise at the output. Depending on the unit and the antennas connected to it, it may not actually reduce the noise as expected. These units are always installed between the antenna(s) and station receiver. However, they may need an additional (external), very reliable by-pass switching for transmitting, otherwise the unit is burned out at the beginning of first transmission. Note also that adjusting one of these units is somewhat of a job and they will require re-setting more or less every time you change frequency or band.

When the noise source is not in your own house, locating it may be very difficult, because it could be quite far away (up to several kilometres or miles). One could try to find the noise source by using a portable AM or SSB short wave receiver tuned to an otherwise empty frequency and walking or driving around your neighbourhood. The received noise becomes stronger, when you are approaching the noise source. If you actually find the house, where the noise is coming from, your problems may really begin. Depending on the mentality of the person, you may be able to convince him/her that the noise is coming from that house, but sometimes that is not possible and you are left on your own. In every country there are regulations, which limit the radiation and conduction of unintended frequencies from ***all equipment*** (not only radios). Depending on your country, you may be able to contact the authorities and make a complaint. But are authorities actually enforcing the regulations, is another question.

C.1 Wire antennas

Wire antennas have been around since the birth of radio and they are still very popular today, especially for the lower HF bands (160 m - 30 m), because they are relatively easy (and cheap) to construct at home.

In general, wire antennas are only used on HF (and sometimes 6 m) bands. For VHF and up stiff antenna elements (aluminium or other metal pipe/rod, fibre glass etc.) are used. For HF the wire antennas are easier to construct than other antenna types, but they need at least two support points. The supports can, of course, be trees or for instance pipe masts.

Theoretically any HF wire antenna can be used even on VHF and UHF frequencies, as long as one is able to match it and feed power into it. On the other hand, for instance even a 100 mm (4") nail could work even on 160 meters, but because of the extremely low feedpoint resistance (very small parts of 1 ohm) and very high capacitive (-j ohm) reactance, it would be impossible to match. Note that these two extreme examples are ***valid only for the theoretical electrical operation*** of the antennas. They do not take into account how lossy they are for transmitting or are they any good at all for receiving.

Decades ago in Finland, I tested for fun how small an antenna could be used for a 2 m FM contact from Oulunkylä (Helsinki) to Lahti (distance about 85 km, 53 mi). The output power of my radio was 10 W (Icom IC-22) and I just connected the "antenna" directly to radio's connector. Using a 4" (100 mm) iron nail the contact was still made, but with a 3" (75 mm) nail it no longer worked.

The antenna wire should be copper or copper clad steel to reduce resistive losses. Because of the so called ***"skin effect", RF always "travels" on the wire's (or pipe's) <u>outer</u> surface***, or e.g. in a coaxial cable on the outer surface of the centre wire and ***shield's inner surface***. So only the resistance near the metal surface is important. Copper has the lowest resistance (= least loss) of commonly available (and economical) metals. Lower frequencies (like 160 m) penetrate a bit deeper in the wire's metal and higher frequencies (like UHF) a lot less. Other metal wires (like steel) have much higher resistance and will cause signal losses both for transmitting and receiving. The wire can be insulated, too, like electrical installation wire. That makes no difference to antenna dimensions or performance. Bare (uninsulated) copper wire oxidizes, of course, but copper oxide is only a very thin layer on wire surface and it is an excellent insulator, so the RF signal just moves a little bit inside the wire because of skin effect and makes no difference to antenna performance.

How deep the RF penetrates conductor's metal ***depends only on the frequency and the metal itself. It does not depend, for example, on the thickness of the conductor or the used transmission power.*** Usually, the RF penetration depth (skin depth) into the conductor is calculated in a situation where the RF current has dropped to approx. 1/3 of what it is on conductor's outer surface. Deeper than that, the RF current decreases logarithmically. The examples of penetration depths below were calculated in internet at:
https://www.everythingrf.com/rf-calculators/skin-depth-calculator:
- **1.8 MHz**: Copper 48.62 µm, Aluminium 61.15 µm
- **7.0 MHz**: Copper 24.65 µm, Aluminium 31.01 µm
- **21.0 MHz**: Copper 14.23 µm, Aluminium 17.90 µm
- **30.0 MHz**: Copper 11.91 µm, Aluminium 14.98 µm
- **50.0 MHz**: Copper 9.225 µm, Aluminium 11.60 µm
- **145.0 MHz**: Copper 5.417 µm, Aluminium 6.813 µm
- **435.0 MHz**: Copper 3.127 µm, Aluminium 3.934 µm
- **1.3 GHz**: Copper 1.809 µm, Aluminium 2.276 µm

- **2.35 GHz**: Copper 1.346 µm, Aluminium 1.692 µm
- **3.4 GHz**: Copper 1.119 µm, Aluminium 1.407 µm

1 µm = 0.001 mm = 0.000 001 m = 0.03937 mil

As you can see from the above, the conductors needed at the lowest frequencies could ***theoretically*** be very thin, e.g. 0.1 mm, but in practice such conductors would not withstand any kind of mechanical or electrical (transmission power) stresses. On the other hand, at VHF, UHF and higher frequencies, the conductors must be relatively thick (e.g. tube), because the RF "travels" in a much thinner layer from conductor's surface and the "cross-section" of metal, which is actually used, must be increased to keep resistive losses low.

Note! Do not be fooled by some wire sellers' claims about the "higher quality" or "better conductivity" of what they call "oxygen free copper". Those wires are much more expensive, but their conductivity (ie. metal's resistance) is exactly the same as in normal (cheap) copper wires and they are not at all better for any kind of domestic use, including ham radio antennas. Oxygen free copper is only required in certain special situations, like in a vacuum, and the lack of oxygen is the only reason to use it. Not its "quality" or "conductivity"! So, why pay extra for something that makes no difference.

Note also that the length of copper wire changes according to varying temperature. The length is shortest at lowest temperatures and longest at highest temperatures. Basically, ***copper wire*** expands 1.0000165 times its length with each 1°C (1.8°F) increase and shrinks 1.0000165 times its length with each 1°C (1.8°F) decrease in temperature. This means that antenna's resonance frequency goes down or up with changing temperature. For instance with 50°C (90°F) change in temperature, antenna's resonant frequency shifts by 0.0825 %, so:

- In a 160 m dipole the resonance frequency shift is ±66kHz
- In a 40 m dipole the resonance frequency shift is ±16.5kHz
- In a 10 m dipole the resonance frequency shift is ±4.125kHz
- However, the wire expansion or shrinkage does not usually have any significance on antenna's operation on HF bands, because the ham radio bands are fairly wide relative to frequency and HF antennas are usually tuned for band centre.

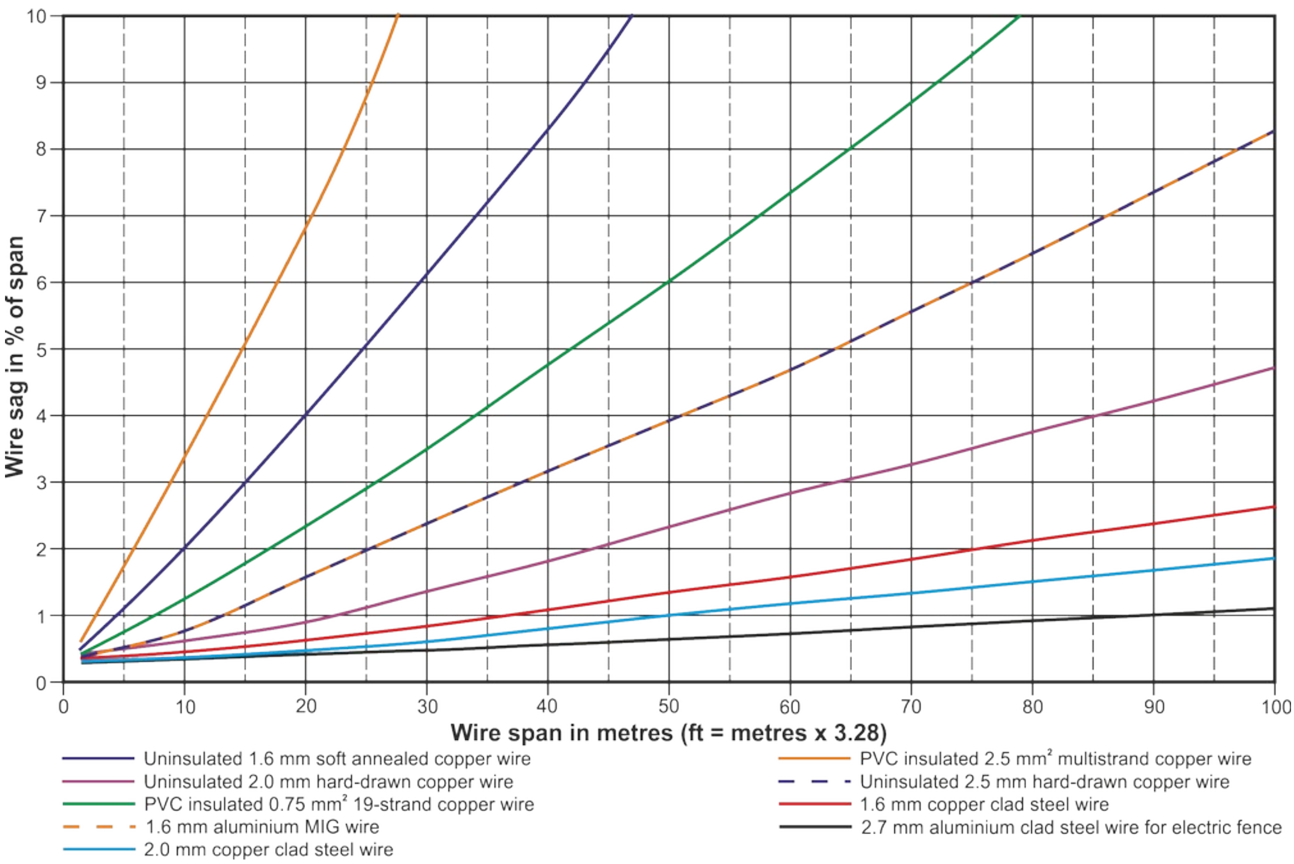
Aluminium ***wire*** would also be electrically very good (and lighter) for antennas, but it has some serious drawbacks:
- It is impossible to solder with normal ham shack tools
- It oxidizes very fast (in a second or less in air), so any pressure contacts (like screws, clamps etc.) disconnect themselves in no time.
- It is not as resistant to mechanical stresses as copper wire, because it is stiffer.
- It must not be in contact with any other metal, because aluminium forms a nice battery with it (up to 0.7 V, depending on the other metal), especially when wet, and the contact will corrode in no time. The other metal "emigrates" to aluminium's surface.

The antenna wire thickness does not have any electrical importance on HF bands, because it will always be miniscule parts of a wavelength. The only requirements are that the wire can take the mechanical stresses (tension, wind load etc.) it is subjected to and that it can handle the transmitting power without heating. Thicker wire is stronger, of course, but it is also heavier, which needs to be taken into account, especially in long antennas for lowest bands (160 m, 80 m). To my experience Ø 1.6 mm (AWG #14) insulated electrical installation wire, which has a single strand of copper, will last decades in every kind of HF wire antenna in all kinds of weather conditions, like during storms and at least -30°C ... +40°C (-22°F ... 104°F) temperatures. It can also easily take at least 1500 W of HF transmitting power. Usually antennas constructed of wires, instead of aluminium pipes, can handle much higher winds without breaking.

Do not pull antenna wires too tight, though, or they start vibrating like a guitar string in high winds and then they will break because of metal fatigue. The antenna wires should always hang a bit loose and be attached to support points with lengths of UV resistant plastic ropes for flexibility. The curves on next page give some idea for the required sag. They were calculated using VK2OMD's (Owen Duffy) "Antenna wire catenary calculator" at https://owenduffy.net/calc/awcc/awcc.htm.

Note that the calculated curves below are for:
- 28 m/s (= 100.8 km/h = 62.6 miles/h = 10 Beaufort) max. wind speed.
- Australia, so they are for relatively high temperatures (say above +15 °C = 60 °F). They do not apply for low temperatures (down to -30 or -40 °C = -22 to -40 °F).
- ***Free hanging*** spans of antenna wire.
- Safety factor of 3.5.
- The curves do not take into account additional snow or ice on the antenna wire.
- The curves do not take into account any extra weight caused for instance by a coaxial cable connected to antenna's feed point.
- So, use the curves only as guidelines and apply also your local conditions for the required wire sag.

VK2OMD's site (https://owenduffy.net/rigging/sag.htm) has also curves for wire sag, ***but they are for 60 m/s (= 216 km/h = 134 miles/h = 12 Beaufort) wind strength***, which is ridiculously high for these purposes. Most likely no ham radio antenna system, including the antenna supports etc., would survive such hurricane!



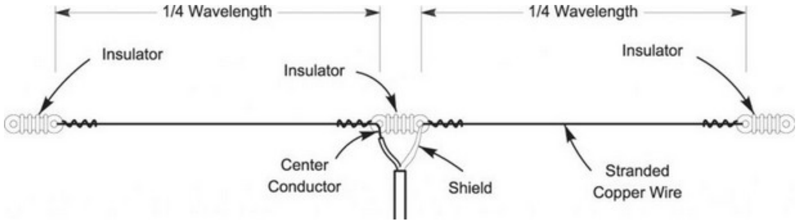
The amount of sag needed for a wire antenna survival depends on a lot of factors, like:
- Antenna wire itself (thickness, material). Thicker wire is stronger and copper clad steel is stronger.
- ***Maximum*** local wind speed. Higher wind speeds require more sag.
- ***Minimum*** local temperature. All metals shrink when the temperature goes down and some sag must be retained even in the lowest local temperatures (say down to -30 ... -35 °C = -22 ... -31 °F in Nordic countries). Also snow and ice on the antenna wire may increase its weight a lot.
- "Stiffness" of antenna supports. Trees sway a lot in high winds. Masts and towers do not move much in high winds, but that depends on their guying system. Some people suggest using a pulley with weighted rope to keep the antenna under tension, but experience has shown that the rope does not last very long, especially in tree supports, because of constant movement. It breaks and the antenna falls down.
- One should consider the fact, that all different factors affecting wire antenna survival may appear at the same time.

All connections to a wire antenna ***must be soldered***. Any kind of pressure connections (screws, clamps, etc.) will rust or oxidize in time and the contact will eventually be lost. It would also be a good idea to cover all solder joints with heat shrink tubing, self amalgamating rubber tape or silicone.

A random length wire antenna can work almost as well as a resonant dipole, but unlike a dipole it can be used on several (or all) ham radio HF bands.

There are many different kinds of wire antennas:

a. ***Center fed resonant dipole***. This is the most basic wire antenna for a single HF band, but it can possibly be used also on ***odd multiples*** of resonant frequency, like a 40 m dipole on 15 meters (3 x 7 MHz = 21 MHz) or 80 m dipole on 30 meters (3 x 3.5 MHz = 10.5 MHz). It will not work on even frequency multiples, because the feedpoint impedance will be very high.



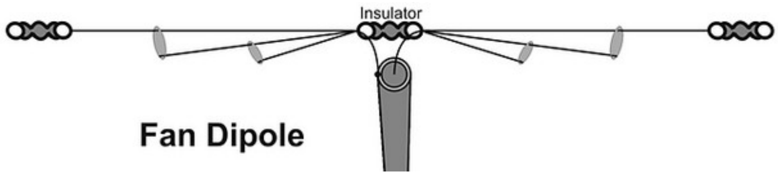
Resonant dipole's theoretical feedpoint impedance is about 73 ohms in free space, but because on HF bands they are installed fairly close to ground (often less than 1/4 wavelength), the actual feedpoint impedance is closer to 50 ohms.

Often a dipole is installed straight, in which case the antenna has deep, narrow nulls towards the ends of antenna wire. The horizontal radiation pattern resembles a wide figure "8" perpendicular to antenna wire. However, for restricted space and/or because of lack of suitable support points, a dipole can also be installed in an angle at the feedpoint, either sloping down (which is called an "inverted V"), or horizontally. In both cases the deep nulls towards antenna wire ends are reduced and the radiation pattern becomes more circular. ***Do not make the angle between wires less than about 120°, or the feedpoint impedance becomes too low!*** *Do not install inverted V's ends so close to ground that people can touch the wires. When transmitting the RF voltage at wire ends will be very high, possibly several kV!*

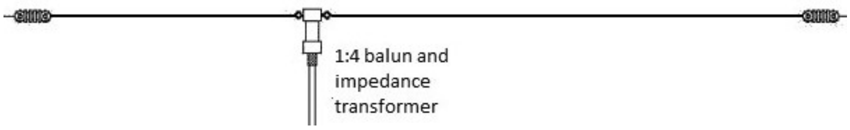
The "standard" formulas for a dipole antenna's total length are:
- Length in meters: L = 143 / MHz with at least three (3) decimals
- Length in feet: L = 468 / MHz with at least three (3) decimals
- Divide the length of the formulas above by 2 to get the length for each side of a dipole.
- ***Note: In most cases the length from formulas above must be adjusted***, ie. the antenna must be made longer or shorter, because for instance antenna's height above ground also affects its length. So, first make the antenna wires a bit longer (say about 0.5 or 1 %), hoist the antenna up and check SWR. Then shorten both ends by the same amount in small steps, until you reach about 1.0:1 SWR.

Normally there is no sense to use any kind of balun at a resonant dipole's feedpoint. It only adds losses to the antenna system. However, the coaxial cable should go at straight angle (90°, vertically, horizontally or at a suitable downwards angle) from the feedpoint for at least 1/4 wavelength. If the feedline cannot be angled 90° from the feedpoint, then one should use a 1:1 ***current*** balun (common mode choke) at the feedpoint to stop RF coming back to the shack on the outer surface of coax shield. The balun must have high enough common mode impedance (at least 5000 ohms) on the operating frequency.

b. It is also possible to connect dipoles for different bands in parallel to a single feed point. These antennas are called ***fan dipoles*** or simply ***parallel dipoles***. Because the wires for one band are loaded and de-tuned by the wires of all other bands, one cannot use the standard dipole formula. A lot of trimming, tuning and adjustments are usually required to make the antenna work as well as possible. And, of course, the adjustments must be made for antenna's final installation height, so a lot of raising and lowering is also involved. Nearby ground does de-tune every antenna. Even after all that effort, an antenna tuner is still often needed for final matching. One could use for instance MMANA-GAL for preliminary antenna simulation.



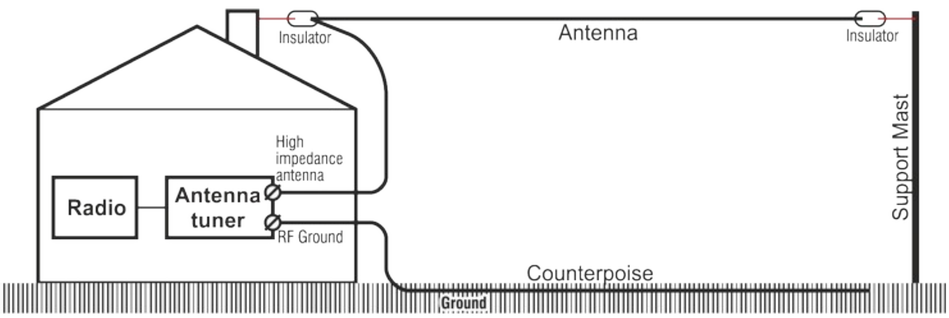
c. ***Off-centre fed (OCF) antennas***. These are essentially multiband antennas. The antenna's feedpoint can be almost anywhere on the wire length, but not too close to one end. The only requirement is that the total antenna length should be roughly ***½ electrical*** wavelength on the lowest frequency it will be used for. The feedpoint impedance varies according to its position on the wire and also depends on frequency. However, it is possible to calculate one or more feedpoint locations, which have nearly the ***same impedance***, for instance 200 or 300 ohms (***not 50 ohms!***), on all bands the antenna is used for. Then only a balun (1:4, 1:6, 1:9 or whatever) would be needed to match it to 50 ohms. However, an antenna tuner may still be needed to match the antenna to transmitter's 50 ohm output on all bands. There are free calculators in internet for this particular purpose. I have used with success DLØHST's "Stromsummen-Antennen-Berechnung" ("Current sum antenna calculation") software, available at:
https://www.dl0hst.de/stromsummenantennenberechnung.htm.
The program is in German, but not difficult to understand.



At the moment I have a 29 + 16 = 45 m long OCF doublet at my QTH for all HF bands (160 m to 10 m). Because the total length is too short for 160 meters, there is a loading coil with bypass capacitor (this is not a trap) in antenna's shorter leg. I feed it through a 4:1 hybrid balun on the roof and use an antenna tuner for final matching.

I also had a parallel OCF doublet for several years in Finland. I designed it so that it was resonant on all HF bands (160 m - 10 m) and fed with a 600 ohm open wire line. The 160 m band had linear loading, so antenna's total length was the same as an 80 m dipole. An antenna tuner was needed for final matching. It was quite heavy, so it needed three (3) support points, at both ends and one at feedpoint.

d. ***End fed wire*** antennas are generally multiband antennas. The total wire length should be roughly ***½ electrical*** wavelength on the lowest frequency it will be used for. The most common shape for an end fed wire is inverted L. It does not really matter, however, which shape the antenna has. It can even zig-zag as needed in the available space. The antenna feedpoint is at one end of the wire (often directly at antenna tuner's connector), with the other end open. An end fed antenna always requires a counterpoise, ie. some kind of wire or other metal on or under ground more or less below the antenna. The counterpoise lowers end fed wire's feedpoint impedance to something the antenna tuner (or transmitter) can handle. Otherwise the feedpoint impedance would be very high, possibly several kohms, depending on frequency. The antenna tuner's (or transceiver antenna output's) ground is connected to this counterpoise and the RF signal to the antenna wire.



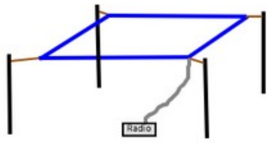
e. ***Quad antennas*** are very good directional wire beams on HF bands, but they are 3-dimensional and can be fairly big in size. That makes mast or tower installation more difficult, because half of the antenna is below rotator's antenna installation point and could interfere with guy wires. The quad elements can be either square or diamond (ie. rotated 45°) shape, it makes no difference to antenna performance. Square radiator is normally fed at the centre of lower horizontal wire. Diamond radiator is normally fed at the bottom corner of the diamond. Because of the size, quads are usually only made for 20 meters and up. The smallest HF quads have only two wire elements (reflector and radiator). The total radiator square circumference is roughly one full ***electrical*** wavelength. The reflector is a bit bigger and additional directors slightly smaller. For instance the gain of a 2 element quad is a fair amount higher (roughly 3 dB) than that of a 2 element yagi. This is because in a quad there are actually twice the number of ½ wave "dipoles" compared to a yagi, but driven through the same feedpoint. The wire element spreaders must be of insulating material. Traditionally bamboo was used on HF bands for those, but nowadays fibre glass pipe is a better solution.

It is possible to construct single or multiband HF quads with up to 4 or 5 elements per band, which gives a lot of gain (something like 10 to 12 dB over dipole). Even bigger quads (up to 15 to 30 elements and more) are used on VHF and UHF bands, but because of size those are mechanically impossible to build for HF. When correctly dimensioned, each band's feedpoint impedance is close to 50 ohms, but: ***the different band radiators cannot always be connected in parallel!*** A multiband quad may need a remote controlled switching arrangement (with relays) in the antenna itself, which connects only the required band's radiator to the 50 ohm feedline. All other radiators must be disconnected and de-tuned with short circuited lengths of coaxial (or other) feed line.

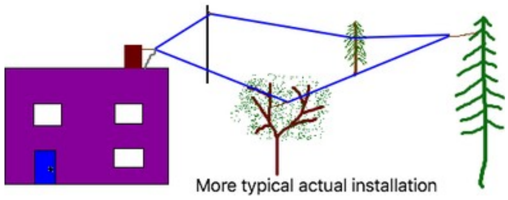
f. The HF ***wire beam*** elements don't need to be squares. Beams have been constructed with for instance triangular delta loop (= Greek letter Δ upside down) elements. The "delta" beam has slightly less gain than a quad with the same number of elements, but the mechanical construction can be simpler. The two upright diagonal sides of the loop can even be of metal (aluminium etc.) pipe, which is only insulated from the antenna boom, and they support the top horizontal wire. The whole antenna is above the rotator's antenna installation point, so the mast guys don't prevent turning the antenna. On the other hand, beams with circular elements are used a lot for instance on 23 cm band.

g. ***Hexbeam*** antennas are basically 2 element yagis, but constructed with wires. The combined shape of radiator + reflector elements is a hexagon, hence the name. Antenna's gain is a bit lower, but its turning radius is much smaller and it is a lot lighter, than full size 2 element yagi. It has six fibre glass spreaders and the driven + reflector elements form a full "circle". The radiator and reflector ends are separated with shortish lengths of plastic rope. The other radiator ends are connected to 50 ohm feedline.

These antennas are made commercially, usually for several HF ham bands, but can also be fairly easily constructed at home. At the moment I have a 6 band (20 m - 6 m) Hexbeam on my roof and it works quite well. A Hexbeam is a directional antenna, so it always requires an antenna rotator.



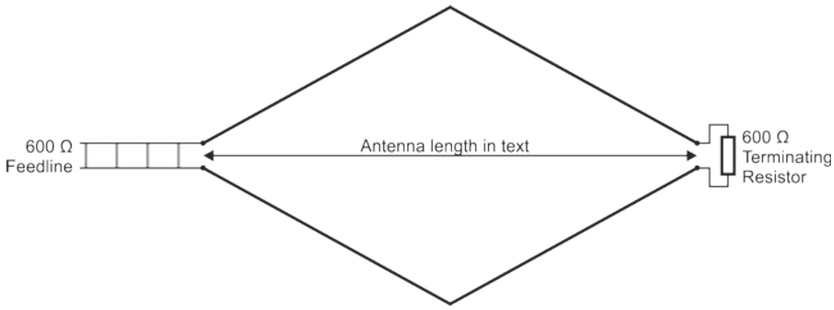
Typical drawing of a horizontal loop.



More typical actual installation

h. ***Horizontal loop*** antennas are also multiband antennas. They are quite good for both transmitting and receiving. The loop circumference should be ***1 full electrical wavelength*** for the lowest band the antenna is intended for. So, roughly 160 meters (525 ft) of wire is needed for a 160 m loop and 80 meters (262.5 ft) for an 80 m loop. This kind of antenna needs at least four (4) support points (one in each corner). The loop's shape can be almost anything from full square to rectangular to circular, but its length to width ratio should not be less than 2:1. The feedpoint can be at any convenient place in the loop, for instance at one of the support points. A horizontal loop needs always a balun at the feedpoint and an antenna tuner for final matching. The balun's impedance transformation ratio depends a lot on how high the loop is installed, because of loading caused by the real ground. Higher loops need higher ratio baluns (like 9:1 or even 12:1), while a lower loop may be OK with only a 4:1 or 6:1 balun.

i. ***Rhombic antennas*** are high gain directional multiband wire antennas. They are ***very*** big, however, so they cannot be rotated and are not very practical for ham radio use. The length of a rhombic antenna must be at least 5 wavelengths to have some gain, but usually they are from 10 to 20 wavelengths long. So, a 20 meter (and higher) band rhombic would be about 200 - 400 meters (660 - 1320 ft) long! Note that this length is from antenna's feedpoint to the other end with terminating resistor and the antenna has a fair amount of width, too. It is not the length of rhombic loop's wire, which would be around 3 times longer than antenna's length.



Years ago I built a rotatable rhombic wire antenna for 2 m band, but it was quite awkward and far too big for the available gain. A 12-element yagi was much better.

The first time I saw rhombic antennas was in 1970's at "Helsinki Radio" maritime radio station near Helsinki, Finland. That was their transmitting station. The receiving station was located some 50 km (31 mi) away to avoid interference. They had several rhombic antennas to different directions, covering a field of about 1 square kilometre (100 hectares = about 250 acres).

j. ***Vertical wire antennas*** are basically single band 1/4 wave antennas with a ground plane of 4 or more 1/4 wave radials. For permanent installation the verticals are normally made of metal (aluminium) pipes, but for portable use wire versions are much more practical. For instance the wire end can be hoisted up to some kind of support, like a tree branch. Another possibility is to acquire a long enough fibre glass fishing pole and fix the wire ***inside*** the pole only at top (thin) end. Then the antenna can be quickly assembled and dis-assembled as needed and is still easy to transport.

k. There are many other kinds of HF wire antennas, too, like slopers, inverted Vs, cage dipoles, Beverages, T antennas, spider and Moxon beams, phase steerable dipole arrays, travelling wave antennas etc. Above I have only described some of the more common ones.

C.2 "Stiff" antennas

By a "stiff" antenna I mean everything, which is made out of pipes, rods or other stiff materials instead of wires. The most common material for the antenna itself is aluminium pipe, because:
- It is much lighter than other metals.

- It is an excellent electrical conductor, almost as good as copper.
- There are special aluminium alloys available in the form of pipes, rods etc., which are much stiffer than pure (soft) aluminium and can withstand wind loads very well.
- For UHF and microwave frequencies aluminium is very quiet (for receiving) because its inherent thermal noise is much lower than in other metals (like copper). On HF and VHF bands the "quietness" makes no difference, because the atmospheric and other background noise is much higher than the antenna noise.
- Aluminium oxidizes very fast, but aluminium oxide is a very thin layer on the surface, an excellent insulator and quite hard, which protects the metal inside really well.

There are some drawbacks with aluminium pipes, too:
- Aluminium is impossible to solder with normal ham shack tools.
- Aluminium oxidizes very fast. So, even the connection of two aluminium pieces must be secured with screws, bolts, clamps etc. to make sure the contact remains intact for years to come. Depending on the shape and strength requirement of two connected aluminium pieces, I have sometimes successfully used aluminium blind rivets ("Pop" rivets) to keep the pieces together.
- It should not be in contact with any other metal, because aluminium forms a nice battery with it and the other metal (usually steel) will corrode in no time, especially if it gets wet. In practice this means that all 2-metal contacts with aluminium (bolts, screws, clamps etc.) must be weather protected one way or another. I have used successfully rust proofing paint or silicone around all 2-metal contacts. There are likely other methods to achieve the same result.
- Because of stiffness, a yagi's aluminium elements, which are fixed at centre to the boom, may be ***mechanically resonant*** and start vibrating in some wind speed. The wind doesn't need to be all that strong. I saw this happening years ago in a 4-element 20 m yagi. The reflector ends were flexing with more than 50 cm (1½ ft) amplitude and eventually about 1 meter (3 ft) broke off from both ends of it. The antenna was repaired and to prevent the same happening again, a thickish plastic rope was installed inside the length of all element pipes. The rope dampens the vibration, but doesn't increase weight much.

Stiff antennas are used on all ham radio bands, all the way up to microwaves. For lower frequencies verticals are the norm, but from 20 m and up yagis are a common choice. For VHF, UHF and up yagis are often used, but multi-element quads and different hybrid antennas can also be constructed from aluminium or copper pipe etc. with excellent results. However, some Finnish radio amateurs did build a full size 3-element yagi for 160 m (!) on a 100 m (330 ft) high rotating tower at their contest station OH8X ("Radio Arcala")! See for instance http://www.radioarcala.com/ and G7VJR's blog at https://g7vjr.org/2013/02/radio-arcala-visit-oh8x-finland/. So, anything is possible with enough money and manpower.

Please understand that all elements of any multi-element antenna are still ½ electrical wavelength dipoles, but the parasitic elements (reflector, directors) are connected to the feed line through the RF field created by the driven element! It doesn't matter what shape they are or how they are installed. In some antennas (like quad, quagi, delta loop etc.) some or all element lengths may be multiples of *½ electrical wavelength, which means in practice that there are two or more ½ electrical wavelength dipoles in series.* In multi-element antennas the gain is achieved by appropriate phasing of RF signals in each element, ie. by making the reflector slightly longer and director(s) slightly shorter than the driven element and by adjusting the spacing between elements.

Antenna element's thickness begins to have some significance already on 20 meters, because the used pipes must be fairly thick to handle the mechanical stresses and are a somewhat significant part of wavelength. On HF frequencies the element pipes are also often tapered in order to reduce weight and element drooping downwards (ie. thicker pipe in the middle and then decreasing sizes as needed towards element ends). The importance of element thickness increases the higher in frequency we go. In addition to other factors, element's physical length is affected by its thickness relative to wavelength. In any case all pipes and all joints in any stiff antenna must be able to withstand all the forces (including wind load) they are subjected to.

Stiff antennas are normally made for a specific ham radio band. They are not "all band" antennas. However, a stiff antenna can be made to work on several bands by using traps, separate elements for different bands or by having variable length elements.

There are many different kinds of stiff antennas:

a. Verticals

On HF bands vertical antennas are usually installed on the ground, but sometimes also elevated to some height with a mast pipe. On VHF, UHF and higher frequencies the vertical antennas are almost always installed above ground.

The advantage of vertical antennas is that they are omnidirectional, so they do not need an antenna rotator and usually the real estate occupied by them is smaller than with some other kinds of antennas. Their down side is that one can't get much gain out of them, especially on HF bands.

On VHF and UHF the gain of a vertical antenna can be increased by connecting two or more 1/2 wave sections in series and inverting the signal phase at every section joint (= ***collinear antennas***). One easy way to make a collinear antenna is to use for instance 5 to 10 pcs of 1/2 electrical wavelength sections of 50 ohm coaxial cable in series. Cross connect the centre wire and shield at each section joint. Then hang the whole thing from top and feed it through an impedance matching section at bottom. There are several other ways to achieve the same result. See detailed instructions in antenna books or internet.

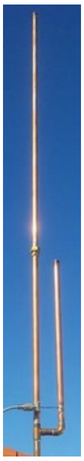
There are many kinds of vertical antennas in common use:

1. ***1/4 wavelength verticals*** are single band antennas with a ground plane of 4 or more 1/4 wavelength radials.
   - On HF bands the vertical part is usually made of aluminium pipe (possibly tapered). The ground plane is often made out of copper (or other metal) wires on (or under) ground, or possibly elevated above ground up to antenna's feedpoint.
   - On VHF and higher frequencies the vertical part may be an aluminium pipe or rod. The ground plane is often made out of stiff aluminium rods or pipes sticking out from antenna's base.
   - For VHF and UHF mobile use the vertical part is often made of flexible stainless steel wire or fibre glass stick with copper wire inside and the ground plane is actually vehicle's metal roof.

2. ***5/8 wavelength verticals*** are also single band antennas with a ground plane of 4 or more 1/4 wavelength radials.
   - 5/8 wave verticals are mostly used on VHF and UHF frequencies, but could also be made for higher HF bands. They have some gain (around 1.5 - 2 dB) relative to a 1/4 wave vertical, but they are also much (2.5 times) longer. This type of antenna needs a matching coil with tap between the vertical part and ground plane. The 50 ohm feedline is connected to coil's tap and ground plane.
   - On HF bands the vertical part is usually made of aluminium pipe (possibly tapered). The ground plane is often made out of copper (or other metal) wires on (or under) ground, or possibly elevated above ground up to antenna's feedpoint.
   - On VHF and higher frequencies the vertical part may be an aluminium pipe or rod. The ground plane is often made out of 1/4 wavelength stiff aluminium rods or pipes sticking out from antenna's base.
   - For VHF and UHF mobile use the vertical part is usually made of flexible stainless steel wire or fibre glass stick with copper wire inside and the ground plane is actually vehicle's roof. In mobile antennas the matching coil is often a steel spring, which flexes when driving, and the coax is connected to it with a small metal clamp.

3. ***Multiband verticals***. Basically a simple HF vertical antenna could be used for several ham radio bands, just like an end fed wire antenna. However, the vertical part's height must be roughly 1/4 electrical wavelength on antenna's lowest intended frequency. The radials must also be roughly 1/4 electrical wavelength long on lowest frequency the antenna is used for. This kind of verticals will always require an antenna tuner to match the impedance to 50 ohms. Depending on antenna's exact height, it may not be possible to match it on one or more ham bands because of very high SWR.

   HF vertical antennas are also made to work on several ham bands by using traps or separate linear tuning sections. Usually this kind of antennas can be fed with a single 50 ohm coaxial cable.



4. ***J-pole*** vertical antennas are nowadays mostly used on VHF and UHF bands, but they have also been constructed for HF bands. The antenna is basically an ***end fed*** ½ electrical wavelength long dipole in series with a 1/4 electrical wavelength "open wire line" shorted tuning stub (made of same pipe as the antenna by bending it into "J" shape), which matches the antenna impedance for instance to 50 ohm feedline. Antenna's gain is the same as that of a dipole (ie. 0 dBd or +2.14 dBi), which is 1 - 1.5 dB more than in a 1/4 wavelength vertical. This antenna was invented in 1909 and was originally used as German Zeppelin aircraft's trailing wire antenna.

5. ***HF mobile verticals***: Many vertical antennas have been constructed for HF band mobile operations from 80 meters and up. They are always single band antennas. The biggest problem for them is the very restricted height to prevent them hitting something while driving (like over hanging tree branches, bridges etc.). Because of low height (in wavelengths) these antennas are not the best for either transmitting or receiving, but are OK for their intended purpose. Still, even these antennas must be ***electrical 1/4 wave length*** tall, so the electrical length must be extended with a loading coil, either at antenna's base or somewhere in the middle. Another problem is that the vehicle's metal body must be used for ground plane and in almost all cases it is too small for the purpose. Vehicle's capacitance to real ground helps a bit with the ground plane problem, but depends a lot on the ground conductivity (like dry or wet tarmac, sand, soil etc.).

   In practice all that causes quite a low resistance (R ohms) and high reactance (-j ohms) at antenna's feedpoint, so some kind of adjustable L/C matching circuit must be located at antenna's base. The low feedpoint impedance also means that the RF currents at antenna's feedpoint are very high and especially the ground connection to vehicle's body must be bonded extremely well with the shortest possible length of ***thick*** wire. Some kind of wide copper braid (resembling coaxial cable's shield) is often used for this purpose.

   The mobile HF vertical antennas (including their matching circuit) are always very narrow band and cover only a small section of the ham radio band the antenna was designed for.

7. ***Directional verticals*** are single band HF antenna arrays. You can get a fair amount of gain out of these, but they occupy a lot of real estate. Basically 3 or 4 ***1/4 electrical wavelength*** verticals are installed for instance with 1/4 free air wavelength from each other in a triangle or square. Then the radiation direction is changed in steps with relay controlled coaxial phasing lines to individual antennas.

<u>b. Beam antennas</u>

The English expression "beam antenna" likely comes from the idea that unlike a vertical or dipole antenna, which radiate to all directions as a normal light bulb does with light, a beam antenna radiates a beam like a flash light or car's headlights.

"Stiff" beam antennas are usually made only for 20 meters and up to VHF and UHF frequencies. Some people are using even 40 m beams, but they are very big and mechanical construction requires special solutions.

The advantage of beam antennas is that they have power gain relative to dipoles or verticals. On HF bands the stiff beams are usually horizontally **polarized**, but for VHF and UHF they can have either polarization (horizontal or vertical) or even circular polarization. On HF bands antenna polarization makes no practical difference, because polarization can rotate whichever way it wants, when the signal is reflected from ionosphere. In addition to ionosphere's ever changing reflection properties, polarization rotation causes the "fading" or QSB in the received signals. On VHF and up antenna polarization becomes important, because even for DX the signal polarization does not rotate much. The VHF and UHF signal reflections are caused by other phenomena, like tropospheric scatter, ducting or refraction, sporadic E layer, aurora or meteor trail reflection etc. The attenuation for a received signal with wrong polarization is around -20 dB.

For fixed VHF and UHF stations the horizontal polarization is much preferred, because the antennas are usually installed fairly high (in wavelengths) and ground reflection has minimal effect, so the radiation is always more or less towards horizon.

In general vertical polarization is used for VHF and UHF mobile operations (including repeaters), because of easier antenna installation in vehicles.

However, in addition to various vertical "whips", I have also built many horizontally polarized, omni-directional 2 m mobile antennas, like halo, "Big Wheel" (cloverleaf - see photo), crossed dipole and slot ("Abe Lincoln", "trash can"). The Big Wheel was excellent even for DX with fixed stations, usually up to 300 - 400 km (215 - 265 mi) away, but occasionally to well over 1000 km (720 mi) distance ***while driving***. It is mechanically large, however, and was hard to keep on car roof at 120 km/h (85 mi/h) speeds on a motorway.

1. **Antenna matching.** Depending on the construction of the antenna feed system, a balun may or may not be needed:

   - ***Simple (split) dipole*** as the driven element of a yagi: Split dipoles are rarely used in HF band antennas, because of mechanical problems at the element centre. A 1:1 balun may be useful at HF antenna's feedpoint, but often it is not necessary, if the feedpoint impedance is 50 ohms. A split dipole could be used in VHF and UHF yagis, but one should not use a balun because of its losses.

   - ***Gamma match*** (from Greek letter "Γ" = capital "gamma"): These are used on all ham radio bands from HF to VHF and UHF. The gamma match has a capacitor (two overlapping pipes of different sizes, one inside the other and insulated from each other) and an inductor (a shorting bar from the inner pipe to driven element) in series. Because of the unbalanced nature of a gamma match, the coaxial cable must be connected directly to it, without any kind of balun. The gamma match is adjusted (both the capacitor and inductor) to get 50 ohm impedance at antenna's feedpoint.

   - ***T-match*** (from letter "T"): These matching systems are used on all ham radio bands from HF to VHF and UHF. The T-match is adjusted to get 50 ohm impedance at antenna's feedpoint by moving the shorting bars between T-section and driven element. A 1:1 balun may be useful at antenna's feedpoint, but often it is not necessary. In VHF and UHF yagis one should not use a balun because of its losses. *Note! The T-match in the picture is far too wide and works as a folded dipole (see below).*

- ***Delta match*** (from Greek letter "Δ" = capital "delta"): These matching systems are used mainly on VHF and UHF. For HF bands they would be mechanically too big. The delta match transforms driven element's impedance to 50 ohms or 200 ohms and is adjusted by changing the position of delta match wires on the driven element. If the matched impedance is 50 ohms, one should not use a balun on VHF and UHF because of its losses. If the matched impedance is 200 ohms, a low loss 1:4 coaxial "balun" (½ electrical wavelength loop of 50 ohm cable) can be used for impedance matching to 50 ohms.

- A ***folded dipole*** increases antenna's feedpoint impedance and is mainly used as driven element in VHF and UHF yagis. The impedance transformation ratio depends on the ***material thickness ratio*** of the driven part and the folded part of driven element. See a calculator at: https://owenduffy.net/calc/fdsurc.htm.

  Most often the material thickness is the same for both parts, in which case the impedance transformation ratio is 1:4. So, the whole driven element is made from a single piece of pipe or rod by bending it. This can be utilized in two ways:
  - To increase the feedpoint impedance to 50 ohms in an antenna, which would otherwise (using a normal dipole driven element) have an impedance of 12.5 ohms.
  - To increase antenna's feedpoint impedance for instance from 50 ohms to 200 ohms, so that a ladder line can be used to feed the antenna. This could be useful in a 4 x antenna array so that when the antennas are connected in parallel with equal lengths of 200 ohm feedline, the total impedance would be 50 ohms.

  Although the folded dipole is a balanced driven element, in VHF and UHF yagis one should not use a balun because of its losses. A low loss 1:4 coaxial "balun" (½ electrical wavelength loop of 50 ohm cable) can be used for impedance matching from 200 ohms to 50 ohms.

There are many kinds of stiff antennas in common use:

2. **Rotating dipole**. I don't see much point in these HF antennas, because a dipole's radiation pattern is almost a circle, with deep, sharp nulls towards element ends. They could only be useful, if one must reduce interference from some particular source by turning one antenna end towards it. You need an antenna rotator for these, but if you already have one, why not install a beam antenna on it instead.

3. **Single band yagi** is probably the most used beam antenna. They are usually built for HF from 20 meters and up and for VHF, UHF and up. Because of directional gain, these antennas always require an antenna rotator. They are easy enough to design for 50 ohm feedpoint impedance, so impedance matching circuits are not needed.

   The more elements (directors) a single band yagi has, the more power gain it has. For HF bands the max. number of elements is normally limited to 4 or 5, because of mechanical problems in building bigger ones. On HF bands the antennas must also usually be made

somewhat shorter (ie. to have a shorter boom) than what would be required for maximum gain available from the number of elements. That reduces antenna's power gain a bit. VHF, UHF and higher bands do not usually have such limitations for antenna's length, so it is possible to have for instance 15, 20, 30 or more elements to increase the gain. The gain is increased by roughly +3 dB ***every time antenna's number of elements is*** **doubled**, so eventually one reaches the point of diminishing returns for added elements.

Often a better way to increase antenna gain is to stack two or more same kind of antennas vertically or/and horizontally. Again, the gain is increased by roughly +3 dB ***every time the number of antennas is*** **doubled**. The gain increase is also affected by the stacking distances. For moonbounce (earth-moon-earth, moon used as a reflector) operations people have even built arrays of say eight 15 element yagis for VHF and sixteen 30 element yagis for UHF. Those antennas need two-axis rotators, too - horizontal and vertical. See more below at "H. Antenna stacking".

4. **Multi-band yagi** is probably the most popular beam antenna to use on several HF bands. They are not very practical for VHF and UHF frequencies. HF multiband yagis are usually built to cover 20 meters and two or more higher bands. Because of directional gain, these antennas always require an antenna rotator. Multi-band yagis are quite difficult to design, because the elements of one band are loaded and de-tuned by the elements for all the other bands. A lot of trimming, tuning and adjustments are required at design stage to make the antenna work as well as possible. It is also hard to design a multi-band yagi to have 50 ohm feedpoint impedance on all used bands, so often the manufactured antenna includes a suitable matching system.

   There are three common ways to make the yagi to work on several bands:

   a. ***Traps***: Each yagi element is built out of several sections, separated by frequency traps. The traps are simple L/C parallel resonance circuits, which stop the higher frequencies, but pass through the lower frequencies. Each trap is designed for a specific frequency division. So, for instance a yagi intended for 20 m, 15 m and 10 m bands has traps as follows:

      - Closest to boom are the 10 m / 15 m division traps on both sides of every element, so for 10 meter operation the elements are electrically of correct length.
      - Next (when counted from boom) are the 15 m / 20 m division traps on both sides of every element, so for 15 meter operation the elements are electrically of correct length (= 10 m element section + 10 / 15 m trap + 15 m element section).
      - The remaining electrically correct element lengths are used for 20 m operation (= 10 m element section + 10 / 15 m trap + 15 m element section + 15 / 20 m trap + the rest of element length).

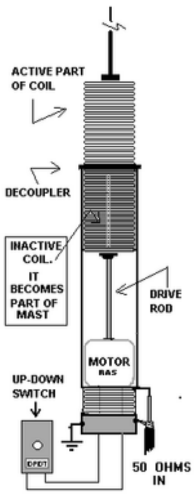
   Trap yagis are generally somewhat smaller and lighter than some other types of multi-band yagis. The element lengths are mechanically shorter, because the trap coils make each element look electrically longer than they actually are. Trap yagis can also be usually fed with a single 50 ohm coaxial cable. However, they have some drawbacks, too:
   - The antenna is always a compromise, because the same element positions on boom are used for all bands. On most bands that position does not produce the best possible gain. In practice it means that some antenna parameter(s), like gain, SWR, F/B ratio etc. must have been balanced between different bands to make the antenna operational. As a result the trap yagi cannot usually have quite as good gain on all bands as single band yagis with the same number of elements would have.
   - The trap capacitors and coils must be intended for high voltage, because a dipole's end (which in this case is the trap on the higher frequency) does have very high RF voltage. Depending on TX power, it can be several kV.
   - Mechanical problems are abundant, because the traps must be fixed only to (usually aluminium pipe) elements one way or another and different element sections must be electrically insulated from each other by the trap's housing. It is very difficult to build a trap, which can mechanically withstand for many years the forces of nature it is subjected to, like sun, wind, rain, snow, ice etc. These problems are the main reason, why a trap yagi must be taken down and repaired at some point.

- The traps do have losses, mainly because the RF must pass through the trap's coil to reach the lower frequency part of element.

b. Separate elements for different bands: This type of yagi antennas are fairly common on HF bands (most often covering 20 m to 10 m bands). 2-band yagis have also been built to cover the 2 m and 70 cm bands on the same boom, fed with separate feed lines. The HF yagi has one or more driven elements (possibly with traps) connected to the same 50 ohm feedline and separate parasitic elements (reflectors and directors) for different bands. Different bands can have the maximum number of elements (directors) that fit on the boom with optimum spacings. The antenna is basically designed as separate single band yagis installed on the same boom. This way each band can have the correct element lengths and spacings for best gain. However, because of loading and de-tuning to one band's elements caused by the un-used elements of all other bands, the antenna is still somewhat of a compro-mise between different bands. Loading and de-tuning effects must have been taken into account when designing the antenna.

c. Variable length elements: This type of HF yagi antennas are made commercially and as far as I know with 3 elements max. (reflector, driven element and one director). The element spacings are fixed, but element lengths can be adjusted continuously to have the best gain and 1.0:1 SWR on any frequency the antenna is intended for.

The basic idea is that the element material is lengthwise stiff, but otherwise flexible metal (something like in a metal tape measure). The elements are installed inside non-conducting pipes, often folded back to make antenna width smaller. Otherwise the plastic pipes could not handle high winds. So, from outside the elements look like folded dipoles, but that they are not. The element halves are rolled up at antenna's middle (boom) and driven by motors through gear boxes. The gears have different ratios for different elements, so that the same control can be used for all of them. This way the elements can be shortened and lengthened continuously as needed for every frequency from the bottom of lowest band (often 20 metres) up.



For HF, VHF and possibly UHF people have built "screwdriver" antennas (mostly verticals), where the element length is adjusted by 2-way remote control ("UP" - stop - "DOWN") to a DC motor, which turns a long screw through a gearbox. A battery operated screwdriver (with its inbuilt gearbox) is often used as the motor part, hence the name.

The downside for all these types of antennas is that because of many mechanically moving parts, things do wear out and repairs are needed every now and then.

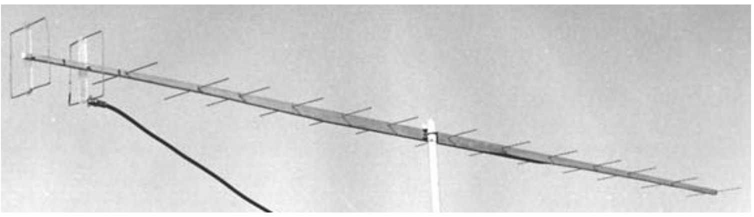
One thing to remember about antennas having ***yagi type elements***, especially on VHF and UHF bands, is that the ***way elements are installed on boom*** affects the element lengths:
- When elements are insulated from boom, there is no effect.
- When elements are attached on the boom pipe "side" (ie. usually top side) they must be slightly longer than insulated elements would be, because the boom partially short circuits the antenna element.
- When elements are installed through the boom pipe and connected to it, they need to be significantly longer than insulated elements would be, because the boom short circuits part of the antenna element.
- The element shortening effect depends on the boom pipe thickness and shape. A round boom shortens the elements a bit less than a square (or rectangular) boom, because the distance RF must "travel" around the boom is somewhat less.
- Antenna simulation software does not always have settings for boom size, shape or element installation method and there is no easy way to calculate the difference between insulated and non-insulated element lengths. However, many radio amateurs have done experiments about the "boom correction". See for instance:
    - http://dg7ybn.de/BC_numbers/BC.htm
    - http://www.sm5bsz.com/antennas/sa/others.htm
    - https://www.qsl.net/yu1aw/Misc/yagi_boom_correction.pdf
    - http://www.yu7ef.com/boom_correction.htm

There are many other types of "stiff" beam antennas, especially for VHF and UHF bands. Most VHF and UHF antennas are fed with 50 ohm coaxial cable. When used in antenna arrays the individual antennas may have much higher feedpoint impedance to be able to feed them in parallel with 50 ohm coax. Some examples:

- ***Quad***: For VHF and UHF bands these antennas are mostly made out of aluminium (or sometimes copper) pipes or relatively thick bars. The quad has about 3 dB more gain than a yagi with the same number of elements.

  While living in Lusaka (Zambia - 9J) in early 1980s, I built a rotating 4-element bamboo/wire quad for TV DX use on VHF-I band (European analogue TV channels 2 - 4, 47 - 68 MHz). We did not have the 6 m band, yet, and one could not get a Zambian radio amateur license those days. With the help of that antenna it was every now and then possible to watch even Spanish TV via trans-equatorial propagation, distance of approx. 6700 km (4160 mi).

- ***Quagi***: These antennas are a hybrid of quad and yagi elements. Usually the reflector and driven element are of quad shape and all directors are yagi elements. The quagi has about 3 dB more gain than a yagi with the same number of elements.



- ***Dipole array***: These antennas have a number of dipoles (like 4, 8, 16 etc.) over a reflector screen, which is either made as yagi type elements or as a combined reflector out of some kind of netting (like chicken wire). The gain can be quite high and depends on the number of dipoles.

- ***Corner reflector***: This antenna is basically a yagi, but the reflector is in the form of folded screen, made of pipes, rods, netting or metal sheet. This type of reflector increases antenna's gain a bit and improves significantly its F/B ratio.

- ***Hybrid double quad***: This antenna has two diamond quad radiators on top of each other, made as a single double-loop and fed with 50 ohm cable at centre. The reflector is just three (3) yagi type pipes on top of each other behind the radiator. A single hybrid double quad has about 8 dB gain over dipole in a relatively small size. I had an array of four (4) 2 meter band hybrid double quads (gain about 14 dBd) for many years in Finland and I was told that my signal was the strongest all over the place (including DX), when running 50 W of RF into it. The photo at left shows one hybrid double quad of my array of four. This antenna was designed by D. Roggensack (DL7KM) and it was first introduced in the German (East Germany = GDR) Funk-Technik magazine no. 9, May 1974.

- ***Crossed yagi***: This antenna has basically two yagis on the same boom, one horizontal and one vertical. The two yagis have separate feedpoints. The crossed yagi can be utilized in two ways:
  - To switch antenna polarization between horizontal and vertical for working with fixed (horizontal) or mobile (vertical) stations.
  - To achieve left or right hand circular polarization by phasing the two antennas correctly with short lengths of coaxial cable. Often also the direction of circular polarization can be reversed. Circular polarization is especially useful for EME (earth-moon-earth) operations, because signal polarization does rotate on the way and antennas with linear polarization (horizontal or vertical) will lose the very weak signal (which also has doppler shift), when the received polarization happens to be wrong. That's not the case with circular polarization.

5. **Helical antennas** are not so common for amateur radio use, but they have been built to fulfil specific antenna requirements. They are only used on VHF, UHF and higher frequencies. An axial mode helix would be far too large for any HF band. A helical antenna looks like a large coil, but the operating principle is not that of a coil, like in a resonance circuit or L/C filter. There are two types of helical antennas:

   a. ***Normal mode*** helix. These antennas radiate perpendicular to the helix axis. The spacing between "coil" turns is much smaller than 1/4 wavelength. People have built these for instance as short verticals for 160 m and 80 m operation. This type of antenna always needs a ground plane and L/C matching circuit. They don't have much gain, but if height is restricted, there isn't much of a choice.

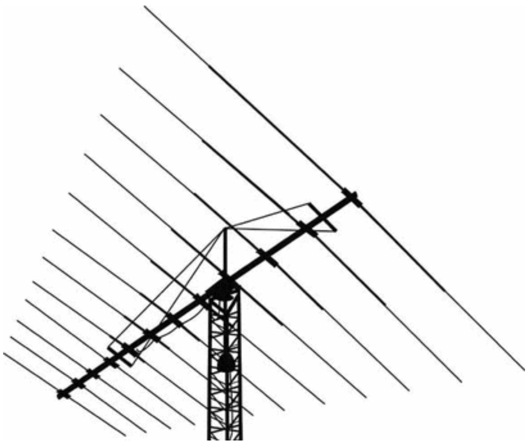
   These antennas are also used a lot for instance in 2 m band (145 MHz) handheld transceivers. Inside the rubber antenna is a normal mode helix. The ground plane is transceiver's frame plus your hand and body.

   b. ***Axial mode*** helix. These antennas radiate towards the end of helix axis and can have a lot of gain. This antenna requires a reflector (metal screen or plate) at the feedpoint. Each "coil" turn is approximately one full wavelength at the operating frequency. The spacing between "coil" turns must be 0.23 wavelength at the operating frequency. This type of antenna always transmits circular polarization. Polarization rotation is determined by the "coil" winding direction. This type of antenna can receive also linear polarization (vertical or horizontal) with about -3dB attenuation. Being a directional antenna, it always needs an antenna rotator. Depending on use, the rotator may need to turn the antenna both horizontally and vertically.

These antennas have been built for satellite and EME (earth-moon-earth) operation on 2 m (145 MHz) and 70 cm (435 MHz) bands. They are also used a lot for wireless networking (Wi-Fi etc.) on 2.4 GHz and 5 GHz bands.

My first experience of an axial mode helical antenna: We used one for receiving weather satellite photos on VHF, when I was working at Helsinki University of Technology (Finland) in early 1970's. The satellites were on fairly low orbit, so to track the satellite, the antenna had to be continuously turned (azimuth and elevation) manually on the roof, using headphones connected to the receiver in the lab. The photos were sent to Finnish Meteorological Institute and distributed to many newspapers.

6. **Log-periodic dipole arrays** (LPDA) are broadband directional antennas. Usually they have a series of different length half wave dipole (pipe) elements installed on a double boom, which is working also as the antenna's internal feedline. However, it can also be constructed using wire elements and suitable rope supports, if there is no need to turn it. All elements are driven elements, connected to the same (boom) feedline. The elements are spaced at intervals following a logarithmic function of frequency. The length of successive elements and the spacing between them gradually decrease along antenna's length. Depending on design, the bandwidth of a log-periodic dipole array can be quite large, for instance covering all frequencies from 40 m to 10 m bands.



   In general, at any given frequency the log-periodic design works sort of like a three-element Yagi antenna. The dipole element closest to resonance at operating frequency acts as the driven element, with the two adjacent elements on either side as director and reflector to increase the gain. The shorter element in front acts as a director and the longer element behind as a reflector. However, the system is more complex than that and all elements contribute to some degree, so the gain for any given frequency is higher than a 3 element Yagi has. Typically the gain of an LPDA is around 7 dBd, front-to-back ratio around -22 dB and SWR about 1.5:1 max. ***through the whole design frequency range***.

   For amateur radio, LPDAs are mainly used on higher HF frequencies, say 20 m and up. In general they are relatively big in size, but that is compensated by not needing more than one directional antenna for all bands. They can be constructed even from 40 m and up, but lower frequencies make the antenna a lot bigger (wider and longer).

C.3 Other types of antennas

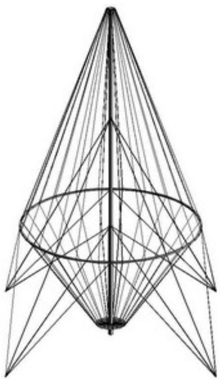
People have also built all kinds of un-conventional antennas. Some of them work better than others, especially for transmitting, but depending on their size, they may not be all that good for receiving. Some examples:

1. ***Tuned loop antennas***: These HF antennas are also called "Magnetic loops". The RF current in them is very high, so people see them as electrical RF magnets, although they (like every other antenna) radiate both a magnetic field ("H") and an electric field ("E"). The radiation pattern has deep nulls perpendicular to loop plane. Some radio amateurs are using these, because they don't have space for a full size antenna. See the many resources in internet.

   The antenna is basically a series resonant circuit consisting of a 1 turn coil (diameter say 50 cm ... 1.5 m, depending on frequency) made out of fairly thick copper pipe (for instance 20 ... 50 mm) and usually a variable capacitor. These antennas have very high Q, so they are very narrow band. Almost every time you change frequency, the antenna must be re-tuned. Note that the tuning can be easily done by peaking the received noise or RF signal on the operating frequency. Depending on the loop size and frequency, the bandwidth can be as little as 5 kHz (ie. a single SSB channel), and is likely no more that 20 - 25 kHz. In practice this means that the antenna must have remote tuning control at operating position, which runs the variable capacitor's motor. It is also possible to make an automatic tuning system for the antenna.

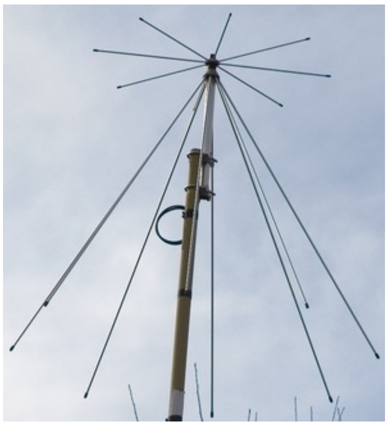
The tuned loop antenna can be made to work on several HF bands. That depends mainly on the variable capacitor's minimum and maximum capacitance. Note that the RF voltage across the capacitor is not much, when the antenna is tuned for the operating frequency. However, ***when the antenna is not tuned to operating frequency, the RF voltage across capacitor can be extremely high, even several kV***, depending on your transmitting power and frequency. A 1 mm spacing air variable capacitor may be able to handle up to about 50 W, but for any higher power you will need a vacuum variable capacitor with 5 ... 10 kV rating. The antenna is sort of OK for transmitting, but not the best for receiving. Antenna's radiation efficiency depends a lot on operating frequency (ie. band) and is lowest on lowest frequencies, but not all that good on highest frequencies, either.

There are several ways to match the tuned loop antenna to 50 ohm coaxial cable:
- A smallish coupling loop
- An L-match
- A Gamma match
- A T-match
- etc.



2. ***Conical monopole***. These are broadband vertical antennas, which need a ground plane. Depending on its size, it can cover for instance 3.5 MHz ... 30 MHz on HF or for instance VHF (145 + 220 MHz) and UHF (435 + 1260 MHz) bands. For HF they are built with a number of wires and for higher frequencies (VHF and up) one can use metal sheet. Radiation elevation angle of these antennas is quit low, close to horizon, so they are quite good for DX. They are relatively big in size, compared to other types of antennas.

3. ***Discone antenna***. These are also broadband vertical antennas. Basically it is a conical monopole (see 2. above) upside down, so that the ground plane is at top. Because the ground plane is above the antenna, there is no radiation above the horizontal plane. Because of shape, these antennas are very difficult to construct for HF bands, but they are used on VHF and up. The bandwidth can be up to about 10 times the lowest frequency (ie. 10:1). These antennas must be installed on a mast at least 1/4 wave length above anything conductive (including ground) at the lowest operating frequency.



4. ***EH antenna***. These are a "recent" development in attempts to make very short vertical antennas for lower HF bands. The name comes from the two fields radiated by all antennas: E-field (electric field) and H-field (magnetic field). In my opinion these antennas are completely useless, but some people have claimed some success with them. Basically the antenna is a very short doublet made of two short and thick cylinders on top of each other. Because of the extremely short length for operating frequency, the antenna is just a "large" capacitor with very high capacitive reactance. To match it to 50 ohm cable, it must be fed through a complex coil and capacitor system with quite high losses. It is also likely to have high RF levels (causing burns) through the coaxial cable's shield to ham shack. The antenna may sort of work with high losses for transmitting, but for receiving it is very poor because of its small size and losses. I would never recommend this antenna to anybody in any circumstances.

C.4 Antenna supports

Wire antennas need at least two support points, but they don't need to be very strong. Often trees or pipe masts are used for this purpose. Masts need to be guyed to keep them upright, but most of the time plastic rope is good enough for them, because they are not stressed all that much. Depending on the ground, you may need to put a rock or small concrete slab under the pipe to prevent it sinking in the ground, especially when the ground gets wet in rain. For instance my 45 meters long OCF doublet is supported at both ends with 5 m tall aluminium pipes, guyed with 6 mm plastic rope and it has stayed up for about 10 years now. The antenna feed point is attached to the rotating aluminium pipe mast on my roof.

Beam antennas need some kind of mast or tower to support them. The most common support is a pipe mast or triangular tower, which is held upright with three (3) guy wires. The guy wires should be fixed to ground at a distance 1/3 or more of mast or tower height from support's base. The guy wire fixings don't need to be all that strong, because they are not stressed terribly much. For instance for a 15 m high aluminium pipe mast with an array of four hybrid double quads on top, I have used lengths of Ø 10 mm (about 0.4") concrete reinforcement steel hammered at a suitable angle into ground. The mast was guyed with three Ø 6 mm plastic ropes.

The easiest way to keep a mast or tower upright is with plastic rope. If needed, it can be fairly thick, like 10 or 12 mm (3/8 or 1/2 inch). All plastic ropes stretch, however, so they may need to be tightened periodically. There is also special non-conductive, fibre-glass cored guy wire available, which does not stretch, but it is more expensive. One can also use for instance Ø 6 mm steel cable for the purpose. However, metal guys may be resonant on one or more operating bands, so they may need to be split into two or more sections using insulators. This depends a lot on the actual guy wire length.

Some people are considering or using free standing masts or towers to avoid the need for guy wires. That may be a possibility, but depends on many factors, for instance:
- Mechanical stress at the mast or tower. The antenna support must be really strong, because the highest stress caused by wind load (which includes both the antenna and mast or tower) is at the base. ***One must calculate the maximum stress caused by the worst storms in your area***. If the support is too weak, it will most likely bend or break near the base. Then the whole antenna system falls down, possibly causing damage to your own or your neighbour's house, car, etc.
- Ground under the mast or tower. If the ground is just soil, one must have a big concrete block to keep the support upright. Depending on the ground type (how soft it is and how wet it can get in heavy rainfall), the block may need to be several cubic meters (or cubic yards) of concrete. In some countries the ground

freezes in winter (even down to over 2 meters / 6 ft depth) and that will add more problems. If the ground is rock, the mast or tower can be bolted directly to it, but that again depends on the type of rock. Granite is very strong, but for instance limestone doesn't hold much anything.

C.5 Antenna rotators and antenna direction

C.5.a Finding the exact North or South

It is important to know the ***geographic directions*** for antennas, especially the rotating ones, otherwise it is not possible to point them towards the desired area. However, finding out some exact direction (say North or South) from your location may not be so easy. There are several ways to try doing it:

- **Magnetic compass** is the worst possible way to find geographic directions. Depending on the surroundings and the location of your QTH the magnetic compass is likely to have large errors:
  - Any magnetic metals nearby, like reinforcement steel embedded in concrete, steel pipe masts etc., will affect the compass needle and there is no way to know how large the error will be.
  - Depending on your location, the ***geomagnetic*** North and South (which is shown by the compass) and ***geographic*** North and South may be in completely different directions and ***you need the direction to geographic North or South***. The ***geomagnetic poles are not in the same locations as the geographic poles*** and the geomagnetic poles are also moving all the time. At the moment (2024) the geomagnetic North pole is located at 80.8°N / 72.6°W (Ellesmere Island in North Canada) and the geomagnetic south pole is located at 80.8°S / 107.4°E (In Antarctica, towards Australia from geographic South pole). When operating in Crete (Greece), the difference between geomagnetic and geographic direction is about 11°. From New York (USA) the difference is 0°, from Los Angeles (USA) about 8°, from Juneau, Alaska (USA) about 18°, from London about 15° and from Edinburgh about 17°.

- **GPS**: Most GPS (Global Positioning System) receivers have also a function to show the geographic North (and South). However, make sure that the ***display accuracy is better than say ±2°***, or the error in detected direction is too large for antenna directions. For instance a 45° (= 1/8 of full circle) accuracy does not help at all! As long as the GPS receiver is able to synchronize to satellites, it is not affected by the surroundings. The "compass" directional accuracy of my GPS vehicle navigator (made by Garmin) is only ±22.5°, so it was not useful at all.

- **Map**: Depending on your location, you may be able to use a map to determine geographic North. The UP direction in most maps is North. I have used with success Google Maps with the "Satellite" display, because it will also show everything on the ground, like trees, roads, other buildings etc. Depending on your location, Google Maps web site may be different from the one I am using (https://www.google.co.uk/maps/). North in Google Maps is always straight UP.

  I used Google Maps for my ham radio antennas, because their -3dB beam widths are fairly large (±20° to ±40°) and high directional accuracy is not needed.

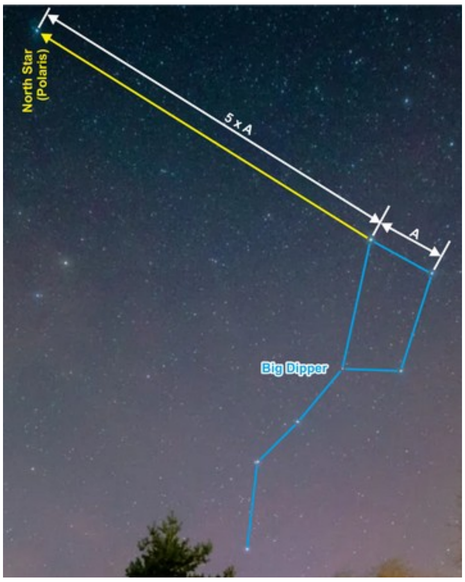
- **Sun time**: Basically the sun is exactly towards South at noon in Northern hemisphere and North in Southern hemisphere, but: ***You must know what local time corresponds to 12:00 noon in sun time!*** In most countries the local time and sun time are not exactly the same. There are on-line calculators for this purpose. One of them is: https://koch-tcm.ch/en/uhrzeit-sonnenzeit-rechner/ ("Local to solar time calculator"). The page is in English. For sun time calculation you will need:
  - Your Longitude in degrees, including decimal parts, East or West (Latitude is not needed).
  - Current local date.
  - Your time zone. For instance UK = "0", Greece = "+2", New York, USA = "-5". "+" means ahead of UTC time, "-" means behind UTC time and the number is hours. UTC = "Coordinated Universal Time", which must always be used for logging amateur radio contacts. Also note that UTC is a 24-hour clock (***not 12-hour AM / PM***).
  - Local time. Accuracy should be better than ±30 seconds.
  - If Daylight Saving Time ("summer time") is in effect or not.
  - Click the "Calculate result" button and the current sun time is calculated.
  - Next change the ***local time*** until the calculated sun time is exactly "12:00" after clicking the "Calculate result" button. ***Now you know what local time corresponds to 12:00 in sun time***. Write down the ***local time***.

You will need some kind of exactly vertical stick, which will show a shadow on the ground (or roof or whatever). Depending on your location and time of year, ie. how high the sun will be around noon, the stick may need to be some meters (or yards) high to have a long enough shadow. If you already have installed the antenna mast or tower, you can use that for the purpose. Next ***wait until the local time is exactly as set in the calculation above*** (ie. the ***local time*** corresponding to 12:00 sun time) and mark the direction of sun's shadow on the ground (or roof or whatever). For instance push a peg in the ground, put a piece of tape on the roof etc. The shadow is pointing exactly to geographic North.

Note that the shadow direction mentioned above is for Northern hemisphere. In Southern hemisphere the shadow will be pointing South and North is exactly the opposite direction (ie. 180° from the shadow).

I used this method for installation of my rotating, polar mounted Ø 1.8 metre (about Ø 6 ft) satellite TV dish, which requires better than ±1° directional accuracy.

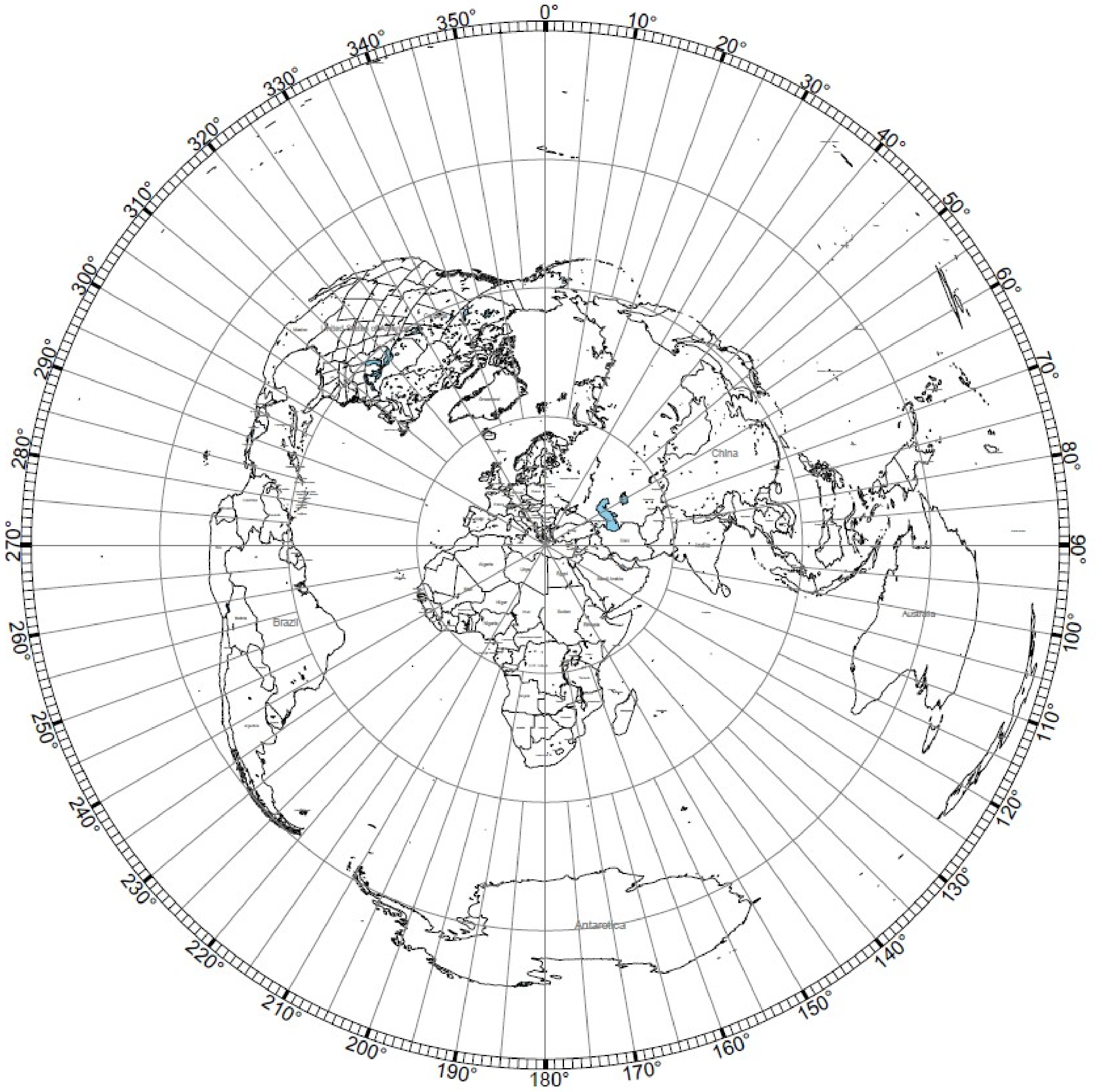
- **North Star (Polaris)**: At night time in Northern hemisphere, when the sky is clear, it is possible to find North by locating the North Star (Polaris) in the sky. North star is exactly above the geographic north pole:
  - Install about 1 m (3 feet) long piece of pipe (Ø 10 - 25 mm, ½ - 1 inch) for instance on a camera tripod.
  - Locate the North Star in the sky.
  - Look through the pipe and adjust the tripod so that North Star is centred within the pipe.
  - Lock the camera tripod adjustments in place. Leave the tripod with its pipe where it is for the rest of night.
  - Next day check the horizontal (azimuth) direction of the pipe. North is exactly in that direction. The directional accuracy may not be better than about ± 3°, but it is good enough for all amateur radio antennas.



C.5.b *Finding antenna directions to all around the world*

An other important thing for correct antenna directions is to have a great circle map (azimuth map) of the world, centred in your station's location. Because Earth is a sphere ("ball"), without a great circle map you may point your antenna to a completely wrong direction. For instance: When operating in Crete, Greece, USA is towards North-West (not towards West, as one might expect) and Japan is towards North-East (not towards East, as one might expect). In both cases the difference is about 45°! Alaska is directly to North and South Africa directly to South from Crete. There is free software available in the internet, which allows you to print a map according to your particular requirements. Some software you can download to your own computer and run it there. Some programs create the map on-line, which can then be copied and printed. Some Great Circle Maps from internet:
- NS6T, which can be used at https://ns6t.net/azimuth/azimuth.html.
- SM3GSJ's "GcmWin", which can be downloaded from https://www.qsl.net/sm3gsj/ .
- VE6EP's "Azimuth3", which can be downloaded from https://www.qsl.net/ve6yp/index.html .
- W4ENE's "Pizza", which can be downloaded from https://tonnesoftware.com/pizza.html .

On the next page is an equidistant great circle map centred in my location near Chania in Crete, Greece. Map circles are at 5000 km (3107 mile) intervals.



C.5.c Rotator and antenna installation

Most antenna rotators are made in such a way, that the "0" position ***in controller*** is towards North. By "0" position I mean the direction, across which the antenna cannot be rotated. In practice the rotator scales are marked in degrees so that the count increases in clockwise direction:
- North ("N") = 0°
- North-East ("NE") = 45°
- East ("E") = 90°
- South-East ("SE") = 135°
- South ("S") = 180°
- South-West ("SW") = 225°
- West ("W") = 270°
- North-West ("NW") = 315°
- North ("N") again = 360°

This means that the antenna must be installed on the rotator in such a way that it always points to the correct direction.

When installing the rotator and antenna:

1. Before installing the rotator, make a temporary (short) connection between the controller and rotator. Then run the rotator so that the controller shows exactly North (ie. 0°).

2. Disconnect the temporary cable and disconnect the rotator controller from power to make sure that the controller is not accidentally run to some other position. The antenna rotator itself is powered by the controller. Most antenna rotators work in such a way, that the rotator itself is always turned to the position set in the controller, also after re-connecting the cable. *However, check the rotator's manual for operation!*
3. Install the rotator in the tower or mast. Connect rotator's control cable to the rotator.

4. Install the antenna(s) on the rotator, so that they are pointing towards North, as determined in section C.4.a above.

5. Install the antenna coaxial cable(s) to antenna(s). ***Make at least 2 or 3 VERY LOOSE cable turns around the rotator and/or its antenna installation pipe to make sure that the coaxial cable(s) are not pulled tight when the rotator is turning the antenna(s).***

6. Fix the control and coaxial cables to the mast or tower. You can use cable ties or for instance pieces of stiff insulated wire every 30 cm (1 ft) or so for the purpose. The idea is that the cables must not flap in wind against the mast or tower.

7. Connect the rotator control cable to the controller.

8. Connect power to the controller.

9. Test the antenna rotator system by turning the antenna all the way around to both directions and check that nothing hits anything or breaks when the antenna(s) are turning. This is easiest to do, if there is another person running the controller and you look yourself at the antennas.

10. Connect the coaxial cable(s) to your radio(s).

D. Baluns and un-uns

There are two completely different kinds of baluns: a voltage balun and a current balun. They cannot be used interchangeably, because of their different design. They are intended for different purposes:
- A ***voltage balun*** is used for ***impedance transformation*** and line balancing purposes.
- A ***current balun*** is not really a balun (impedance transformer), but a common mode choke, which ***stops*** RF signal on the ***outer surface*** of coaxial cable's shield. It could for instance return to the ham shack. The forward signal towards antenna "travels" ***inside*** the coaxial cable, between centre wire and inner surface of cable shield.
- There is no such thing as a "bal-bal" (balanced to balanced) unit. If you need impedance transformation between two balanced lines, you must use a real RF transformer with two separate windings.

D.1 Voltage baluns and un-uns

All voltage baluns and un-uns are RF ***impedance*** transformers. The difference between the two is that a balun (balanced to unbalanced) performs also the balanced to unbalanced transformation, un-un (unbalanced to unbalanced) is unbalanced at both input and output. All voltage baluns are wound on a core (which could be air in some cases) as an ***auto-transformer***, ie. with a single winding with one or more additional connections somewhere in the middle. The impedance transformation ratio depends on balun's or un-un's design, starting from 1:1 and up to 16:1 or even more. For HF frequencies these units are usually made on a core (often a powdered iron or ferrite toroid) using a single winding with one or more taps, like in an auto-transformer. In general baluns or un-uns are not used on VHF and higher frequencies because of difficulties in designing one and their relatively high losses. At VHF and UHF frequencies the needed impedance transformations are performed with short lengths of feedline (most often coaxial cable), which has significantly lower losses - see section E.2 below.

Note! Most of the time you cannot use a balun, if an un-un is needed or vice versa, because of their different design principles!

Many different baluns and un-uns are manufactured commercially, but many radio amateurs also make them themselves according to their own requirements. There are several factors to consider when buying or making a balun or un-un:

- ***Impedance transformation ratio***. This depends only on your specific requirements, ie. on the impedance, which must be transformed to 50 ohms. For all amateur radio baluns and un-uns the reference is 50 ohm coaxial cable to transmitter, so one side of the unit must be designed for 50 ohms. The other side must have more or less the required impedance. Note that depending on the balun or un-un design, the impedance transformation may be up or down. For instance a 4:1 balun may be ***either*** from 200 ohms to 50 ohms, ***OR*** from 12.5 ohms to 50 ohms, ***but not both***. Note also that baluns and un-uns cannot be designed for every transformation ratio. The most common ratios are 1:1, 2:1, 4:1, 6:1, 9:1 and 12:1.
- ***RF Power handling***. This depends mainly on the core size and material, but also on wire thickness. Higher (average) power requires a bigger core and thicker wire. If one exceeds the specified power level, the core saturates losing its magnetic properties and both the core and wire may heat up so much that the core shatters. Commercial baluns are generally specified only for ***peak power*** ie. for SSB and CW. Remember that SSB signal's ***average*** power (which causes balun heating) is only around 15 to 25 % of continuous carrier power, so for instance a commercial 1 kW balun can be used with only 250 W maximum power, when running digital modes (like RTTY) or FM.
- ***Frequency range***. This depends a lot on the balun or un-un design, including core material. It is somewhat difficult to make a balun or un-un, which covers for instance the whole HF spectrum from 160 m to 10 m without impedance transformation ratio or loss variations, especially for higher power levels (up to 1500 W). For low frequencies the biggest problem is core material and size. For high frequencies the biggest problem is stray capacitance between winding turns. Often one must compromise and accept a bit higher losses at the lowest and highest frequencies.

D.1.a Selecting balun or un-un core

The size and material for a balun's or un-un's core depends mainly on required RF power and frequency range. Higher power and/or lower frequencies require a larger core. Traditionally people have used "undersized" powdered iron cores for high power, because they saturate at higher temperatures than ferrite cores. That has sometimes lead to balun's melted plastic box, although the balun itself was still working. Nowadays most home-made baluns are wound on ferrite toroids, because of their higher permeability, which results in less wire turns and lower stray capacitance in the balun or un-un winding, meaning better high frequency range. ***Note that because this is an RF transformer, the core must be able to handle without heating your maximum transmitting power!*** *That is enough for a single band balun.* ***But, if the balun is intended for a multiband antenna, it may need to handle ALSO up to 10:1 antenna side SWR!***

It is generally accepted, that a voltage balun winding's inductive reactance, at lowest frequency the balun will be used for, must be at least four (4) times the impedance, to which the balun winding is connected to. So, for instance for a 50 ohm coaxial cable the winding's inductive reactance must be at least 200 ohms. In practice this means that a fairly big core is required for 160 - 10 m and 1500 W, or otherwise a few smaller cores of same material can be piled on top of each other and the winding done through the whole stack. However, do not use cores, which are too small, or your winding does not fit through the centre hole. Note that the available inductance for the same number of turns will double every time you double the number of cores. On the other hand you will need less turns on the core stack to get the same inductance. So, for instance, if the inductance for 16 turns on one (1) core is 0.96 µH:
- Inductance for two (2) stacked cores is 1.92 µH, so you'll need only 8 turns for 0.96 µH.
- Inductance for four (4) stacked cores is 3.84 µH, so you'll need only 4 turns for 0.96 µH.
- Inductance for eight (8) stacked cores is 7.68 µH, so you'll need only 2 turns for 0.96 µH.

There is no easy way to select a core needed in a balun or un-un. However, I have used with success F1FRV's spread sheets available from: http://f1frv.free.fr/main3c_Baluns.html . The page is in French. Scroll all the way down to "Téléchargement des feuilles de calculs et de quelques docs:" ("Download the spreadsheets and associated docs:") line and click the "BALUNS.ZIP" link. Save the *.ZIP file into a convenient folder in your PC, and then extract the compressed files into the same folder. Open the "Baluns_rev0b2-.XLT" file, which is for toroidal core baluns. You could also use the "Binocular_Baluns_rev2b2-.xlt" file, which is for binocular style baluns. These are Excel spread sheets both in English and French. There are also several other files and folders in BALUNS.ZIP. Note, however, that although these spreadsheets are largely self-explanatory, you still need to have some basic understanding of RF transformer design, or you will end up with a balun, which does not work as intended. One important thing is to make sure that the winding covers fairly evenly about 75 ... 80 % of core circumference. So, the number of turns must be somewhat sensible. For instance 2 turns are far too few, but say 5 or 6 turns or more are OK.

Many people have experimented with different RF power levels on cores of different sizes and materials, but usually only in "laboratory" environment and perfect termination for the balun or un-un. It seems the best ferrite for wide band HF baluns and un-uns (160 m to 10 m and even 6 m) is nowadays material #61 (Micrometals/Amidon). It offers better overall performance than material #43 used in earlier designs. However, you can also use other materials according to your frequency and bandwidth requirements.

Note! In addition to F1FRV's spread sheets mentioned above, I have not been able to find any sensible recommendations for selecting a ferrite toroid core for voltage balun or un-un. *There are a lot of balun instructions for instance in internet, but they NEVER mention the balun's frequency range or power handling capability. On the other hand commercial manufacturers do give balun's power handling and frequency range, but they NEVER tell the core's size and material.* So, unfortunately I am not able to give you more instructions on this subject.

<u>D.1.b Winding a balun or un-un</u>

There are different ways to wind a balun or un-un, depending partly on the required impedance transformation ratio. For more winding information check the RSGB or ARRL antenna handbooks or the many internet sources.

Balun or un-un winding must have high enough impedance, ie. inductive reactance, at the lowest frequency the balun will be used. In general it is accepted that if the 50 ohm side has about 4 times the required impedance (4 x 50 ohm = 200 ohm) at lowest frequency, the unit will work well enough on all frequencies it is designed for. The impedance for the other side must be calculated according to impedance transformation ratio. ***Note that impedance transformation ratio IS NOT winding's turns ratio!*** The calculations are relatively simple:

1. As an example for a 4:1 balun, calculate the required inductance for the 50 ohm side: $\mathbf{L = X_L / (2 \times \pi \times f)}$, where:
   - L = the required inductance in ***Henries***. Convert value to microHenries (µH) by multiplying the result by 1000000 (= 1 million).
   - X_L = inductive reactance, ***200 ohm in this case***.
   - "2" is just a multiplier.
   - π = mathematical constant π (3.14159)
   - f = the lowest frequency the balun or un-un must work ***in Hz***. For instance "1800000" Hz (= 1.8 MHz) in this example.
   - The inductance is needed for calculation of required wire turns on your selected core.

2. Calculate the required number of turns for the 50 ohm side. If you use only core manufacturer's published data, the calculations are somewhat complex. It is much easier to use a PC program intended for this particular purpose. I have used successfully for many years the free "mini Ring Core Calculator" written by Wilfried Burmeister, DL5SWB (SK), available from: https://mini-ring-core-calculator.software.informer.com/1.2/. The program can be used for all kinds of other coil calculation purposes, too, of course. It runs in German, English and French:

   a. Select the type of core you have from the tabs on top:
      - "Iron powder T" = Amidon's (Micrometal) T cores
      - "Ferrite FT" = Amidon's (Micrometal) FT cores
      - "SIFERRIT" = Ferrite cores made by TDK / Epcos
      - "Ferroxcube" = Ferrite cores made by Ferroxcube

- "Unknown Cores" = The core material is unknown. Requires the use of tool included in the program ("R_L ? μ_i", window's upper left corner).
- "Air Cores" = Air-core coils
- In this example select "Ferrite FT"

b. Select the core size from the FT50 ... pull-down menu.
- In this example select "FT114".

c. Select the core material from the 43 ... pull-down menu.
- In this example select "61".

d. Enter the inductance calculated at step 1 above to the "Inductance" box and use the µH ... pull-down menu to select the inductance multiplier ("nH", "µH", "mH" or "H").
- In this example enter "21" (µH) and select "µH" as the multiplier.
- The results are:
  - "Turns" box shows the number of wire turns (7 in this example). ***Note! toroid core turns are counted ONLY when the wire passes through the core centre*** *Wire outside the centre hole does not count for turns!*
  - "Length (wire)" box shows the required wire length for this winding in centimetres (cm), 18 in this example. Use somewhat longer wire for coil connections. To convert the length to inches, divide the shown number by 2.54.
  - "max. D (wire)" box shows the maximum wire diameter for this winding in millimetres (mm), 5.76 in this example. ***Note! Do not use this wire thickness for balun or un-un winding!*** *The core will have one or more other windings, too, so much thinner wire must be used!*

e. Enter the lowest frequency into the "Frequency" box and use the MHz ... pull-down menu to select the frequency multiplier ("Hz", "kHz", "MHz" or "GHz").
- In this example enter 1.8 (MHz) and select MHz as multiplier.

f. Check that the inductive reactance is more or less correct in the "XL =" box.
- In this example the box shows "237.504 Ω", which is very good for 50 Ω feedline, which requires 200 Ω reactance. It is always better to deviate towards higher reactance.

3. Calculate the number of turns for the non-50 ohm side of balun or un-un. In this example the required impedance of non-50 ohm side is 200 ohm, ie. we are designing a 4:1 balun. The formula is quite simple:
T = SQR (Z1 / Z2), where:
- T = ***ratio*** of turns for the non-50 ohm side.
- "SQR" is square root
- Z1 = the impedance of higher impedance side (200 ohm in this example)
- Z2 = the impedance of lower impedance side (50 ohm in this example)

So: Z1/Z2 = 200 / 50 = 4 and square root of 4 = 2. ***In this example you need 2 times the turns number of low impedance side for the high impedance side***, ie. 14 turns (from step 2.d above).

However, remember that this is a balun or un-un, which is ***wired as an auto-transformer***. So in this case you will actually need two (2) parallel 7 turn windings on the core, which are connected in series. The 50 ohm side is connected across one of the windings and the 200 ohm side across both series connected windings. Then you will have the required 2:1 turns ratio (= 4:1 impedance ratio).
- For a ***balun***, the 50 ohm coaxial cable's shield is connected to windings centre tap and centre wire to one end of the winding. The 200 ohm side is connected across the whole winding.
- For an ***un-un***, the 50 ohm coaxial cable's shield is connected to one end of the winding and centre wire to the centre tap. The 200 ohm side is connected across the whole winding.

D.2 Current baluns

These units are only intended for ***preventing*** RF from entering the coaxial feed line shield's ***outer surface***, where it could be conducted to the ham shack and cause problems there. Feedline radiation could also cause problems (interference) to other nearby equipment. A current balun has normally 1:1 impedance transformation ratio. However, they have also been made for transforming the feedline 50 ohm impedance to 200 ohms. This type of current balun must use two (2) separate cores and windings.

Because the main purpose of a current balun (common mode choke) is to ***stop*** RF signals on the lowest operating frequency, it must have quite high inductive reactance. It is generally accepted that at lowest operating frequency the reactance must be at least 100 times the line impedance. For a 50 ohm coaxial cable it means that the reactance at lowest frequency must be at least 5000 ohms. However, because there must not be any power going through the current balun core, it can be fairly small, but the wire or cable must be able to handle your maximum transmitting power. Remember that all your transmitting power is going through the winding and travels between parallel winding's wires or ***inside*** the coaxial cable.

There are several ways to achieve the required 5000 ohm reactance, like:
- Bifilar winding on one or more ferrite toroids.
- Winding a thinnish coaxial cable on one or more ferrite toroids.
- Several ferrite tubes or snap-ons installed on a piece of coaxial cable.
- Or a combination of those above.

D.2.a Bifilar winding on toroid core

Basically you must make a 50 ohm parallel transmission line, which is wound on the core. ***Parallel (not coaxial!) 50 ohm cables are not available commercially.*** This line must be able to handle your maximum transmitting power without heating. It must also be long enough (ie. to have enough turns) to achieve the 5000 ohm impedance goal ***for each wire*** on the lowest operating frequency, when wound on the ferrite core. However, there can be three problems with the parallel line itself:
- Making a parallel line with 50 ohm impedance is quite difficult, because the wire spacing must be very small. Thin wires result in far too high line impedance, so fairly thick wires are needed to achieve the 50 ohm impedance.
- The parallel line must be very well insulated from the core and the wires from each other, because depending on your transmitting power, frequency and the antenna side real impedance, the peak RF voltage at line's antenna end can be 1000 V or more. So the wires must be insulated separately with teflon (PTFE) tubing (or wound with teflon insulated wire) to prevent flash-over to the core and between wires. The extra insulation increases wire separation, which then increases significantly the line impedance.
- The wire pair distance from each other must be held constant for the whole winding. The pair turns are separated from each other as needed, to cover say 80% to 90% of the core circumference.
- An example: If Ø 2.0 mm (AWG #12) dynamo wire is used, 50 ohms is achieved when the center-to-center distance between the wires is 2.176 mm (0.087"), so 0.176 mm (6.93 mil) remains between the wires. But after both wires have been insulated with Ø 3.0 mm (0.118") Teflon tubing (wall thickness 0.5 mm = 0.0197"), the parallel line's impedance is over 82 ohms!

D.2.b Coaxial cable on toroid core.

When using an actual coaxial cable for current balun winding, you will not have problems with the line itself. However:
- The cable must be able to handle your maximum transmitting power without heating. RG-213 can take any ham radio power, but it is very stiff. RG-58 can handle up to 150 W or so and it is a bit more flexible. There are also available relatively thin teflon (PTFE) insulated 50 ohm coaxial cables, which can take quite high transmitting power. They are relatively easy to wind on a ferrite toroid, or if needed a stack of them, to achieve the 5000 ohm reactance goal. For instance:
  - **RG-142**: Diameter 4.95 mm (0.195"). 3.2 kW up to 30 MHz into 50 ohm load.
  - **RG-316**: Diameter 2.5 mm (0.098"). 430 W up to 30 MHz into 50 ohm load.
- ***Note! Do not use any kind of foam insulated cable for winding on a toroid core!*** It will short circuit sooner or later, because the soft foam insulation is not able to hold the centre wire in place in the very tight corners of a toroid core.
- Depending on your transmitting power, frequency and the antenna side real impedance, the peak RF voltage at line's antenna end can be 1000 V or more. So the cable may need to be insulated with teflon (PTFE) tubing to prevent flash-over from cable shield to core.

D.2.c Ferrite tubes or snap-ons on coaxial cable

This is likely the easiest way to make a current balun. Just push suitable size ferrite tubes over a piece of coaxial cable or install snap-on ferrites on it. Most likely you will need more than one tube or snap-on to achieve the 5000 ohm reactance goal on the lowest operating frequency. If you have an L/C meter, measure the inductance between the ***two ends of coaxial cable shield*** and calculate the reactance:
X_L = 2 x π x f x L, where:
- X_L = Inductive reactance. It should be around 5000 ohm.
- "2" = just a multiplier.
- π = Mathematical constant π (3.14159)
- f = The lowest operating frequency ***in Hz*** (for instance 1.8 MHz = 1800000 Hz)
- L = The measured inductance ***in Henries (H)***, for instance 53 µH (microHenries) = 0.000 053 H (Henries).

If (ie. when) this kind of balun is installed outside, it would be a good idea to weather protect it for instance with heat shrink tubing and/or silicone. The ferrite material is iron based, after all, and it will eventually rust if it gets wet. I have no idea how much, if at all, the corrosion would affect balun's performance.

D.3 Hybrid balun

Both the voltage and current balun have their limitations in RF sense, mainly in the frequency range, impedance stability and common mode rejection. The hybrid balun solves most of those problems, but it is a lot more complex than a simple voltage or current balun. It was first described by Andrew Roos (ZS1AN) in QEX September/October issue in 2005. The PDF file is available from:
http://www.arrl.org/files/file/Technology/tis/info/pdf/QEX_Sep_2005_p29-34.pdf

Basically a hybrid balun has a voltage balun and balanced current balun connected in series. The voltage balun is located at the 50 ohm feedline side and current balun at "high impedance" side:
- The 1:1 voltage balun is wound on a single ferrite toroid core as usual.
- The balanced 4:1 current balun is wound on two separate ferrite toroid cores, each of which has a 1:1 current balun. For "primary", ie. the 50 ohm side, one winding of the two cores are connected in parallel. For "secondary", ie. the 200 ohm side, the other windings of the two cores are connected in series. So, now you have a 200 ohm to 50 ohm (4:1) current balun.

I have built a 1500 W 4:1 hybrid balun using 3 stacks of four FT240-43 cores (I didn't have #61 material cores available at the time). It is on my roof in a plastic box, weather proofed of course, and feeds my 45 m long OCF (Off Centre Fed) doublet. It works very well. When terminated to 200 ohms at high impedance side and measured with an antenna analyzer at feedline side of voltage balun, the impedance remains at 50 ohms (±0.1 ohm) all the way from 1.8 MHz to 30 MHz. No impedance dips or peaks at any frequency.

E. Feed lines

A common misconception seems to be that a feedline must be of a certain length or that it must not be a certain length. ***These "rules" are generally not true!*** They are applicable only in some special cases, where the feedline itself is used as an impedance transformer. (See "E.2 Impedance matching using feed lines" below). Normally every matched feedline can be of any length.

The basic requirement is that a feedline must be terminated ***at both ends*** (transmitter and antenna) to line's nominal impedance, for instance to 50 ohms for the most commonly used coaxial cables. Then the power transfer from transmitter to antenna is most efficient and the cable can be of any length, within reason. On HF bands there are usually no limitations for matched cable length, unless the cable is many 100s of meters or feet long. For VHF and UHF frequencies cable's attenuation (loss) needs to be taken into account. For instance it makes no sense to heat the cable with half of transmitter's output power, if cable's attenuation on the used frequency is -3 dB.

E.1 Feedline types

The most common feedline used in ham radio systems is 50 ohm coaxial cable. There are many other kinds of feed lines commonly available, too:

- 75 ohm (or 73 ohm) coaxial cable: These cables are the standard for TV (and radio) antennas and cable TV networks, but they can also be used for ham radio, especially if such impedance is needed for impedance matching. In general, 75 ohm cables have a bit lower attenuation than 50 ohm cables of the same diameter.
- Ladder lines (window lines): These are balanced feed lines available with at least 300 ohm and 450 ohm impedances. They have significantly lower losses than coaxial cables, but they must be terminated with balanced feeds at both ends (like a folded dipole driven element in antenna and a balun at transmitter end). Years ago the 300 ohm (or 240 ohm) lines were used for analogue (B/W) TV antennas. The down side of ladder lines is that they must be held at least 3 x line's width apart from everything electrically conductive, like mast pipes, gutters, metal roofs, trees (when they are wet) etc.
- Open wire line: These are "high impedance" balanced lines and they have significantly lower losses than coaxial cables. They should be terminated with more or less balanced feeds and line's "nominal" impedance at both ends. In general open wire lines are made at home by using two parallel wires (electrical installation wires are quite OK) and keeping them apart with 10 cm (4", +/- a lot) long insulator pieces at say 30 cm (1 ft) intervals. In most cases the line's exact impedance is not so critical, because they are mainly used for feeding multiband HF wire antennas, the feedpoint impedance of which can vary a lot between different bands. So the open wire line's impedance can be for instance from 400 ohms to 1000 ohms. I think the most commonly used impedance is about 600 ohms. There are on-line calculators for balanced and other types of feed lines. One open wire line calculator is at http://www.smrcc.org.uk/tools/OpenWire.htm. The down side of open wire line is that they must be held at least 3 x line's width apart from everything electrically conductive, like mast pipes, gutters, metal roofs, trees (when they are wet) etc.
- There are cables available for other impedances, too. Those mentioned above are just the most common ones for ham radio.

E.2 Impedance matching using feed lines

Every length of any feed line acts as an impedance transformer, ***when it is not terminated to line's nominal impedance*** in one end or at both ends. The line's length does not matter for the impedance transformation ***action*** as such. However, if the feedline, instead of a balun for instance, is actually used for impedance transformation purpose to match an antenna system, the matching section length should be as short as possible. This is because the matching section itself has the highest SWR in the whole antenna system with associated high losses.

Impedance transformation with feedline section(s) is in common use on VHF, UHF and higher bands, because their losses are a lot lower than in other kinds of matching circuits. Sometimes these matching cables are called "coaxial baluns". They are, however, also used in certain types of multiband HF antennas instead of a balun. Years ago I made a 4:1 HF coaxial balun by winding RG-213 on a section of Ø 11 cm (4.3") PVC sewer pipe to feed 600 ohm open wire line to my parallel OCF doublet antenna on all HF bands (160 m - 10 m), see https://pa0fri.home.xs4all.nl/Ant/Balun/balun%20eng.htm . That balun worked very well. In general the matching section length is calculated as part of ***electrical wavelength*** on the operating frequency.

Electrical wavelength is not the same as RF signal's wavelength over the air!

Every other medium, like coaxial cable, ladder line etc., slows the RF signal's speed down, which makes the wavelength shorter when measured in metres or feet. The difference between over-the-air wavelength and electrical wavelength is called "***velocity factor***" and is expressed as a percentage or decimal number relative to over-the-air wavelength. The physical (= electrical) wavelength is needed for all kinds of antenna system calculations, like feedline lengths for impedance transformation sections, tuning stub lengths and positions, antenna phasing lines etc. Velocity factor examples for some mediums:
- Air and space: 100% or 1.00
- 50 ohm coaxial cable with solid polyethylene (PE) insulation (RG-58, RG-213): 66% or 0.66
- 50 ohm coaxial cable with foam polyethylene insulation (Ecoflex 10): 85% or 0.85
- 75 ohm coaxial cable with solid polyethylene (PE) insulation (RG-59): 82% or 0.82
- 75 ohm coaxial cable with foam polyethylene insulation (RG-6): 85% or 0.85
- 300 ohm window line (ladder line): 91% or 0.91
- 450 ohm window line (ladder line): 90% or 0.90
- 600 ohm open wire line: 98% or 0.98

So, as you can see from above, the ***electrical wavelength*** is in most cases a lot shorter than the over-the-air wavelength, especially in coaxial cables, meaning that also the actual cable lengths are physically shorter.

Note that there are significant velocity factor variations between different cable types and in same type of cables made by different manufacturers! So, if a piece of feedline must be of a specific length (in wavelengths), please check the specifications for the particular cable you are using (don't rely on the list above) and use its stated velocity factor for cable length calculation. Note also that the measured length must include possible cable connectors. This is not so critical on HF bands because the connector "lengths" are very small parts of wave length, but it ***is important*** on VHF or UHF frequencies and up, where the connector "lengths" are significant parts of wavelength.

For instance, if an antenna's feedpoint impedance is not 50 ohms, as required by the coaxial cable to transmitter, the impedance matching can be done with length(s) of transmission lines instead of a (lossy) balun. Especially on VHF and UHF frequencies the matching with short lengths of cable is also mechanically much easier to do than using other kinds of matching circuits. There is one problem with matching feedlines, however, especially on HF bands: The matching section is always relatively narrow band and is usually calculated for the band centre. It works only on one band. In general each amateur radio band needs a separate matching section, but they cannot be connected in parallel or series. From this follows that feedline matching sections can only be used with single band antennas. However, if the matching section is made of high impedance line, like ladder line or open wire line (as in Windom antennas, for instance), the matching can work on several ham radio HF bands.

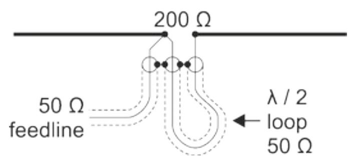
Often a 1/4 electrical wavelength of coaxial (or other) cable can be used for impedance matching. In that case the ***impedance of this series matching section*** can be calculated for any antenna and feedline impedances using the formula **Zo = SQR (Zs x Zl)**, where:

- Zo = Impedance of 1/4 electrical wavelength matching section.
- SQR = Square root
- Zs = Source impedance (feed line to transmitter).
- Zl = Load impedance (antenna's feedpoint impedance).

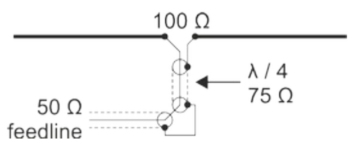
Note that if needed for covering the mechanical distance between feedpoints of separate antennas, it is possible to use also odd multiples of 1/4 electrical wavelength (like 3/4, 5/4 etc.) for the impedance matching cable sections. *Do not use even multiples of 1/4 electrical wavelength (like 2/4, 4/4 etc.) for matching sections. They* ***will not*** *work as intended!*

For coaxial cable matching sections it would be best to use as low loss pieces of cable as possible, to reduce losses caused by high SWR in these sections, regardless of the feedline type to transmitter and individual antenna cables in an array. Some commonly used examples for impedance matching with lengths of coaxial cable:

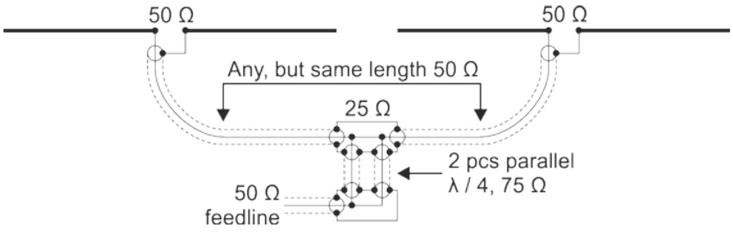
a. ***Antenna impedance is 200 ohms and feedline 50 ohms***: Use a ½ electrical wavelength loop of 50 ohm cable to match the antenna.



b. ***Antenna impedance is 100 ohms and feedline is 50 ohms***: Use 1/4 electrical wavelength matching section of 75 ohm cable in series from antenna's feedpoint and the antenna is matched to 56 ohms. To 50 ohm feedline the SWR is then 1.12:1, which is good enough for all practical purposes. If you have 70 ohm cable available for the matching section, the matching would be even better, resulting in 49 ohms for feedline and an SWR of 1.02:1.

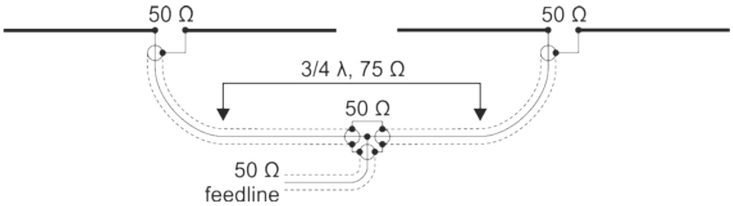


c. You have an ***array of two (2) 50 ohm antennas and 50 ohm feedline*** to transmitter. In this case you need an impedance transformation from 25 ohms to 50 ohms. Using the formula above for a 1/4 electrical wavelength matching section, the impedance is 35.4 ohms. That kind of cable is not available, but if you connect two (2) 1/4 electrical wavelength 75 ohm cables in parallel, the combined cable impedance is 37.5 ohms. To 50 ohm feedline the SWR is then 1.06:1, which is good enough for all practical purposes. If you have 70 ohm cable available for the matching section, the matching would be even better, resulting in 49.4 ohms for feedline and an SWR of 1.01:1.



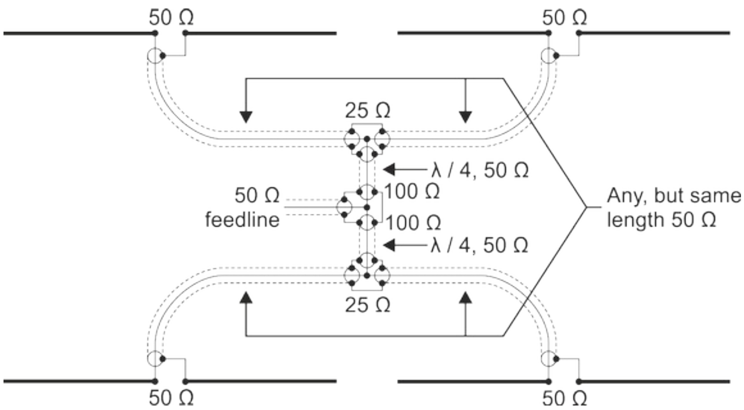
There is also another way to achieve the same result. In this case you need an impedance transformation from 50 ohms to 100 ohms. Using the formula above for a 1/4 electrical wavelength matching section, the impedance is 70.7 ohms.

Use two 3/4 electrical wavelength matching sections of 75 ohm cable from each antenna's feedpoint and the array is matched to 56 ohms. To 50 ohm feedline the SWR is then 1.12:1, which is good enough for all practical purposes. If you have 70 ohm cable available for the matching section, the matching would be even better, resulting in 49 ohms for feedline and an SWR of 1.02:1.

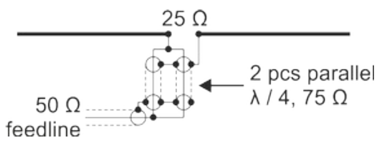


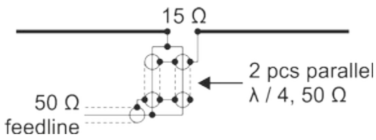
I am using this matching system for the 2 x 4 element antenna array for 2 m on the roof. I designed my antennas for 56 ohm feedpoint impedance, so the matching for 50 ohm feedline is 50 ohms and SWR is 1.0:1.

d. You have an ***array of four (4) 50 ohm antennas and 50 ohm feedline*** to transmitter. If you connect all four antennas in parallel, the combined impedance would be only 12.5 ohms and SWR would be 4:1! So, don't do that, but connect the four antennas together as in the drawing below. The matching system can be expanded using the same principle for instance for an array of 8 or 16 antennas.



e. ***Antenna impedance is 25 ohms and feedline is 50 ohms***: Using the formula above for a 1/4 electrical wavelength matching section, the impedance is 35.4 ohms. That kind of cable is not available, but if you connect two (2) 1/4 electrical wavelength 75 ohm cables in parallel, the combined cable impedance is 37.5 ohms and for two 70 ohm cables 35 ohms. With 75 ohm parallel matching cables the SWR to 50 ohm feedline is 1.12:1, which is good enough for all practical purposes. If you have 70 ohm cable available for the matching section, the matching would be even better, resulting in 49 ohms for feedline and an SWR of 1.02:1.





f. ***Antenna impedance is 15 ohms and feedline is 50 ohms***: Using the formula above for a 1/4 electrical wavelength matching section, the impedance is 27.4 ohms. That kind of cable is not available, but if you connect two (2) 1/4 electrical wavelength 50 ohm cables in parallel, the combined cable impedance is 25.0 ohms. With 50 ohm parallel matching cables the resulting impedance to 50 ohm feedline is 54.8 ohms and SWR is 1.10:1, which is good enough for all practical purposes.

g. ***Other matching systems***: There are also many other ways to use feedline for impedance matching, like:
- Two cable sections of different impedances in series. The original website is down, but you can download the calculator from https://www.softpedia.com/get/Science-CAD/Series-Matching-Calculator.shtml .
- Pawsey balun (see for instance https://owenduffy.net/blog/?p=14882)
- Matching stub: An open or short circuited feed line stub can be used for matching any impedance ratios (like any antenna impedance to 50 ohm feed line). I tried to find a working calculator for matching stubs in internet without success, but there are many other resources with formulas and Smith charts available.

F. SWR and transmitting power

SWR ("Standing Wave Ratio") is a quality indication for ***antenna system's*** matching.

SWR should be more correctly abbreviated as VSWR ("Voltage Standing Wave Ratio"), because it is usually measured as voltages related to forward and reflected power. Basically 1.0:1 SWR means that the antenna system is perfectly matched and any reading higher than that (for instance 1.5:1 or 2.3:1) means that there is some mismatch in the antenna system. ***But note: an SWR meter measures the matching situation only at that point, where its measuring bridge is located***. So, in mismatched situation the reading shown by an SWR meter is valid only for that particular point in the antenna system and is often not the actual SWR at antenna's feedpoint nor at transmitter's output. ***Note also that an SWR meter shows only the impedance ratio relative to 50 ohms. It does not show, if the impedance is higher or lower than 50 ohms.*** The SWR reading is always 1.00:1 or higher. It can never be less than 1.00:1.

Note! Always keep an eye on your SWR meter when transmitting! This is especially important, if you are using a linear amplifier! The transmitter's RF output power must go somewhere and could cause damage in the case of high SWR! If the SWR is higher than normal, it means that something has happened to your antenna system! For instance:
- The antenna feedline is damaged or disconnected.
- The antenna tuner is misadjusted.
- The antenna itself is damaged.
- A balun in the feedline is damaged.
- etc.

It is very simple to calculate the SWR, if you know the two impedances at a mismatched joint, for instance the feedline impedance and antenna's feedpoint impedance. Generally the feedline impedance is always known: 50 ohms for the most common coaxial cables. Depending on the antenna's feedpoint impedance, use the following two formulas:

- Antenna feedpoint impedance is higher than cable impedance: **SWR = Za / Zc**, where:
  - SWR = Standing Wave Ratio as a decimal number
  - Za = Antenna's feedpoint impedance
  - Zc = Cable's nominal impedance
  - For instance: Antenna impedance is 135 ohm, feedline impedance 50 ohm: SWR = 135/50 = 2.70:1 ***or***
    Antenna impedance is 50 ohm, feedline impedance 50 ohm: SWR = 50/50 = 1.00:1

- Antenna feedpoint impedance is lower than cable impedance: **SWR = Zc / Za**, where:
  - SWR = Standing Wave Ratio as a decimal number
  - Zc = Cable's nominal impedance
  - Za = Antenna's feedpoint impedance
  - For instance: Antenna impedance is 28 ohm, feedline impedance 50 ohm: SWR = 50/28 = 1.79:1 ***or***
    Antenna impedance is 50 ohm, feedline impedance 50 ohm: SWR = 50/50 = 1.00:1

When the antenna system is not perfectly matched (ie. SWR is higher than 1.0:1) the transmitter power (= forward power) is partly reflected back from antenna's feedpoint (= reflected power). At transmitter end the reflected power is again partly re-reflected towards antenna, because the transmitter "sees" an impedance, which differs from its specified load impedance (50 ohms in most cases). The two reflections happen repeatedly until all power of that RF wave has been dissipated either by radiation from antenna or loss in the feedline.

Every feedline has some loss (although it may be quite low), which depends on the line's inherent loss (per meter or foot), cable's length and operating frequency. The longer a line is, the more loss it has and the higher we go in frequency, the more loss it has (per meter or foot). So, every time the "same RF wave" travels through the cable, some of the power is lost as heat.

Unfortunately in ham radio community there is a common misconception that the reflected power is "absorbed" by transmitter's output circuits and can cause damage there. ***In general that is not true!*** Basically all transmitter power (minus loss caused by the back and forth reflections in feedline) is always radiated by the antenna. Feedline loss is the main reason to strive for low SWR, because with higher SWR the RF signal has to "travel" the length of feedline more times, before it is radiated by the antenna, and every "trip" increases the power loss. However, for lower SWR readings the loss may not be significant. For more clarification see for instance K5DVW's article "Understanding SWR by Example", available at:
https://www.arrl.org/files/file/Technology/tis/info/pdf/q1106037.pdf

In some specific cases of very high SWR readings (say 5.0:1 or more), there is a ***theoretical*** possibility of transmitter damage:
- The load impedance "seen" by the transmitter is extremely low, in single ohms range. In that case transmitter's output stage may have to deliver more RF current than it is designed for. This may lead to output stage over heating and damage.
- The load impedance "seen" by the transmitter is extremely high, in three- or four-digit ohms range. In that case transmitter's power amplifier may not be able to handle the very high RF voltage and over voltage breakdown may occur in the output stage.

--- !!! HOWEVER !!! ---

- All modern transmitters, which utilize bipolar or MOSFET ***transistors***, have ***internal protection for excessive SWR*** and they start reducing the output power to protect the power amplifier, when SWR exceeds the design limit (often 2.0:1). High power linear amplifiers have usually an ALC output to transceiver and the transceiver itself takes care of drive power reduction to linear amplifier (ie. it lowers RF voltage and current).
- ***Valve*** transmitters don't usually have internal protection, but they are also ***more tolerant to high SWR***. Valve linear amplifiers also have often an ALC output to transceiver:
  - Valve's internal resistance is relatively high and it simply cannot deliver much more RF current into a low impedance load than what the power stage is designed for. From this follows that the RF voltage at transmitter's output goes down and output power becomes lower with lower load impedance.
  - Valves are run with quite high anode (plate) voltage and can usually withstand temporary RF voltages many times the anode voltage. If the high impedance load condition continues for a long time (while transmitting), valve anode may start overheating, which could mechanically damage the valve itself (glass bulb melts or ceramic envelope cracks). This is because the valve cannot get rid of all the RF output power to antenna, so the excess power must be lost as heat in the anode.

F.1 Feedline losses

Even when the feedline is terminated to its nominal impedance at both ends (ie. measured SWR is 1.0:1), it still has inherent loss, which depends on the cable type and operating frequency. Feedline RF loss is converted to heat, mostly in cable's internal insulation material. In low loss coaxial cables the internal insulation is mostly air, in higher loss cables usually some kind of solid plastic (often polyethylene). On HF bands that loss is usually not significant, but on VHF, UHF and higher frequencies one must keep the feedline as short as possible. For instance it makes no sense to heat the cable with half of transmitter's output power, if the cable itself from transmitter to antenna has -3 dB loss. If the measured SWR is higher than 1.0:1, the cable's inherent loss is still there, but the total loss is increased because of RF signal's reflections back and forth. *Note that all cable manufacturers' attenuation figures are always given only for a matched condition, ie. when the SWR is 1.0:1. The attenuation increases with increasing SWR.*

Especially on VHF and UHF frequencies one must also consider the following situation:
- SWR meter is at transmitter end of feedline.
- Coaxial cable has some loss, of course, let's say -3 dB.
- In this case the antenna may have quite high SWR (for instance 5:1), but because of feedline loss, which hides the antenna end SWR, the SWR shown by the meter can be almost perfect (ie. 1.0:1). ***So SWR meter's display is not correct.*** The signal radiated by the antenna will be down a lot from what is available from the transmitter and the lost part of power is converted into heat in the coaxial cable itself.
- Here is an extreme example: Take a 100 m (328 foot) roll of RG-58. Connect one end through an SWR/power meter to say 100 W, 70 cm (UHF) transmitter. Leave the other end open. The transmitter is happily running with full power and 1.0:1 SWR into the cable, although there is nothing in the other end. After a while the cable starts warming up (you can feel it with hand, for instance), because all transmitter power is lost in the cable.

Attenuation values for some cable types:

See also the two notes after the table below!

In the table below attenuation for different frequencies is given for 100 metre and 100 foot cable lengths, when the cable is terminated to its nominal impedance at both ends.

Cable type	Frequency (MHz)	Attenuation (dB/100 m / dB/100 ft)	Frequency (MHz)	Attenuation (dB/100 m / dB/100 ft)
RG-58C/U (50 ohm)	5	2.7 / 0.82	400	30.0 / 9.15
	10	4.1 / 1.25	600	37.9 / 11.6
	50	9.7 / 2.96	1000	51.8 / 15.8
	100	13.9 / 4.24	1500	65.6 / 20.0
	200	20.4 / 6.22	-	-
RG-213/U (50 ohm)	5	1.2 / 0.82	400	13.7 / 4.18
	10	1.8 / 0.37	600	15.9 / 4.85
	50	4.3 / 1.31	1000	23.1 / 7.04
	100	6.4 / 1.95	1500	30.4 / 9.27
	200	9.5 / 2.90	3000	48.9 / 14.9
RG-59B/U (75 ohm)	5	2.4 / 0.73	450	25.7 / 7.84
	55	8.4 / 2.56	600	30.3 / 9.24
	187	16.1 / 4.91	1000	40.0 / 12.2
	300	20.7 / 6.31	-	-
RG-11A/U (75 ohm)	50	4.2 / 1.28	500	15.5 / 4.73
	100	6.2 / 1.89	600	17.1 / 5.21
	200	9.3 / 2.84	860	21.1 / 6.43
	400	13.8 / 4.21	1000	23.4 / 7.13
300 ohm ladder line (DX Engineering)	5	0.43 / 0.13	No data available for higher frequencies!	
	10	0.49 / 0.15		
	50	0.89 / 0.27		

Cable type	Frequency (MHz)	Attenuation (dB/100 m / dB/100 ft)	Frequency (MHz)	Attenuation (dB/100 m / dB/100 ft)
450 ohm ladder line (Wireman 552)	5	0.39 / 0.12	400	4.66 / 1.42
	10	0.56 / 0.17	600	6.07 / 1.85
	50	1.35 / 0.41	1000	8.57 / 2.61
	100	2.00 / 0.61	1500	11.4 / 3.76
	200	3.02 / 0.92	3000	19.0 / 4.88
RG-62A/U (93 ohm)	5	1.9 / 0.58	400	17.0 / 5.17
	10	2.4 / 0.73	600	21.1 / 6.41
	50	5.8 / 1.76	1000	27.8 / 8.45
	100	8.2 / 2.49	1500	34.7 / 10.6
	200	11.8 / 3.59	3000	52.6 / 16.0
Ecoflex 10 (50 ohm)	5	0.76 / 0.23	432	8.46 / 2.57
	10	1.14 / 0.35	500	9.12 / 2.77
	50	2.66 / 0.81	1000	13.5 / 4.14
	100	3.80 / 1.16	1500	17.0 / 5.17
	200	5.51 / 1.68	3000	25.4 / 7.72
RG-6 (75 ohm)	67.5	6.29 / 1.91	750	19.8 / 6.02
	100	7.25 / 2.20	1000	23.3 / 7.08
	143	8.46 / 2.57	1500	30.0 / 9.12
	270	11.3 / 3.44	2000	34.9 / 10.6
	540	16.2 / 4.92	-	-
1/2" (12.7 mm) Heliax (50 ohm)	10	0.67 / 0.21	800	6.46 / 1.97
	50	1.52 / 0.46	1250	8.23 / 2.51
	150	2.67 / 0.82	1500	9.09 / 2.77
	300	3.84 / 1.17	2000	10.7 / 3.25
	450	4.80 / 1.45	3000	13.4 / 4.09

Note 1! The feedline attenuation values above were picked from data sheets of different manufacturers and are for reference only. Do not take them as absolute values for all cables with the same type number! Always use the data sheet values from the manufacturer of your cable!

Note 2! I have noticed that some people do not understand what the cable attenuation values given in data sheets actually mean for their particular length of cable. The data sheet values DO NOT APPLY for every cable length! They are valid only for the specified 100 m or 100 ft lengths! The mathematics is really simple: Multiply the data sheet attenuation value ***given for your operating frequency*** by the length of your cable ***RELATIVE*** to the 100 m or 100 ft length given in data sheet in same length units. So, for instance:

- Your cable is 15 m long: 15 m / 100 m = 0.15. The attenuation for your cable is the data sheet value for 100 m length multiplied by 0.15: Data sheet 9.8 dB/100 m x 0.15 = 1.47 dB.
- Your cable is 150 m long: 150 m / 100 m = 1.5. The attenuation for your cable is the data sheet value for 100 m length multiplied by 1.5: Data sheet 9.8 dB/100 m x 1.5 = 14.7 dB.
- Your cable is 35 ft long: 35 ft / 100 ft = 0.35. The attenuation for your cable is the data sheet value for 100 ft length multiplied by 0.35: Data sheet 2.96 dB/100 ft x 0.35 = 1.036 dB.

- Your cable is 200 ft long: 200 ft / 100 ft = 2.0. The attenuation for your cable is the data sheet value for 100 ft length multiplied by 2.0: Data sheet 2.96 dB/100 ft x 2.0 = 5.92 dB.

There are also other, much lower attenuation 50 ohm coaxial cables available, than what is listed above, like 7/8" (Ø 22.2 mm) and 1-1/4" (Ø 31.7 mm) Heliax and other even thicker ones. They are mostly used in high power radio and TV broadcasting. They are much more expensive than the more common types and require special (expensive) connectors. In worst case they may even need to be pressurized with dry nitrogen gas to keep all moisture out from inside the cable. Moisture increases attenuation. But if the feed line loss at the operating frequency is an actual issue, like in 50 kW UHF TV transmitter's antenna feed up a 200 m (660 ft) high tower, one doesn't have much of a choice.

When selecting a cable for your antenna system, there are also a *couple of other important things* to remember:

- Cable's ***minimum bending radius*** is given in cable's data sheet. You ***must not bend*** the cable into sharper "corners" or tighter coils than what is specified, because if that is done, something in the cable (especially nominal impedance) will not fulfil the specifications and something (like cable shield and/or centre wire) may even break in it without showing anything outside the cable.
- Solid dielectric coaxial cables (like RG-213) are mechanically much ***stronger***, but they also have higher attenuation. Foam dielectric coaxial cables (like Ecoflex 10) have lower attenuation, but they are also mechanically ***weaker***. Foam dielectric cables have a tendency to short circuit, especially in too tight bends near connectors, because the soft insulation foam is not able to hold the centre wire in its place at cable's centre. Also, if any soldering is required for instance in a cable connector, the foam insulation melts much easier than solid insulation and a short circuit may appear already at that stage.

F.2 Cables, connectors and transmitting power

There are limitations on how much power a cable and associated connectors can handle. The maximum allowed power depends also a lot on transmitting frequency and SWR in the length of cable.

Measuring a transmitter's accurate output power can be a bit problematic. In general RF power and SWR meters sold for amateur radio purposes are not well calibrated and their accuracy is often no better than ±10 %. The accuracy also varies a lot according to frequency and can be even worse than that, for instance ±15% or ±20 %. In practice this means that if for instance the meter reads 100 W, the transmitter's real output power can be anywhere between 80 W and 120 W. Additional error is caused, if the meter has "traditional" pointer meters, because one cannot be sure about scale accuracy and reading a meter's pointer adds to the error. Usually a digital display in the power / SWR meter is more accurate than a pointer meter, but that again depends on the meter's calibration accuracy. Professional power meters are generally more accurate, but see the specifications. For instance the well known Bird 43 is specified for only ±5 % accuracy and although the pointer meter's scale is likely accurate, reading the small meter will cause more error.

Some examples of max. allowed power for different cables, when they are matched to nominal impedance at both ends:

- **RG-58** (50 ohm): 150 MHz = 210 W, 450 MHz = 150 W
- **RG-213** (50 ohm): 50 MHz = 1860 W, 150 MHz = 1074 W, 450 MHz = 620 W, 1000 MHz = 416 W
- **RG-59** (75 ohm): 50 MHz = 452 W, 150 MHz = 261 W, 450 MHz = 151 W, 1000 MHz = 101 W
- **RG-11** (75 ohm): 10 MHz = 2800 W, 100 MHz = 810 W, 200 MHz = 450 W, 400 MHz = 370 W, 1000 MHz = 110 W
- **Ecoflex 10** (50 ohm): 10 MHz = 3100 W, 100 MHz = 960 W, 500 MHz = 410 W, 1000 MHz = 285 W
- **RG-6** (75 ohm): 10 MHz = 1500 W, 30 MHz = 750 W. No info about higher frequencies.

Note 1! The maximum allowed power values above were picked from data sheets of different manufacturers. Do not take them as absolute power for all cables with the same type number! Always use the data sheet values from the manufacturer of your cable!

Note 2! If there is any significant SWR (say over 1.5:1) in the length of cable, the maximum allowed power must be reduced a lot because the RF voltage and/or current does exceed the cable's design values. As a rule of thumb: divide the specified power value by the SWR reading. For instance: SWR = 1.5:1, specified max. power is 150 W, so allowed max. power is in this case 150 / 1.5 = 100 W. In general, this is not a problem for matched feed lines, but it is important for impedance matching cable sections (see D.2 above) and for instance feed lines from antenna tuner to antenna, because the SWR in those lines can be quite high.

Some examples of RF power the connectors themselves can handle, when the attached cable has no SWR (ie. SWR is 1.0:1). The max. allowed power through connectors goes down with increasing frequency. Note that a connector's RF power handling is usually not specified. What is specified are the max. (DC) voltage and max. (DC) current, but you cannot determine RF power handling from those values because of skin effect:

- **UHF (PL-259 / SO-239)**: 100 MHz = 500 W.
  Note! UHF connectors ***are not 50 ohm connectors****, although they are used a lot in ham radio equipment.* The theoretical impedance is about 35 ohms, so these connectors should only be used on HF, 6 meter and possibly 2 meter bands, where the connector "length" is a small part of wavelength and does not affect SWR much. ***Never use UHF connectors on 70 cm and up***. Some hams call the UHF connector an "armoured banana connector". Note also that coaxial cable's ***shield should always be soldered*** to the UHF plug. Unsoldered shield connections are quite unreliable in these connectors and may cause unexpected behaviour in the antenna system. UHF connector was designed in 1930's, when all frequencies above 30 MHz were considered to be UHF.
- **BNC (50 ohm)**: 1000 MHz = 316 W.
- **BNC (75 ohm)**: 1000 MHz = 316 W.
- **N (50 ohm)**: 20 MHz = 5000 W, 2000 MHz = 500 W.
- **F (75 ohm)**: These connectors are mainly used in TV and satellite antenna networks to over 2 GHz. They are fast and easy to install on cables. I haven't found any power specifications for them. However, because the coaxial cable's centre wire (often plain copper) is used as male connector's centre pin, with somewhat unreliable contact to female socket, the power handling cannot be all that much. As a guess 100 W max. on HF bands and 10 W max. on VHF.
- ***All cable connections outdoors must be weather sealed***, to prevent moisture and water getting in the connectors and cables. Any amount of water will cause corrosion and does increase significantly cable losses. I use self-amalgamating rubber tape and/or silicone for this purpose.

Note 1! The maximum allowed power values above were picked from data sheets of different manufacturers. Do not take them as absolute power for all connectors of the same type! Always use the data sheet values from the manufacturer of your connectors!

Note 2! If there is any significant SWR (say over 1.5:1) in the length of cable, the maximum allowed power through connector must be reduced a lot, because the RF voltage and/or current does exceed values the connector was designed for. As a rule of thumb: divide the specified power value by the SWR reading. For instance: SWR = 1.5:1, specified max. power is 500 W, so allowed max. power in this case is 500 / 1.5 = 333 W. In general, this is not a problem for matched feed lines, but it is important for impedance matching cable connectors (see D.2 above) and for instance feedline connectors between antenna tuner and antenna, because the SWR in those lines can be quite high.

Some radio amateurs say that they are using all the above mentioned cables and connectors (except RG-6 and F type) with 1500 W (and higher) RF power on HF and VHF frequencies without problems. However, there is no way to know how their antenna systems have been constructed and what kind of mechanical and electrical stresses the cables and connectors themselves are actually subjected to. Also, what do they mean by the power of 1500 W:

- Amplifier ***input*** power? This is the power amplifier draws from the mains network and it doesn't have much to do with amplifier's output RF power, which is needed for cables and connectors. One can estimate that the RF output power is around 40 % to 50 % of input power. The ***theoretical*** efficiency of a high power amplifier stage is around 58 %, but in real life it is never possible to achieve that efficiency because of circuit losses.
- Peak SSB power (PEP)? In most cases the ***average*** SSB RF power is roughly 15% to 25% of SSB peak power. The average power is what causes heating in the antenna system, not peak power.
- So the actual ***average*** RF power they are running may be only 90 W!

Anyway, it is better to take those claims with a grain of salt before applying them to your own antenna system. I haven't been able to find any other ***reliable RF power specifications*** (ie. from manufacturers) apart from the few values given above.

My personal choices for feed lines and RF connectors are:
HF bands: - RG-58 for up to 100 W or 150 W transmitting power.
- RG-213 for higher transmitting power (up to 1500 W).
- UHF (PL-259 / SO-239) connectors.
VHF: - RG-213 for up to 100 W or 150 W transmitting power, if the cable is short enough to have less than -1 dB loss and UHF (PL-259 / SO-239) connectors.
- Heliax or Ecoflex 10 for longer cables and up to 1500 W transmitting power and N connectors made for that specific cable.
UHF: Heliax or Ecoflex 10 for any transmitting power and cable length and N connectors made for that specific cable.

G. Antenna tuners

Antenna tuners are only used on HF bands. They would be very difficult to design for VHF and UHF and in general are not needed there, because antennas themselves are matched to 50 ohms.

Antenna tuners are very useful for making the transmitter to "see" the 50 ohm load they are designed for, especially when using some kind of "all band" or multi-band antenna. Note that although these units are called "antenna tuners", ***they do not tune the antenna, but match the antenna system so that the transmitter is loaded with resistive 50 ohms***. When an antenna tuner has been correctly adjusted, also the received signals are as good as possible.

Warning! NEVER use two antenna tuners in series to the same feed line! The operation of both will be messed up, because there is no way to know which impedances either of them is matching. So, if you have an external antenna tuner, ***make absolutely sure that your transceiver's internal tuner is switched OFF (disabled)!*** Otherwise the result is in most cases an impedance, which your transceiver cannot handle.

Note! In general commercially made antenna tuners are specified only for peak SSB power (PEP)! *They will fail, if they are used with the specified amount of continuous carrier power!* To use those tuners with continuous carrier, like FM, many digital modes etc., the max. allowed transmitting power is about 1/3 or 1/4 of the specified PEP power.

There are also manufacturers (for instance MFJ), who specify the antenna tuner's power handling in a really strange way. For instance one particular tuner is sold as a 3000 W tuner. However that 3000 W means the ***peak input power of linear amplifier!*** Because an amplifier's efficiency is 50% or less, the tuner can handle perhaps 1500 W or less RF peak power. In reality it may be able to handle only about 375 W of continuous carrier RF power. Quite a difference between the specified and real power capability! I myself have had to repair and modify such an antenna tuner (MFJ-986 - property of my ham radio friend here) several times, because it can't even handle 500 W SSB power on 20 m!

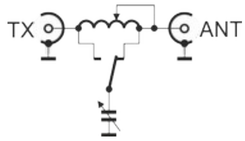
An antenna tuner is basically a passive L/C circuit with one or more variable capacitors and one variable coil. Many kinds of antenna tuners are manufactured and also made at home. They can either be manual or automatic and inside the transceiver, in a box at operating position, or remote controlled. They have always an SWR meter, which shows the SWR at the tuner's transmitter ("TX") connector. ***Note that the SWR shown by the antenna tuner is ONLY for tuner's transmitter connection, ie. for the feedline between transmitter and tuner. It is NOT the feed line's SWR from tuner to antenna!*** If you need an antenna tuner for ***antenna system*** matching, it means that antenna's feedline has always relatively high SWR (for instance more than 1.5:1). The impedance matching range between different antenna tuners can vary a lot, even when the circuit ("network") is the same.

It seems some radio amateurs think that only variable capacitors and roller coils are OK for a "serious" antenna tuner. With those one can adjust the matching continuously, of course, but they are usually bigger in size and cost a lot more money than "step type" tuners, especially the high power automatic ones. ***In general you do not need continuously adjustable capacitor(s) and coil in an antenna tuner!*** A "step type" antenna tuner can always match an antenna system well enough, unless the antenna itself is ridiculously short for the operating frequency. A continuously adjustable tuner will also have problems with that kind of antennas! ***You DO NOT need to have 1.00:1 SWR at the transmitter side!*** 1.50:1 SWR or less is always

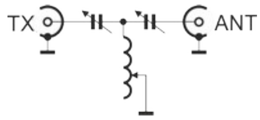
OK for any transmitter, and a step type tuner can almost always match the antenna system to better than 1.05:1 SWR. The additional feedline losses caused by an SWR of 1.05:1 or up to 1.50:1 are also insignificant.

Some common antenna tuner circuits:

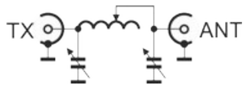
- **L network**: These tuners have one variable capacitor and one variable coil. One end of capacitor is connected to ground. The coil is connected between transmitter connection and antenna connection. The position of capacitor can be selected to transmitter connection or to antenna connection for any particular matching requirements.



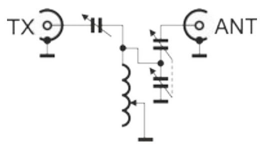
- **T network**: These tuners have two variable capacitors and one variable coil. One capacitor is in series with the transmitter connection and the other in series with the antenna connection. The coil is connected to ground from between the two capacitors.



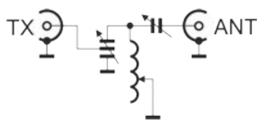
- **PI network** (from Greek "Π" = capital pi): These tuners have two variable capacitors and one variable coil. One capacitor is connected to ground from the transmitter connection and the other to ground from the antenna connection. The coil is connected between the transmitter and antenna connectors.



- **SPC** (Series Parallel Capacitor) network: These tuners have one variable capacitor, one dual variable capacitor and one variable coil. The single capacitor is connected in series from the transmitter connection to the centre tap of dual variable capacitor. The dual capacitor is connected from the antenna connection to ground. The coil is connected from dual capacitor's centre tap to ground.



- **Ultimate Transmatch**: These tuners have one dual "butterfly" variable capacitor, one single variable capacitor and one variable coil. "Butterfly" capacitor's centre tap is connected to the transmitter connection. One end of the "butterfly" capacitor is connected to ground. The other end of the "butterfly" capacitor is connected to the coil and one end of the single capacitor. Coil's other end is connected to ground. The other end of single capacitor is connected to the antenna connection.



There are many variations of the circuits mentioned above and other kinds of antenna tuners have also been made, usually for some particular purpose.

In every antenna tuner circuit there are three possibilities for the coil:
- A roller coil, which can be adjusted continuously from min. to max. In automatic antenna tuners the roller coil is run with a motor.
- A coil with taps. The taps are selected with a multi-position switch or by relay control. In automatic antenna tuners the relay control is used.
- A set of separate series connected coils. The coils are selected with a multi-position switch or by relay control. In automatic antenna tuners coil inductance values are in a "binary" series (like 1, 2, 4, 8, 16 etc. times the minimum inductance). This way the minimum number of control lines (usually 8) are needed for coil selection. With 8 control lines you get 256 different inductance values in steps of the lowest inductance (for instance 0.05 or 0.1 µH). The coils are connected in series (or by-passed) as needed with relay control.

Note, however, that depending on the roller or tapped coil construction and how it is connected in tuner circuit, the coil may have a major problem. Usually one end of the coil is connected to the tuner circuit, the roller or tap is connected to ground and the other coil end is floating. So, depending on required matching and frequency, the coil acts as a step-up RF voltage transformer and can have extremely high RF voltage (possibly several kV) in the open end. The voltage can arc to ground or some other part of the tuner. Manufacturers of this kind of tuners are using some sort of switching to prevent the transformation action. For instance MFJ calls that circuit a "self resonance killer", but the transformer action has nothing to do with "self resonance". Note also that a tuner with a set of separate coils doesn't have this problem, because all unused coils are short circuited and the coils themselves are installed in such a way that they do not affect each other, for instance at 90° angles from each other.

In every antenna tuner circuit there are two possibilities for the capacitor(s):
- In manual antenna tuners variable capacitors (air or vacuum) are used. In automatic antenna tuners these capacitors are run with motors.
- A set of separate high voltage capacitors. The capacitors are selected with a multi-position switch or by relay control. In automatic antenna tuners the relay control is used.
- In automatic antenna tuners the most common circuit is the L network. The capacitance values are in a "binary" series (like 1, 2, 4, 8, 16 etc. times the minimum value). This way the minimum number of control lines (usually 8) are needed for capacitance selection. With 8 control lines you get 256 different capacitance values in steps of the lowest capacitance (for instance 5 or 10 pF). The capacitors are connected in parallel to ground as needed with relay control.

In many antenna tuners there are several possibilities for the antenna side connections:
- 50 ohm coaxial cable.
- 200 ohm connection through a 4:1 balun for balanced feed lines (ladder line, open wire line).
- End fed wire antenna connection with associated ground, often through a 4:1 balun.

G.1 Antenna tuner matching range

When selecting an HF antenna tuner for your station, the first things to consider are its ***power handling*** capacity and ***SWR matching*** range. The maximum power (SSB peak = PEP) is usually specified and so is the SWR matching range. However, make sure you understand:
- What the manufacturer actually means by "power handling"? In general only peak power is specified, but if you are using digital modes (like RTTY) or FM, be sure to select a tuner for at least three or four times (3 x, 4 x) your maximum transmitting power, otherwise the tuner ***WILL fail*** during continuous carrier transmissions (like RTTY or FM).
- Most of the time SWR range is only specified as a common value (like 3.0:1) for all frequencies at the specified max. (peak) power, but that doesn't tell the whole story. There are some limitations, which every antenna tuner has difficulties in handling:
  - ***Minimum capacitance*** value is important especially for 10 m and 12 m bands. The minimum capacitance ***can never be "0"*** because of significant stray capacitances and in case of variable capacitors their minimum capacitance.
  - ***Maximum capacitance*** value is important especially for 80 m and 160 m bands. The maximum capacitance is always limited by the tuner's maximum capacitance. In case of variable capacitors their maximum capacitance.
  - ***Minimum inductance*** value is important especially for 10 m and 12 m bands. The minimum inductance ***can never be "0"*** because of significant stray inductances and in case of a roller coil its minimum inductance.
  - ***Maximum inductance*** value is important especially for 80 m and 160 m bands. The maximum inductance is always limited by the tuner's maximum inductance. In case of a roller coil its maximum inductance.

From the above follows that any tuner's matching range especially on 160 m, 80 m, 12 m and 10 m bands may be severely limited to even less than what is specified (3.0:1, for instance). Another big problem is to match a very low impedance on any band to 50 ohms, because the minimum inductance value is too high and maximum capacitance value too low. In general there is no problem to match high impedances (say at least up to 3 kohms) to 50 ohms on any of the "middle" bands (ie. 80 m to 15 m), because there is always enough inductance and low enough capacitance available.

G.2 Antenna tuner types

An antenna tuner can of course be either manual or automatic. Manual tuning takes usually more time than automatic tuning, but that depends.

Transceiver's internal antenna tuner is always automatic and "local". External antenna tuners can be either manual or automatic. A manual tuner is always "local". An automatic tuner can be either "local" or "remote".
- A "local" antenna tuner is usually installed at the operating position near the transmitter. In this case the whole ***antenna system*** is matched by tuner to 50 ohms for the transmitter. The ***antenna system*** includes everything from tuner's antenna connection to the antenna itself. There can be quite high SWR in the feed line from tuner to antenna with associated extra losses (see "D. SWR and transmitting power" above). This

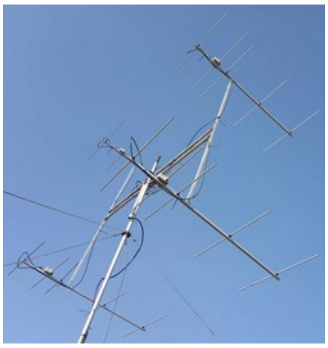
depends on how well or badly the antenna itself is matched to the 50 ohm feed line at the operating frequency.

- A "remote" antenna tuner is always an automatic one and usually installed as close to the antenna as possible (in tower, mast etc.) to minimize losses caused by high SWR in the feedline. In this case the ***antenna system*** is matched by tuner to 50 ohms for the feedline to transmitter. It is connected to the SWR etc. display at operating position, either through the feed line or through a separate cable. Either cable has both the data connection and power feed to the remote antenna tuner. The remote antenna tuners are more expensive than manual ("local") ones, especially for high power, but if at all possible, they are a much better solution for any antenna system, because there are no extra losses in the long feed line between transmitter and tuner.

H. Antenna stacking

The gain of an antenna system is often easier to increase by installing more than one antenna instead of a bigger (= longer boom) one, especially on HF bands. All antennas in a multi-antenna system must be same kind and spaced a certain distance from each other either vertically or horizontally. This is called "stacking". Each time you double the number of antennas, you get about 3 dB more power gain. Vertical stacking reduces antenna array's vertical beam width and horizontal stacking the horizontal beam width.

On HF bands antennas are usually stacked only vertically, because horizontal stacking is mechanically almost impossible to do. However, one needs a much higher tower than for a single antenna to achieve the best results, and the ***tower must rotate***. For more or less maximum gain the lower antenna should be at least ½ wavelength up from ground and the upper antenna the stacking distance above the lower antenna.



Both vertical and horizontal stacking are used on VHF and UHF bands, because the antennas are much smaller and horizontal stacking doesn't cause any major mechanical problems. Most of the time VHF or UHF antenna arrays can be easily constructed in such a way that they can be installed on the rotator itself, so there is no need for a rotating mast or tower.

All antennas in an array must be fed in the same phase and the combination must be matched to the (usually) 50 ohm feedline. For some matching solutions see "E.2 Impedance matching using feed lines" above. There are many other ways to achieve the same result.

Many older amateur radio books recommend fixed stacking distances like "half-wavelength", "5/8-wave length", "half the boom length" etc. Some of those "rules" are little more than guesswork. They are ***wrong*** for modern antenna designs.

First, some antenna stacking basics:

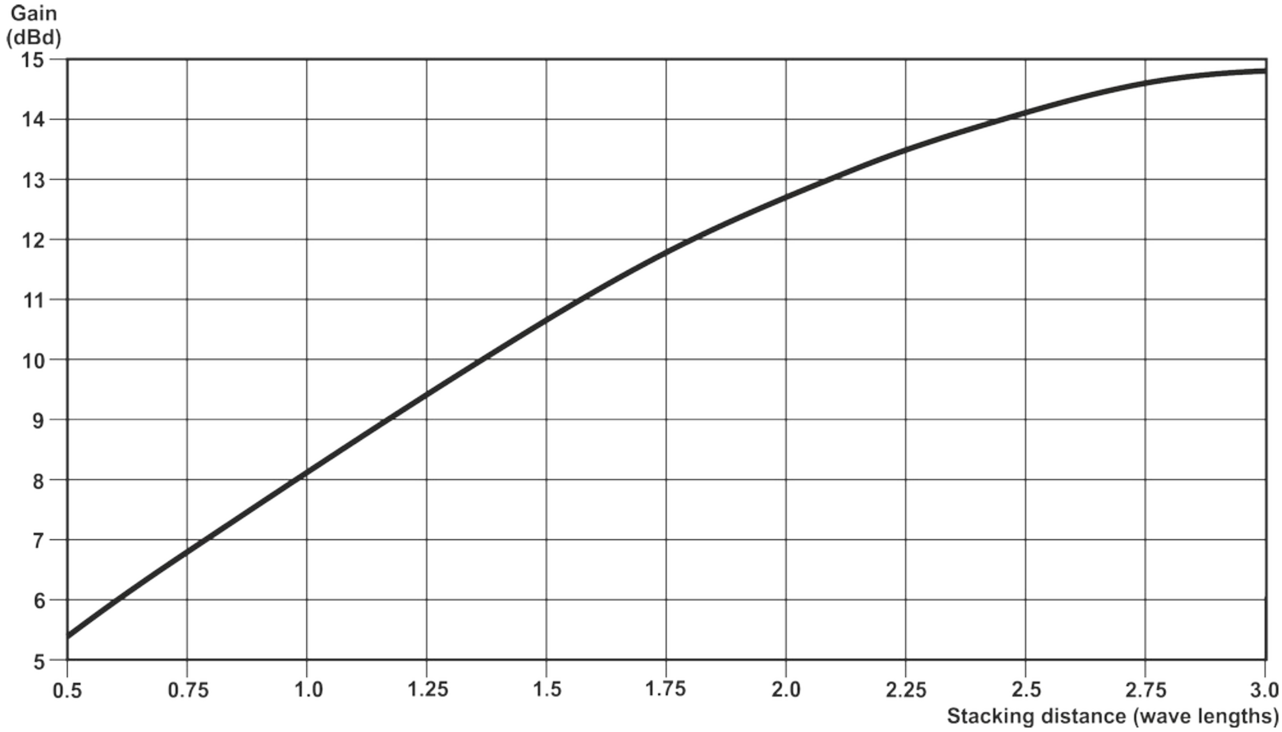
1. The optimum horizontal and vertical stacking distances to achieve the maximum available gain ***depend a lot on the gain of individual antennas*** (ie. their horizontal and vertical beam widths). For "low gain" HF antennas the stacking distances ***in free-air wavelengths*** are smaller and for "high gain" VHF and UHF antennas bigger.

2. The stacking distances are always ***measured*** in free-air wavelengths (or parts thereof) ***from the centre of each antenna***, which in the case of yagis is the antenna boom. For quads and other "3-dimensional" antennas it is the mechanical centre of each antenna.

There is no easy way to calculate the optimum stacking distance of antennas, unless you know the "real world" horizontal and vertical -3 dB beam width of an individual antenna. In that case the formula is:
D = 57 / BW, where:

- D = Optimum stacking distance, vertical ***or*** horizontal, ***in wavelengths***.
- "57" = Constant for stacking distance calculation
- BW = -3dB beam width, vertical or horizontal, ***in degrees***.
- ***Note that many beam antennas do have different beam widths in horizontal and vertical*** plane, so the stacking distance will also be different horizontally and vertically.

Otherwise you can use the graph below to estimate the stacking distance for maximum gain of your antenna array, based on ***individual antenna's gain over dipole (dBd)***. The graph is not always accurate, because the antenna gain depends also on radiation pattern's side lobes in horizontal and vertical plane, but it should get you close enough as a starting value for all practical purposes. The graph was copied from DK7ZB's page at: https://www.qsl.net/dk7zb/Stacking/stacking.htm .



There is still ***another adjustment***, which must be made to get the final stacking distances. With the results of both the formula and graph above, you will get the maximum available gain for the antenna array. But with that stacking the array's side lobe levels are increased a lot, which is often not a good thing. Side lobes are RF radiation to non-intended directions on every side of the main lobe (= intended radiation). Especially during RX the side lobes can pick up all kinds of interference. However, if you reduce the stacking distance a bit, you lose very little array gain, but the side lobe levels are reduced a lot. So, ***multiply the stacking distances*** (in wavelengths) from the formula or graph above for instance:
- by 0.95: Gain reduction -0.1 dB, side lobe reduction -13 dB.
- by 0.9: Gain reduction -0.2 dB, side lobe reduction -16 dB. *This is the best compromise!*
- by 0.85: Gain reduction -0.4 dB, side lobe reduction -22 dB.

So, for instance for 8.1 dBd antennas the stacking distance from graph is 1.0 wave length. Multiply that by 0.9 and the ***final stacking distance is 0.9 wave lengths***.

H.1 Stacking multi-band antennas

It is somewhat problematic to stack multi-band antennas, like HF trap yagis or multi-band quads. Basically it is possible to have optimum stacking distance only for one band and all other bands are off a lot, which in general means less array gain and increased side lobe levels on those bands. But, if you must do that, find the optimum stacking distance for one of the bands (your favourite) and then be satisfied with less gain and higher side lobes for all the other bands.

H.2 Vertical stacking of beam antennas for different bands, like HF, VHF and UHF.

Usually the higher frequency antenna (for instance VHF) is installed above the lower frequency antenna (for instance HF) to keep mechanical stresses for the rotator, mast, tower etc. as low as possible.

a. The best solution would be to find out the stacking distance (see "H. Antenna stacking" above) for the lower frequency antenna (HF in this example) and install the higher frequency antenna (VHF in this example) that stacking distance above the lower frequency antenna. That would mean, however, that the rotating mast above the lower frequency antenna must be really high and could pose mechanical problems.

   This is not a big problem for stacking VHF and UHF antennas, because the mechanical distance is not all that much.

b. However, it is possible to reduce the stacking distance a lot: Find out the stacking distance (see "F. Antenna stacking" above) for the higher frequency antenna (VHF in this example) and install it that stacking distance above the lower frequency antenna. This can be done, because:
   - The lower frequency antenna (HF in this example) is not resonant at all on the VHF frequencies and when spaced the VHF antenna's distance away, doesn't affect the operation on VHF frequencies.
   - The higher frequency antenna (VHF in this example) is not resonant at all on the HF frequencies and when spaced the VHF antenna's distance away, doesn't affect the operation on HF frequencies.

c. There is one drawback with the "narrow" antenna spacing: You cannot use the two antennas at the same time so that one is transmitting and the other receiving. The transmitted signal picked up by the receiving antenna is very likely so high, that the receiver's RF input is overloaded and the receiver is "dead" or produces weird noises during transmissions. That depends a lot on the quality of RF filtering in receiver's front end. It is very unlikely that anything would be actually destroyed in the receiver, though. To be able to use one radio for transmitting and the other one for receiving at the same time, one could use external L/C filters at the antenna connections of the two ***transceivers***:
   - About 40 MHz low pass filter for the HF radio. This filter must be able to pass transceiver's (***not*** linear amplifier's!) full transmitting power in all HF bands.
   - About 120 MHz high pass filter for the VHF (145 MHz) radio. This filter must be able to pass transceiver's (***not*** linear amplifier's!) full transmitting power in the VHF band.

   Both antennas could, of course, be always used for the same purpose (ie. either receiving or transmitting) at the same time.

I. Electrical safety of a radio amateur station

This part is mainly related to creating a safe radio amateur station, and the antenna system is of course part of electrical safety. Every ham station must be protected against electric shocks and overvoltages. There are two parts for guaranteeing station safety:
- Protection for dangerous voltages.
- Protection for lightning.

I.1 Protection against dangerous voltages

Voltage protection concerns mainly the radio operator him/her self and everyone visiting the station, including members of your own family. The idea is that there must be no way for anybody to touch any parts having dangerous voltages (including the 230 VAC mains wiring).

<u>I.1.a Mechanical protection</u>

All ham station equipment must be covered with boxes (enclosures)! It does not matter, if the equipment are manufactured or home made. The boxes are made out of metal most of the time, but they could also be made of plastic. The boxes ***must not have holes*** for ventilation etc., which are too big. Remember that a small child could insert a finger through a 5 mm (0.2 inch) hole.

The mechanical protection must function for high AC and DC voltages, of course, but also for high RF voltages. ***RF can cause severe burns!*** For instance the output RF voltage of a 1500 W linear amplifier into 50 ohm load (SWR 1.0:1) is about 275 V_{RMS} or 388 V peak or 775 V peak-to-peak. Into a 100 ohm load (SWR 2.0:1) the RF voltage would be about 387 V_{RMS} or 546 V peak or 1091 V peak-to-peak.

I.1.b Safety grounding

All ham radio station equipment, which have a mains voltage input ***MUST BE safety grounded!*** It does not matter, if the equipment is manufactured or home made. Inside equipment the safety ground ***MUST BE always connected to the metal box or chassis!*** Most of the time the mains safety grounding is done through the mains cord, which ***MUST BE plugged into a safety grounded wall socket!***

In RF sense there is a major problem with mains safety grounding, however: Because the RF ground of most ham radio equipment is the metal box or chassis, which must always be connected to safety ground, the mains network's safety ground wiring and cabling ***WILL BE part of the antenna system***, which is not a good idea. That may lead spreading the transmitted RF signal all over the place causing interference to other equiment. It may also cause antenna matching problems because of un-intended wiring. I am always using an RF choke wound over a ferrite toroid in the safety ground wire of my station's combined mains cable, which separates the station RF ground from mains network safety ground. A 97 µH choke has a reactance of 1097 ohms at 1.8 MHz and 18294 ohms at 30 MHz. The choke does not defeat the mains safety protection, however, because its combined resistance and reactance at 50 Hz mains frequency is extremely low (around 0.04 ohm).

Note that in most ham station 13.8 VDC power supplies the DC side negative (-) pole connects to transceiver chassis. If measured with an ohm meter between power supply negative output and its metal box, there is almost always an open circuit. BUT: Inside the power supply there may be a fairly big ceramic capacitor from the negative output to power supply box, which is a direct RF path for the transceiver antenna output's ground (= chassis) to mains network safety ground.

All ham radio station equipment, which have a mains voltage input, wether they are manufactured or home made, ***should have mains voltage fuses FOR BOTH WIRES (phase and return)!*** Unfortunately most manufactured equipment have just a single mains fuse. That is not a problem in some countries (for instance England and United States), where the mains plug can only be inserted one way into wall socket and the fuse will always be in the phase wire. It is a problem in most of Europe, however, because the mains wall sockets (often "schuko" type) do not have any mechanical polarisation and the plugs can be inserted either way to them. So, there is no way to know which wire happens to be phase or return within equipment and either could make a short circuit into the equipment box. A fuse must always blow in both cases.

I.2 Lightning protection

Because most ham radio antennas are installed outside and fairly high, they may be susceptible to lightning strikes. ***However, please understand that no kind of protection will work for a direct lightning strike!*** Because of extremely high voltage and current, ***everything in the strike's path WILL BE TOTALLY DESTROYED!*** That includes the antenna itself, its mast or tower, feedline, all ham shack equipment and possibly even your house. Note also that a direct hit can jump several meters or yards over the air and continue destruction in the next place. Even if there is a lightning rod in the house, there are no kinds of guarantees that the lightning "wants" to strike exactly there.

Fortunately it is quite rare that a lightning strikes directly to a ham radio antenna. The very tall broadcasting towers (AM, TV, FM) are a completely different matter. You will need protection for nearby lightning strikes, though. Even a strike several hundred meters or yards away can cause damage at the ham radio station, because of very high voltages induced into the antenna.

As a first protection, the metal mast or tower of the antenna should be grounded to real earth. Good grounding can sometimes be quite difficult due to the type of ground, i.e. its conductivity. Note that grounding does not have to be good in high frequency sense, but it should be good for AC and DC. In principle, the "ground connection" should only be in the order of a couple of ohms, but how could you measure it? The conductivity of the soil also varies a lot depending on its moisture content. Dry ground can be almost an insulator, but when wet, like during a thunderstorm, it can have a fairly low resistance. In principle, stone is always an insulator.

The next method of protection could be a surge protector in the antenna coaxial cable, but ***can it really protect your station?*** Surge protectors for ham use have UHF connectors for input and output and a gas-filled "capsule" as overvoltage protection. Surge protectors are usually specified for maximum power, ***but only into 50 ohms***. If the coaxial cable has a high impedance (for example SWR is more than 1.5:1), gas capsule's "firing" voltage must be calculated from the specified power and impedance (= 50 Ω): **Up = 1.41 x SQR (P x Z)**. For example, in a 2000 W surge protector, the peak voltage into a 50 Ω cable is 445 V. You must ensure that the peak voltage (not RMS or peak to peak) of your high frequency signal never exceeds this value. For example: for a 100 Ω load (SWR = 2.0:1) the maximum allowed power of a 2000 W surge protector is only 996 W: **U = Up / 1.41** and **P = U^2 / Z**. Otherwise, the high-frequency signal also "triggers" the gas capsule, which causes splatter and possible damage to the transmitter. When conducting, the gas capsule is practically a short circuit. ***The surge protector must always be grounded directly to station's common RF ground point***. However, please also note that ***the surge protector may not be able to protect receiver's front end from nearby lightning strikes***. Usually the trigger voltage of gas capsule is too high (several hundred volts) and the front end of a receiver cannot withstand such voltage spikes.

The last line of defence would be to disconnect your antenna cables, when a thunderstorm is approaching. However, locate the disconnected cable connectors in such a place, where possible over voltage spikes (ie. sparking from the connector) cannot cause problems. When I was still in school, I had sort of a dipole (about 40 m = 130 ft long) for shortwave AM SWL. It was fed with 300 ohm parallel line. When disconnected from receiver, the sparks between parallel line wire ends were around 100 - 150 mm (4 to 6 inches) long, although the thunderstorm was not directly above.

Nowadays I am using an "automatic" lightning protection with a power relay. The relay is powered directly from transceiver's 13.8 VDC supply. So, when the PSU is OFF, the relay disconnects the antenna from transceiver and its NC contact short circuits the coaxial cable centre wire to station's common RF ground point. The cable shield is always connected to RF ground, of course. When the PSU is switched ON, the relay is activated and transceiver is connected to the feedline through relay's NO contact. If you're on the bands, you can hear the approaching thunderstorm as receiver audio crackle from many kilometres or miles away. When lightning starts to appear in the sky, it's time to turn off the station. In any case, operating would be quite difficult because of very strong interference.

J. Abbreviations

There are a lot of abbreviations used in radio technology and more widely in electronics. In the early days everybody used their own abbreviations, so to make information exchange easier, they have been internationally standardized many decades ago. They are used in various formulas and as symbols for different values. Below are samples of the most common ones:

J.1 Formula symbols

- U (in some countries V) = Electrical voltage
- I = Electrical current
- R = Electrical resistance
- P = Electrical power
- Z = Electrical impedance (AC "resistance"). Do not mix this up with resistance (R). They are not the same thing.
- λ (small Greek letter "lambda") = Wavelength
- +j = Inductive reactance (AC reactance of a coil)
- -j = Capacitive reactance (AC reactance of a capacitor)
- ° = Phase angle in degrees. The angle of a sine wave at a specific moment of time. Degrees are also used for instance for phase difference between two AC signals.
- rad = Phase angle in radians. 1 rad = 57.2958 degrees

J.2 Multipliers

The multipliers are used for all kinds of values to make the length of required text shorter:
- p = "pico" = 1/1'000'000'000'000 = 1000 billionth part
- n = "nano" = 1/1'000'000'000 = 1 billionth part
- μ = (small Greek letter mu) "micro" = 1/1'000'000 = 1 millionth part
- m = "milli" = 1/1000 = 1 thousandth part. ***DO NOT mix this up with "M" = "mega"!***
- "   " (no multiplier) = 1 time
- k = "kilo" = 1000 times
- M = "mega" = 1'000'000 times. = 1 million times. ***DO NOT mix this up with "m" = "milli"!***
- G = "giga" = 1'000'000'000 times = 1 billion times
- T = "tera" = 1'000'000'000'000 times = 1000 billion times

For instance:
- "120 pF" = 0.000'000'000'12 F (farad)
- "560 Ω" = 560 Ω (ohm)
- "14.25 MHz" = 14'250'000 Hz (hertz)

It seems to me that in countries using the imperial measurement system (typically USA), people still (in 2024) do not know how to use the multipliers correctly, which does result in mix-ups and non-sensible values.

Note! The multipliers in the list are the most common in electronics and radio technology! There are also many "intermediate multipliers" that are not mentioned in the above list.
See e.g. https://en.wikipedia.org/wiki/Metric_prefix

J.3 Symbols for values

The multipliers listed above are used for all values.

J.3.a Mechanical dimensions

- mm = millimetre = 1/1000 meter (= 0.03937 inch). In general millimetres (mm) are used in all European mechanical drawings.
- m = meter (= 39.37 inch = 3.28084 feet).
- km = kilometre = 1000 meters = 0.621371 miles
- " (or in) = inch (25.4 mm)
- mil = 1/1000 inch (0.0254 mm)
- ft = foot (304.8 mm)
- yd = yard (0.9144 m)
- mi = mile (1609.34 m = 1.60934 km)
- ° = angle in degrees. Right angle is 90°.
- ^{2} (superscript "2") = square (area). For instance 100 mm^2 = an area of 100 square millimetres.
- ^{3} (superscript "3") = cube (volume). For instance 100 mm^3 = a volume of 100 cubic millimetres.

In countries, where the imperial measurement system is used (typically USA), the conversions between different dimensions are complicated. I have seen numerous times that for instance computer programs based on the imperial system cannot convert dimensions correctly to and from the metric system. So, for instance when sending mechanical documentation by e-mail from Europe (metric system) to USA (imperial system), the recipient's computer software may produce really strange results.

J.3.b Basic symbols for electrical values

- V = Volt (for voltage)
- A = Ampere (for current)
- W = Watt (for power)
- Ω (Greek capital letter "omega") = Ohm (for resistance, impedance or reactance)
- F = Farad (for capacitance)
- H = Henry (for inductance)
- Hz = Hertz (for frequency)

- DC = Direct Current
- AC = Alternating Current
- VDC = Direct voltage
- VAC = Alternating voltage

J.4 ITU Frequency Bands

As a matter of convention, ITU (International Telecommunication Union of UN) divides the radio spectrum into 12 bands, each covering a decade of frequency. Each of these bands has a name. Especially the abbreviations (like "HF", "VHF", "UHF" etc.) are commonly used in all kinds of documents handling radio frequencies:

- ELF (Extremely Low Frequency) = 3 ... 30 Hz
    - No ham radio bands
- SLF (Super Low Frequency) = 30 ... 300 Hz
    - No ham radio bands
- ULF (Ultra Low Frequency) = 300 Hz ... 3 kHz
    - No ham radio bands
- VLF (Very Low Frequency) = 3 ... 30 kHz
    - No ham radio bands
- LF (Low Frequency, "Longwave") = 30 ... 300 kHz
    - Ham radio: 2200 m, 135.7 ... 137.8 kHz
- MF (Medium Frequency, "Mediumwave") = 300 kHz ... 3 MHz
    - Ham radio: 630 m (472 ... 479 kHz), 160 m (1.81 ... 2.00 MHz)
- HF (High Frequency, "Shortwave") = 3 ... 30 MHz
    - Ham radio: 80 m (3.5 ... 3.8 MHz), 60 m (5.3515 ... 5.3665 MHz), 40 m (7.0 ... 7.2 MHz), 30 m (10.10 ... 10.15 MHz), 20 m (14.00 ... 14.35 MHz), 17 m (18.068 ... 18.168 MHz), 15 m (21.00 ... 21.45 MHz), 12 m (24.89 ... 24.99 MHz), 10 m (28.0 ... 29.7 MHz)
- VHF (Very High Frequency) = 30 ... 300 MHz
    - Ham radio: 6 m (50 ... 52 MHz, Europe), 4 m (70.0 ... 70.5 MHz, Europe), 2 m (144 ... 146 MHz, Europe)
- UHF (Ultra High Frequency) = 300 MHz ... 3 GHz
    - Ham radio: 70 cm (430 ... 440 MHz, Europe), 23 cm (1. 24 ... 1.30 GHz, Europe), 13 cm (2.30 ... 2.45 GHz)
- SHF (Super High Frequency) = 3 ... 30 GHz
    - Ham radio: 9 cm (3.400 ... 3.475 GHz), 6 cm (5.65 ... 5.85 GHz), 3 cm (10.0 ... 10.5 GHz), 12 mm (24.00 ... 24.25 GHz)
- EHF (Extremely High Frequency) = 30 ... 300 GHz
    - Ham radio: 4 mm (75.5 ... 81.5 GHz), 2 mm (122.25 ... 123.00 GHz), 134.0 ... 141.0 GHz, 241.0 ... 250.0 GHz
- THF (Tremendously High Frequency, "Terahertz") = 300 GHz ... 3 THz
    - No ham radio bands

The radio propagation ("DX") properties of the bands listed above differ significantly from each other. That has been the original reason for band divisions. The band frequency limits have changed many times, until the above division was approved by the International Radio Conference held at Atlantic City, NJ, USA in 1947. So, for instance, as you can see in the list above, the 6 m band (50 ... 52 MHz) is actually VHF, although it is often included in modern HF transceivers.

K. Epilogue

I hope this document helps to understand the many aspects of antenna systems and how they affect each other. I know that there is a lot of information here to keep in mind, but I haven't really written much about the finer aspects of efficiently working antenna systems. This text is more about general rules.

I hope this text is understandable enough for English speakers. English is not my native language. I have tried to keep the spelling according to British English, but likely many differences can be found, like GB "aerial" vs. US "antenna" or GB "valve" vs. US "tube".

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