20 MTR HALF-SIZE TWO-ELEMENT "YAGI" BEAM ANTENNA

Latest page update: 25 Sept 2021 (added ref. 22A-22L).
Previous updates: 9 April 2021 (expanded Uda-Yagi section), 2 July 2020 (added ref. 19)

INTRODUCTION

In 2008, when I was between jobs for a while, I decided to build an HF antenna with more directivity than a simple dipole. Installation at my QTH basically had to be on my terrace, so space is rather limited. Such a directional antenna requires at least two elements, a full-size antenna for wavelength over 10 mtr will not fit, and 10 mtr is (usually) not my favorite band. So I narrowed it down to a simple half-size 2-element beam antenna.

In its simplest form, this antenna consists of a *driven* element (typ. a ½ λ dipole) and one *passive* "parasitic" element parallel to it at some distance. The EM waves radiated by the driven element induces a current in the passive element. This induced current causes the passive element to also radiate waves. These waves combine with the waves of the driven element. Depending on the phase difference, the waves from the two sources reinforce each other (= constructive interference) or partially cancel each other (= destructive interference). This is illustrated below for various lengths of the passive element and various distances between the active and passive element:

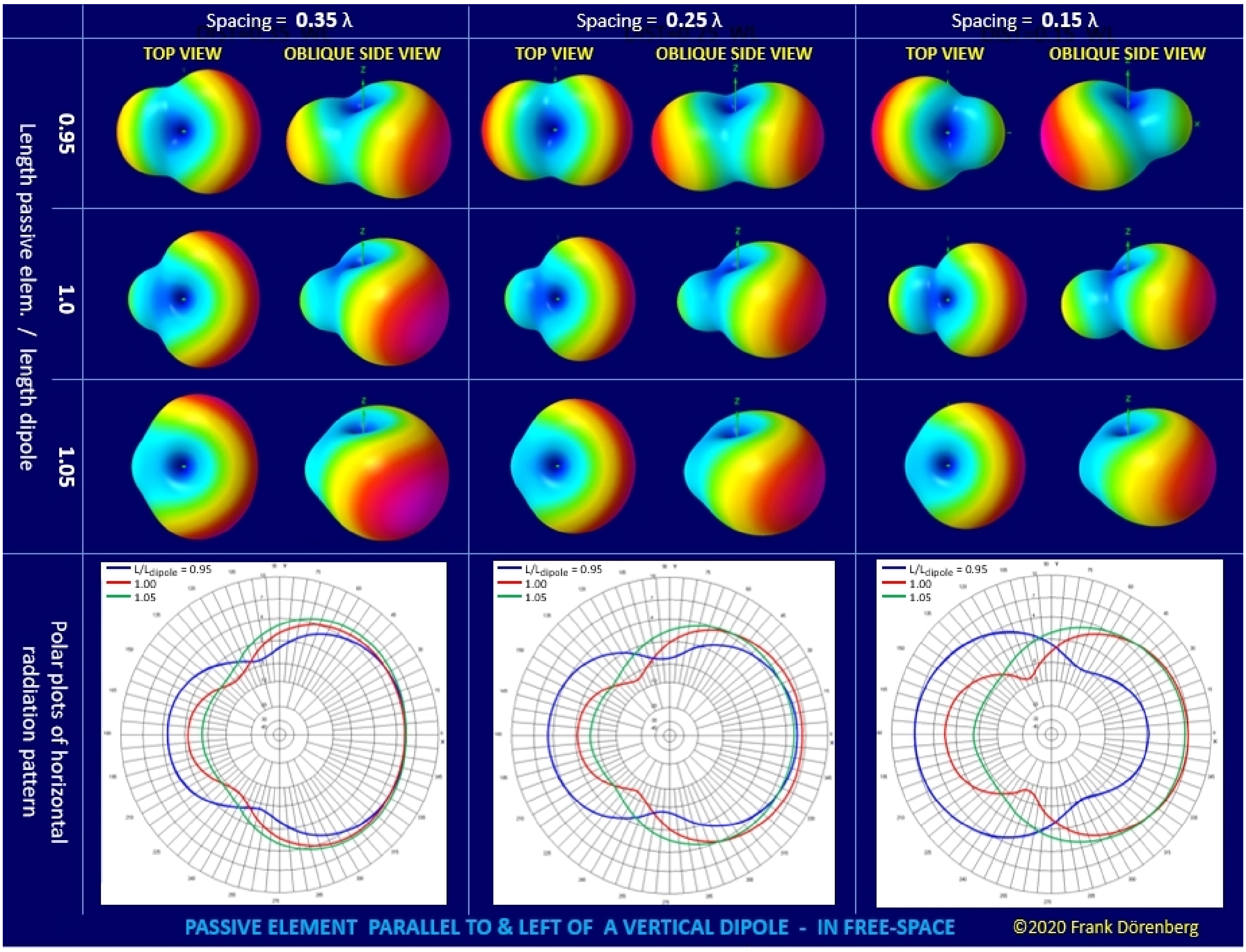


Fig. 1: Radiation pattern of a vertical dipole with a passive element to the left of it - in free-space

(the NEC file of my model is provided as ref. 15; I use the excellent [4NEC2 freeware modeling package](#))

YAGI-UDA LINEAR PHASED-ARRAY BEAM-ANTENNA

In 1924/25, Shintaro **Uda** - engineer and assistant professor at Tohoku Imperial University in Japan - invented a highly directional multi-element antenna system. During 1925-1929, he published his research in about a dozen articles in the Journal of the Institute of Electrical Engineers in Japan. In 1926, he co-published a first article outside Japan (USA, ref. 18D) with professor Hidetsugu **Yagi**, who only had a subordinate involvement in the actual R&D. The latter article also proposes to use this type of antenna for directional radio beacons. In December of 1925, Yagi patented the antenna system in Japan (69115), listing himself as the sole inventor. In 1932, Yagi filed a similar patent in Germany (475293) and in the USA (1860123). The latter has Radio Corp. of America (RCA) as the patent assignee/owner. RCA was the Marconi Wireless Telegraph Company of America ("American Marconi") until it was acquired by the General Electric Co. in 1919.

Eversince, this type of antenna system is commonly referred to as a "Yagi-Uda" antenna, or even worse, just "Yagi" antenna.... Ref. 18A-18C.

In its simplest form, the Uda "beam" antenna is a 2-element antenna. It has a single radiating element that is "driven", i.e., is connected to a transmitter (or receiver, or transceiver), and a single passive element. The latter is not driven. Typically, the driven element is a simple standard 1/2 wavelength resonant dipole. The passive element is a mono-pole: basically a rod that is slightly longer or shorter than the driven element. This element is placed at some distance (typ. 0.1 - 0.25 wavelength) to, and in parallel with, the driven element. The two elements are electro-magnetically (EM) coupled: EM radiation from the driven element induces current in the passive element. This way, the passive element "feeds" on the driven element. This is why the passive element is also referred to as a "parasitic" element. In turn, the induced current is partially re-radiated by that passive element.

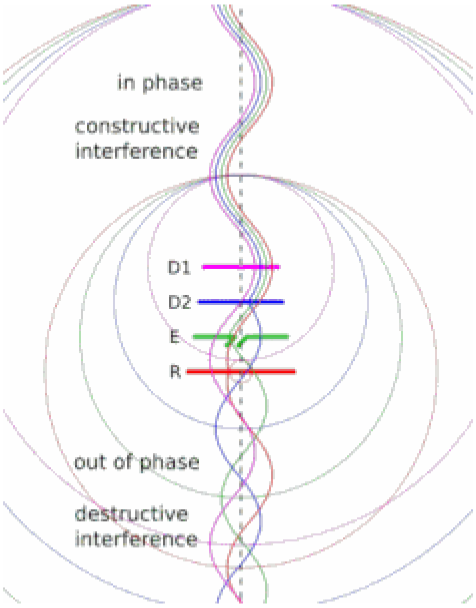


Fig. 2A: Principle of a 4-element Yagi-Uda antenna
(source: [wikipedia.org](); D = director, R = reflector, E = excited/driven element; look closely: the green wave emanates from E, the red, blue, and pink waves from R, D2, and D1, respectively)

The waves that are radiated by both elements, combine in all directions - they are superimposed. This results in a 3-dimensional interference pattern around the antenna. Due to the spatial distance, there is a phase delay between the radiation from the driven element, and the re-radiation by the passive element. If the passive element is slightly *longer* than driven element (typ. by about 5%), then its radiating current *lags* the voltage that is induced in this element by the driven element. Consequently, the waves of the two elements combine *constructively* (= amplifying) on the side of the driven element that is away from the passive element.

On the passive element side of the driven element, the waves combine in a *destructive* (= extinguishing) manner. Hence, such a passive element is called a "reflector". Conversely, the re-radiated current *leads* the induced voltage if the passive element is slightly *shorter* than the driven element. Its re-radiation combines *constructively* on the *same side* of the driven element as that passive element. Such a passive element is called a "director". The driven element by itself has a radiation pattern that is symmetrical: a torus ("doughnut" shape), with the element poking out both sides of the torus hole. Effectively, a reflector or a director concentrate the energy radiated by the driven element in a particular "beam" direction, by reducing the radiated energy in all other directions. Uda antennas with more than two elements have one reflector and one or more directors, all in parallel. I.e., a linear array. Note that each element is coupled to all other elements: all re-radiations are re-radiated by all other elements, etc. The size and individual spacing of the elements determines how much the radiated energy is concentrated in the forward beam lobe (= forward gain), how much in the rearward lobe (= the front-to-back or front-to-rear ratio), side-lobes (if any), the beam width, feedpoint impedance (hence, SWR bandwidth), etc. A standard 3-element beam antenna typically has a forward gain of about 6 dB (4x power factor). In accordance with the universal *Law of Diminishing Returns*, each additional director *N+1* increases the gain relatively less than the adding the preceding director *N*.

Clearly, on HF frequencies (i.e., below 30 MHz), full size many element Uda

Clearly, on HF frequencies (i.e., below 30 MHz), full-size many-element Uda antennas are impractially large for experimentation and most applications. This is why Uda's experiments focussed on VHF frequencies and above. During World War II, both sides of the conflict used Uda antennas for radio beacons and radar. Since WWII, basically all VHF "FM" radio and VHF/UHF broadcast TV receiving antennas on earth are "Yagi" antennas.

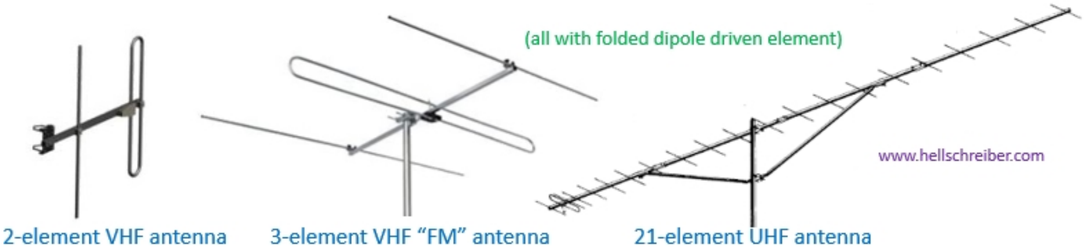


Fig. 2B: Examples of "Yagi-Uda" antennas

Note that the above antennas are *linear* phased arrays: all elements are placed on the same base line. The phased array antenna as such was actually invented by Karl Ferdinand Braun in 1905, twenty years before Yagi and Uda! Ref. 20, 21. This was also mentioned by Marconi and Franklin in their 1919 Australian patent nr. 10922. Braun's array comprised three vertical monopole antennas, placed at the corners of an equilateral triangle. Two of the antennas were fed in-phase. A 1/4 wavelength phase-delay line could be put in series with the third antenna. By selecting which antennas where fed in-phase or with a phase-delay, the beam could be turned into three directions, spaced 120°.

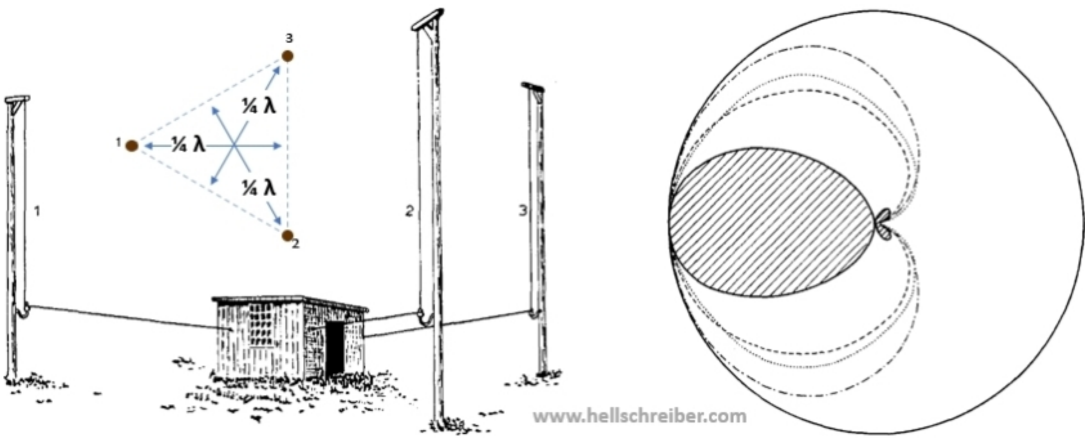


Fig. 2C: World's first phased-array antenna and its far-field polar plot - by K.F. Braun, 1905

(source: Fig. 13 & 14 in ref. 20)

Braun also invented the Cathode Ray Tube (CRT, Braun's Tube, *D:* "Brauns'sche Röhre") and the oscilloscope in 1897, and in 1901 he introduced the capacitor-inductor oscillator circuit and replaced literal "grounding" to earth, with a "counterpoise" that was not connected to earth/ground. After several nominations, Braun received the 1909 Nobel Prize in Physics for his contributions to "wireless telegraphy". He shared the prize with Marconi.

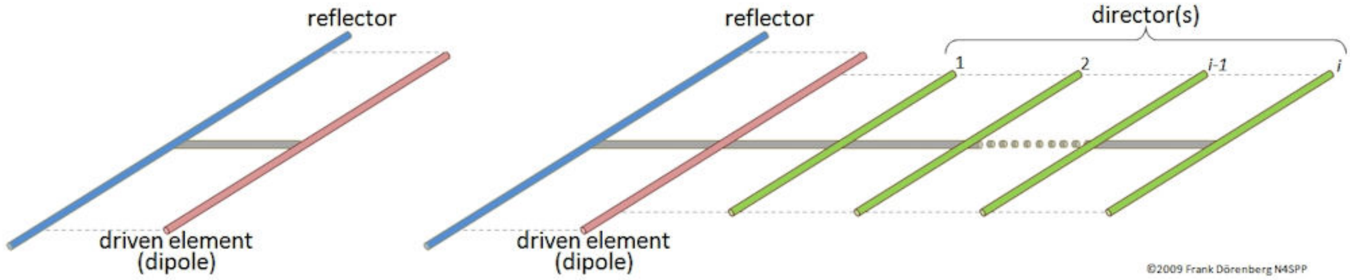


Figure 3: Two-element Yagi-Uda and general Yagi-Uda geometry

Yagi antennas are "mono-band". However, it is possible to combine several 2-element Yagis on the same boom, e.g., for the 20-17-15-12-10 meter band (ref. 3).

THE HALF-SIZE 20M YAGI

A full-size (= ½λ) dipole antenna for the 20 mtr band spans about 10 meters (33 ft). Searching for a half-size half-size 2-element Yagi, I found the design by Gary Hanson (KJ5VW), ref. 4. See ref. 5 and 6 for similar designs. Note that scaling-down a full-size antenna by more than 50% causes significant performance reductions. However, I have actually built very small loaded dipoles for 80/40/20 that are scaled-down by 95% (!) and work interestingly well for their size (but, sorry, no miracles...). A half-size 2-element Yagi should be expected to perform like a full-size dipole. The 20 mtr version is compact and light enough that you can use it with a simple TV antenna rotor/rotator.

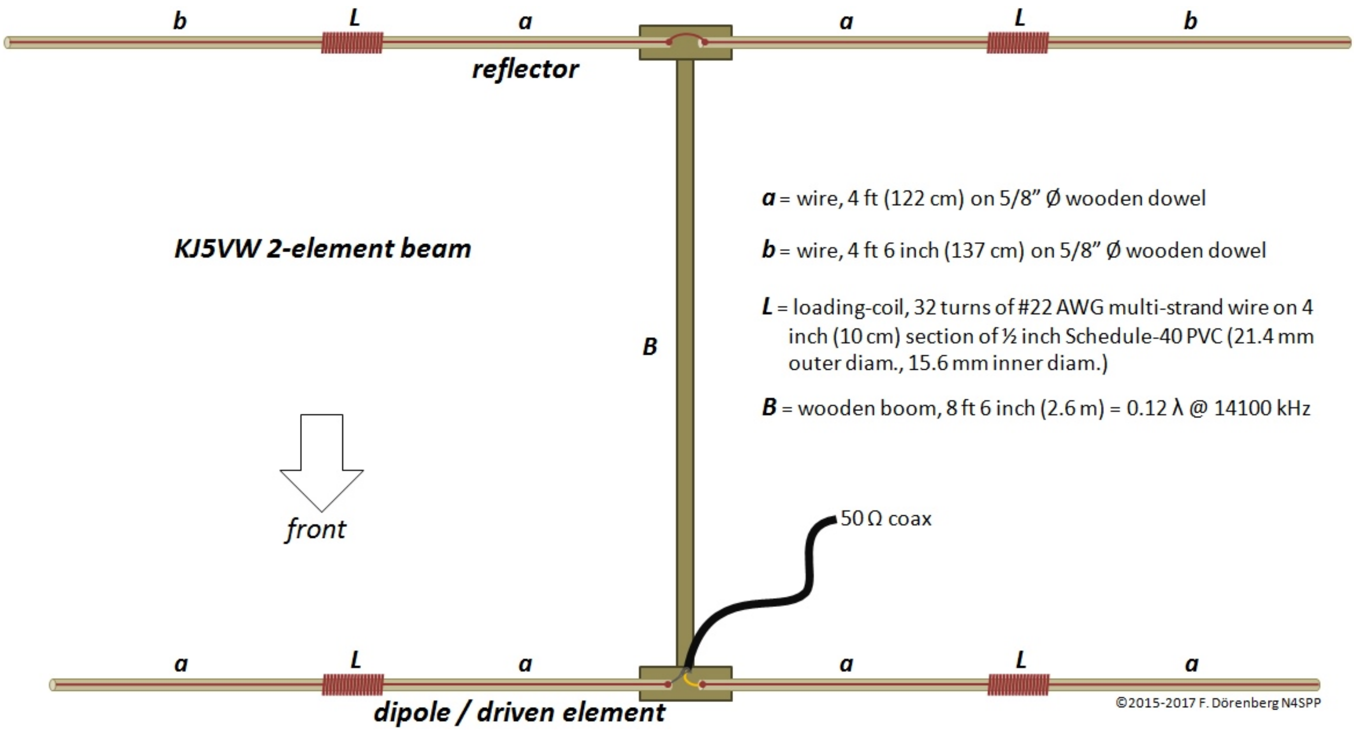


Figure 4: Nominal dimensions of the KJ5VW 2-element yagi
(wire lengths b and c are before adjustment of the resonance frequency)

To make a shortened dipole (i.e., span < ½λ) resonant at the desired frequency, some form of loading is required. One standard solution is "inductive loading": adding a loading coil to each "leg" of the dipole. Ref. 22A-22L. The loading coils is placed somewhere between the feedpoint and the tip of each dipole "leg". The current-distribution along the main elements is such that the current is highest at the feedpoint. Placing a loading coil here, requires the smallest inductance. The current-distribution tapers off, from maximum at the feedpoint to zero at the tip of the radiator element. So, as the loading coil is placed farther away from the feedpoint, a larger inductance is required. At the tip of the main element, the current is zero. This would require an infinitely large inductance. See the diagram below. The placement of the coils *does* affect the shape of the current distribution, but does not change the fact that it is maximum at the feedpoint and zero at the tip.

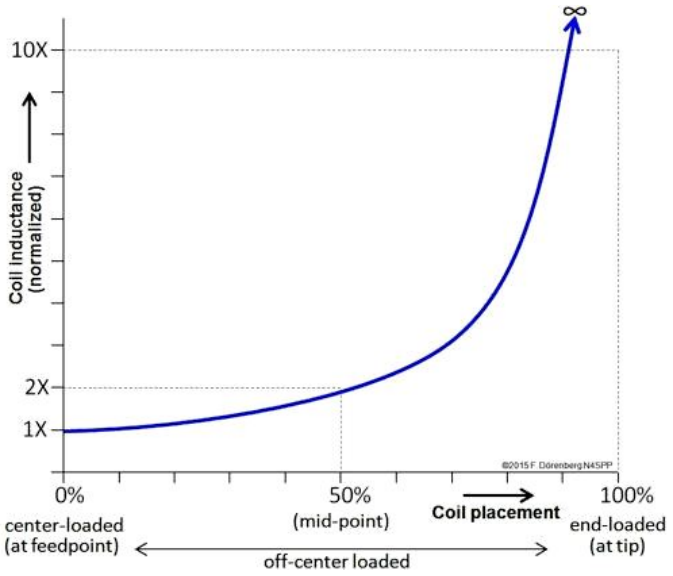


Figure 5: Required loading-coil inductance as function of coil placement

Center-loading a dipole (also called "base loading" when talking about vertical monopole antennas) requires the smallest inductance, and is often easier to construct than *off-center* loading. So why not always use center-loading? This is primarily driven by coil losses, hence, efficiency of the antenna. The coil losses basically depend on the current, coil dimensions, material, construction, and core. Depending on the diameter of the radiator element (tubing, wire) and installation height, compared to the wavelength, the most efficient placement of the loading coil is somewhere between 30 and 60% away from the feedpoint (ref. 8, 9). I.e., around the mid-point. The radiator and reflector of the KJ5VW antenna are "mid-element loaded". Note that the efficiency-vs-placement curves are fairly flat over a relatively large range around the mid-point.

CONSTRUCTION

I decided to build a lightweight version of the KJ5VW design. Instead of attaching the dipole wires to wooden dowels, each leg of my dipole and reflector consists of a 10 ft (= 3 m) lightweight telescopic fiberglass fishing poles. Got them at the end-of-summer sale at a local supermarket. The poles have 3 collapsible sections of 4 ft. Each pole only weighs 4½ ounces (130 grams)! Note: some such poles are made of carbon fiber or with graphite. I do not know if they are conductive for RF and cause undesirable loading (or losses) of the dipole. The total weight of my design is only 2.4 kg (5.3 lbs) - about one third of the KJ5VW design (6.8 kg, 15 lbs). Obviously, the fishing poles are more flexible than dowel rods, so they tend to flop around when its windy!

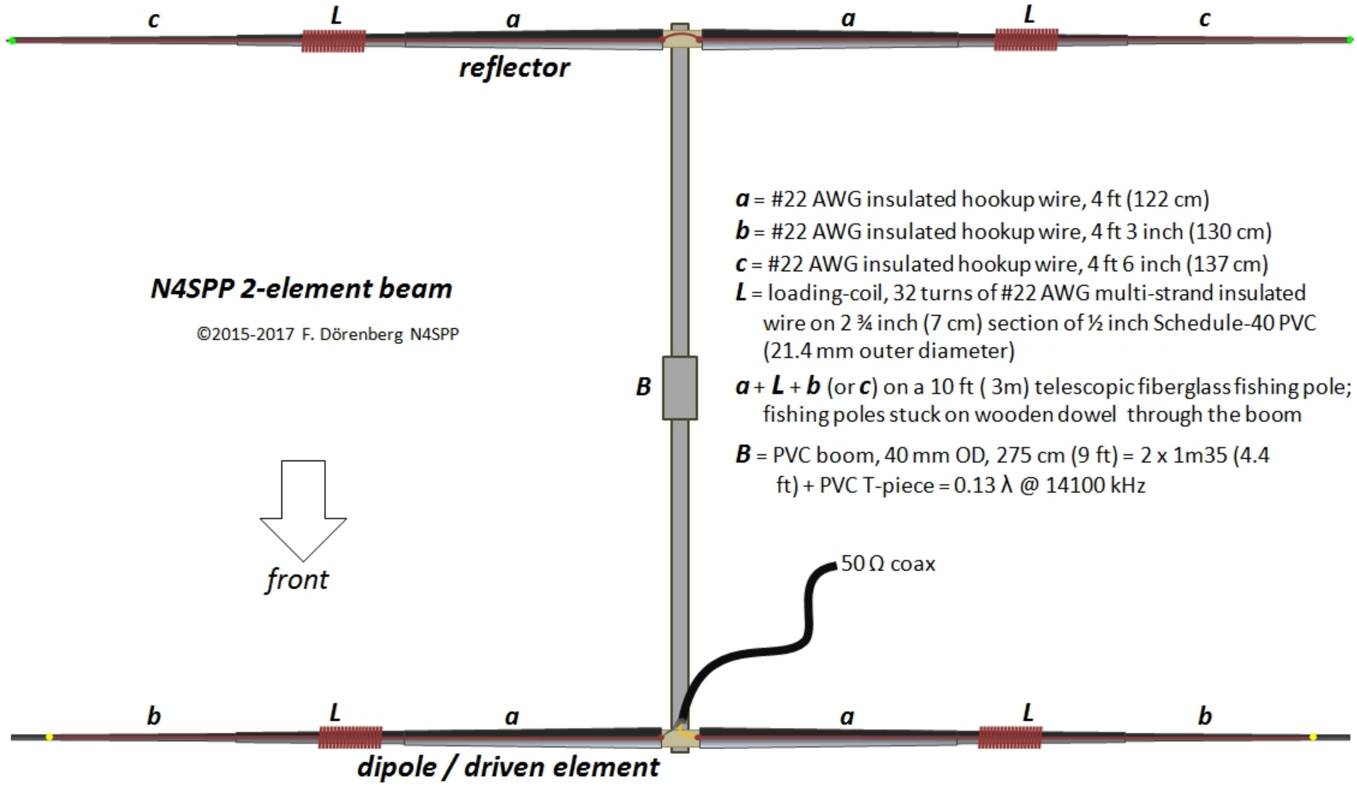


Figure 6: Nominal dimensions of the N4SPP yagi

(wire lengths b and c are after tuning & pruning the wire beyond the coils for my desired f_{res} and my installation)

The first step in making the 2-element antenna, is building the dipole. So, first I built & tested the dipole with loading coils by itself, see this page. This is how I made my loading coils:

Each coil core consists of a 7 cm (2¾ inch) long section of 1/2 inch Schedule-40 PVC pipe from the building supply store (21.4 mm outer diameter; 15.8 mm inner diam). This is not the lightweight light gray pipe, but heavy duty, thick-walled "rigid non-metallic conduit - above ground underground" pipe. However, this is not critical for this application!

I have drilled out a small groove from the edge of the coil core to each of the holes. (see photo below)

For each dipole leg (incl. the coil), I used 5.2 m (17^+ ft) of #22 AWG (0.64 mm Ø, 0.33 mm^2) multi-strand insulated hook-up wire (1.6 mm total diameter):

2.2 m (7^+ ft) of wire for the coil itself.

1.5 m (5 feet) sticking out beyond each coil-end (i.e., 2x 1.5 m). This includes margin for "tuning-and-pruning" the antenna to the desired center frequency.

note that the wire is not cut - I simply pulled 2.2 + 1.5 m through the starter hole in the coil core, wound the coil, and pulled the remaining 1.5 m wire through the exit hole of the coil core.

With this type of wire, the required 32 turns produce a coil that is just over 5 cm long (2"). Drill feed-through holes with a distance of 5.1 cm (2") between the holes (not center-to-center) to nicely fit the coil. See photo below. I used a 5/64" (2 mm) drill bit.

The wire is fixed in place with small dabs of waterproof glue on the outside of the first and the last turn. I have used both the universal 2-component epoxy glues "UHU Endfest 300" and "Eccobond 286 Blue" (which even holds up in the dishwasher and the microwave oven). Gorilla Glue® also works.

As always, "Harry's Law of Coils" applies. As Harry (SMØVPO) says

You cannot wind coils like *I*, and *I* cannot wind coils like *you*.

Coil-winding data is a constant that varies from person to person.


Figure 7: Two blank PVC coil cores and a finished 32-turn coil
(notch of groove is visible in top blank core)

Loaded-dipole calculators (e.g., ref. 10A/B/C) suggest that - *for the given dimensions of the antenna* - the loading coils should have an inductance of about 8.5 µH. Coil calculators (e.g., ref. 11A/B/C) suggest that the KJ5VW coils have an inductance of about 9 µH. That's in the ballpark - and, as over 30 years of professional engineering experience has taught me: *anything within ±20% is within engineering accuracy*, hi! Out of curiosity, I checked the actual inductance with my miniVNA antenna analyzer (series & parallel resonance) and with my dip-meter (ref. 12), and found 8.9 µH. Of course, accuracy of the measurement is affected by the tolerance of the capacitor value. When new, ceramic disk caps typically have +80/-20% tolerance, milar polyester typ. ±5 or ±20%, tantalum typ. ±10 or ±20%, metalized polypropylene typ. ±5, ±10, or ±20%, electrolytic typ. ±20%, etc. Note that cheap LC-meters typically measure inductance and capacitance well below 100 kHz, and the indicated values may not be valid at RF frequencies. For the effect of coil "Q" on bandwidth and Front-to-Back gain, see ref. 16.

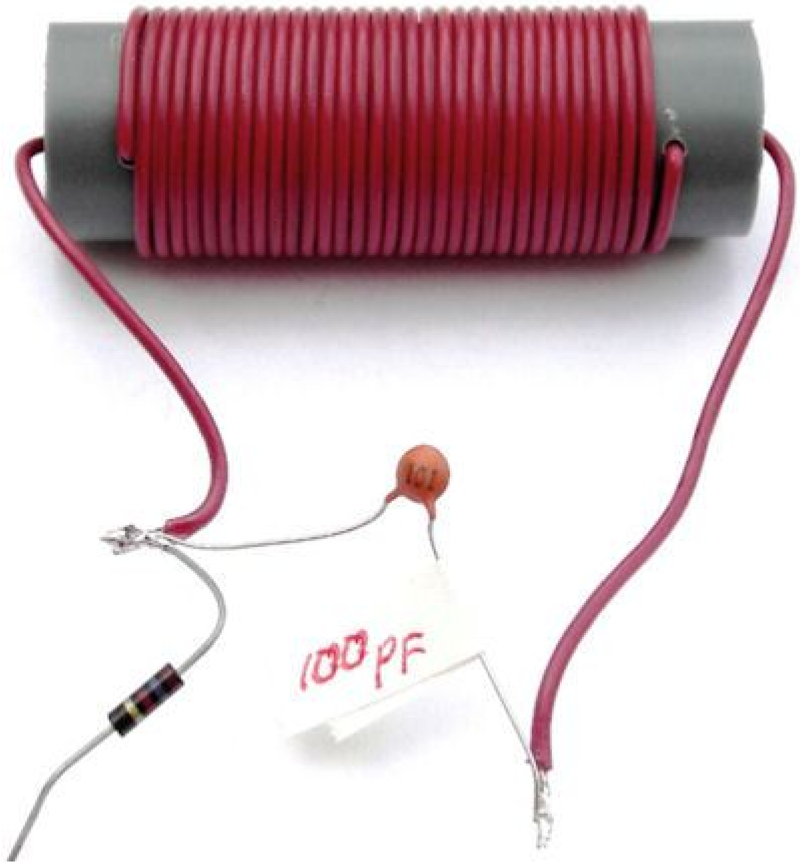


Figure 8: Test set-up for parallel-resonance inductance measurement

$$f_{res} = \frac{1}{2\pi \cdot \sqrt{LC}} \quad \Leftrightarrow \quad L = \frac{1}{C \cdot (2\pi \cdot f_{res})^2}$$

My coils are cylindrical and wound on a PVC core. The same inductance can be obtained with small toroidal iron powder cores: e.g., about 30 turns on a T-130-2 core (1.3" diameter), and about 45 turns on a T-50-2 core (0.5" diameter). Ref. 13. You may have to stack 2 or 3 such small cores to get 4x or 9x power handling.

Figure 9: The components of my antenna (PVC mast included, fishing poles partially collapsed)

I used 2 meters of PVC tube of 4 cm diameter as a temporary mast, stuck into a heavy cast-iron umbrella stand (see Fig. 12 below). The antenna boom is made of the same material: 2 sections of 135 cm (4 ft 5") in length (cut from a standard 3 m section). They are mounted on top of the mast with a T-piece. I did not glue the sections into the T-piece. This way, it is easy to disassemble and experiment with the boom length. Once installed into the T-piece, two long nails prevent the boom-sections from turning and slipping out, and the T-piece from turning about the mast. Obviously this won't hold up under windy conditions, but it is fine for experimental trials and fair weather mobile/portable use. The fishing poles fit tightly onto 18 mm diameter dowel rods that run through the ends of the PVC boom sections. The dowels were cut to length such that the fishing poles are almost up against the boom when they are fully "impaled" on the rods. Shrink tube was used at the tip of each pole segment, to keep the wire taught. For the same purpose, tie-wraps were used at the base of the poles (didn't have shrink tube of sufficient diameter). It takes about 10 minutes to assemble or disassemble the antenna.

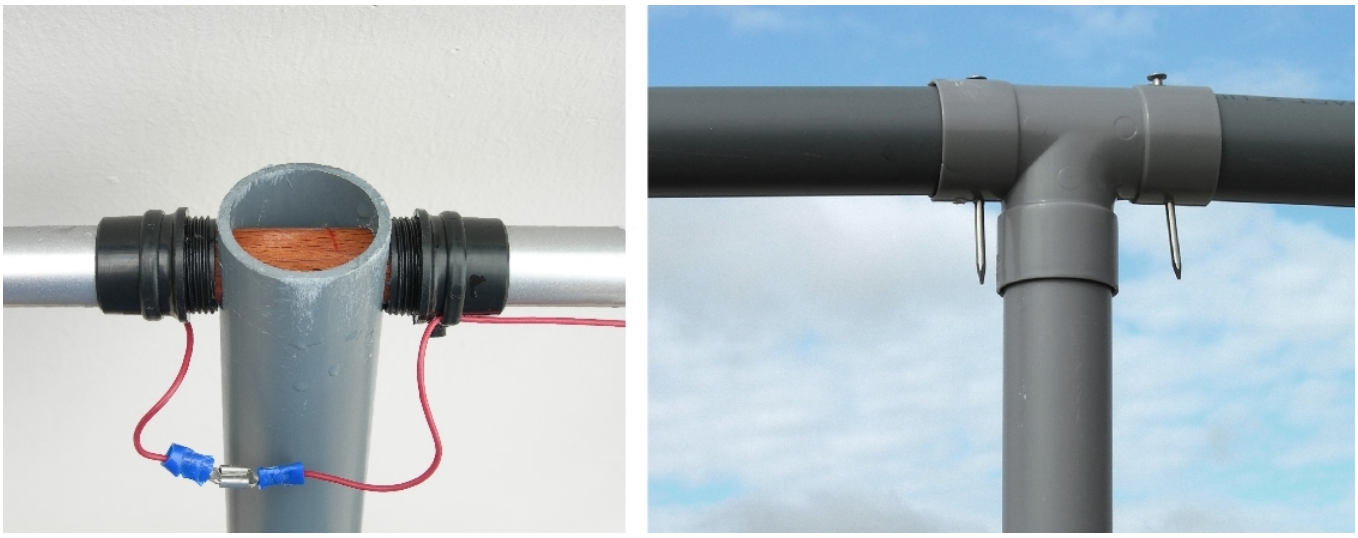


Figure 10: Close-ups: quick-disconnect of the reflector and T-joint of the PVC boom and mast

(you may want to cut the sharp tip of the nails through the T-piece, to reduce risk of injury)

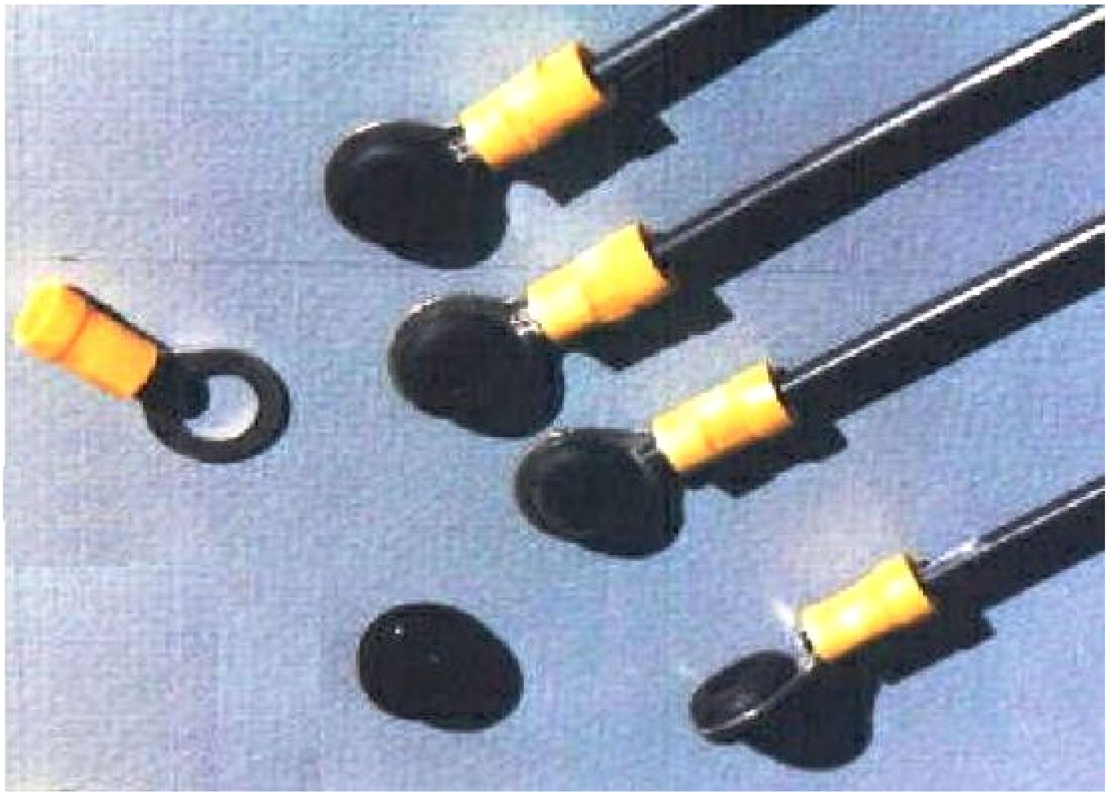


Figure 11: Idea - crimp-on ring terminals with a rubber grommet for the tip of the fishing poles
(purpose: make it easier to attach the wire ends to the tip of the fishing poles)

TUNING-AND-PRUNING

As indicated above, I first built the dipole by itself. The coils are slid over the fishing poles, until they are at the mid-point. The wire on the feedpoint side of the coils is attached at the feedpoint, with about 10 cm (4") excess, for connecting to the feed line. The wire on the opposite side of the coil is pulled taught and attached near the tip of the fishing pole. The dipole is then installed on the boom - by itself (i.e., without the reflector).

My desired resonance frequency is about 14150 kHz, so as to cover both 14230 kHz (SSTV) and digi-modes around 14070 kHz. With the help of a dip-meter or antenna analyzer, the resonance frequency is checked. For the starting length of wire beyond the loading coils, the initial resonance frequency should always be low. The resonance frequency is now increased bit-by-bit to the desired value: trim the tip-wires 1-2 cm (½-1 inch) and re-check the resonance frequency. Resonance frequency went up by about 50 kHz per centimeter trimmed (≈125 kHz per inch). The cut-and-check operation is repeated until the desired resonance frequency is obtained. Keep in mind that it is much easier to cut "off" a small piece of wire, than to cut it "on"! So, keep track of how much the resonance frequency increases each time your trim a piece, and stop pruning before you overshoot the target frequency too much.

Once the dipole of the driven element is tuned, remove it from the boom, and install the reflector "dipole". Tune this dipole just like the driven element, but to a resonance frequency that is about 5% lower than that of the driven element. In my case: 0.95 x 14150 = 13445 kHz. This requires that the wires on the inside and/or the outside of the loading coils be longer than those of the driven element. Alternatively, the loading coils could be made slightly larger, but coils are much harder to tune... After tuning the reflector, interconnect the wires at the feedpoint. See Figure 8 above. Then re-install the driven element dipole. Done!

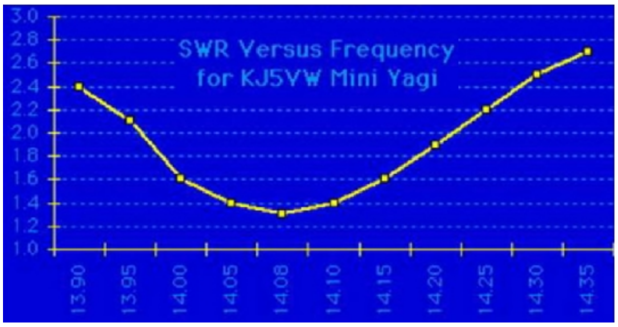
Note that the final wire length beyond the coil depends on parameters such as the desired resonance center frequency, the coil winding spacing, wire diameter, wire insulation (velocity factor), the wire length between the feedpoint, objects below and near the antenna, soil/ground conditions, and installation height above ground. The height is a major factor for installations below 1/2 wavelength (ref. 17)! If you cannot tune the antenna at its final installation position, you will have to install/deinstall antenna each time you trim/tune the antenna!

Figure 12: My first Yagi, fully assembled and installed

I use a 1:1 "common-mode choke" balun at the antenna's feedpoint (not shown in the photo above). Common-mode currents on the feedline will distort the radiation pattern.

MEASUREMENTS

An SWR plot of the antenna is shown below. The original KJ5VW design indicates a 2:1 SWR bandwidth of about 250 kHz. At the installation height shown in Figure 9 above (only about 2 mtrs = 6+ ft), my Yagi has a bandwidth of about 220 kHz . I did not play with the antenna geometry to get to SWR = 1. My transmitter has no problem with SWR = 1.34.



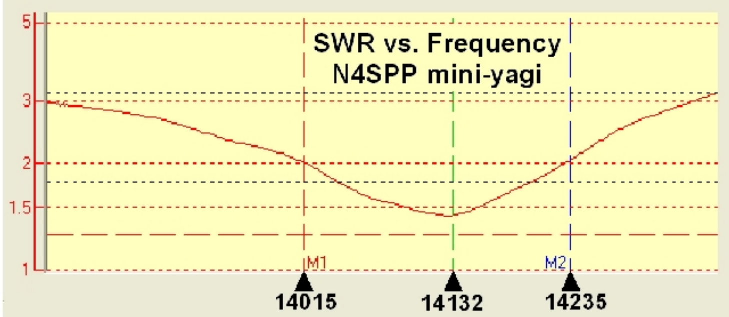


Figure 13: SWR curves from original KJ5VW design vs. mine

Update of September 2018. At the time that I built and toyed with this mini beam (10 years ago!), I did not do any pattern measurements or simulations. Also, as you can see from the photos, I installed the antenna only about 2 meters (6+ ft) off the ground, which is only about 0.1 wavelength, which is not enough, and results in too much upward radiation. These days, Web-SDRs are plentiful (e.g., websdr.org), so measuring the pattern would be relatively easy. I expect this half size beam would perform like a full size dipole, with some directivity and F/B depending on the installation height. Ref. 15 is a simplified NEC model that I just slapped together. It works fine with the excellent 4NEC2 freeware modeling package. You would have to tweak it to the exact dimensions and your installation height.

Early 2019, Nick (KE4ZMY) in southern Florida, built my design (with some mechanical changes). He is very pleased with it: "*I was able to work more than 87 countries and all continents in approximately 30 days. Not to mention that antenna tunes and performs well with my tuner on 10m and 6m (worked Canadian FT8 on 6M). One interesting fact is that the antenna center frequency changes from 13.950 MHz at 6' to 14.175 MHz at 28' height above ground. Had to bring it up and down several times to fine tune it. Even though I have significant sensitivity from the back, without any scientific data, back to front ratio appears to be 8-10db. I use my MFJ-898B in bypass mode for the SSB portion of the 20M and in tuner mode for all other frequencies. It requires very a small tuning touch up for FT8 band. It tunes to 1:1 on 6, 30 and 40m but with understandable significant loss in radiation patterns. Typically, on those bands I receive 6-8 db lower reports then I would have had on 20m for a similar ranges.*"

Figure 14: The antenna built by Nick (KE4ZMY)
(photo ©2019 KE4ZMY, used with permission)

Figure 15: One of Nick's loading coils and SWR reading
(photo ©2019 KE4ZMY, used with permission)

OTHER 2-ELEMENT WIRE-BEAMS

The Yagi described above is a straight-forward 2-element beam antenna. The driven element and the reflector are straight and parallel. There are many variations that have a bent driver and reflector. These shapes allow a significant reduction in size (and turn radius) compared to a full-size 2-element Yagi - without having to resort to loading coils and associated losses. On top of that, they can have larger forward gain and significantly larger front-to-back (F/B) ratio than the standard full-size configuration. Ref. 14.

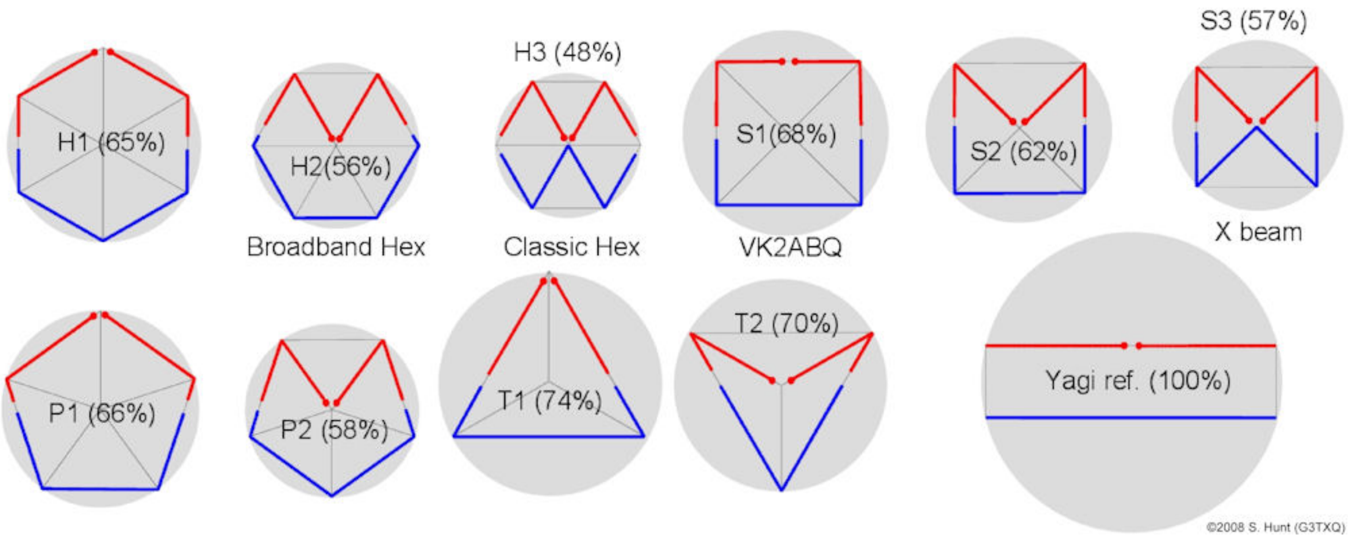


Fig. 16: Some reduced-size 2-element wire-beam configurations - size and turn radius referenced to full-size
(source: ref. 14)

If, you have space for a turn radius of almost 4 m (13 ft), have a look at the 2-element/6-band beam antenna from the 1960s in ref. 14 (in German language) or search the internet for "Maria Maluca antenna".

REFERENCES

Ref. 1: "Yagi Antenna Design", Peter Viezbicke, NBS Technical Note 688, US Dept. of Commerce, Nat'l Bureau of Standards, December 1976, 30 pp. Source: NIST

Ref. 2: "Simple gain antennas fir the beginner", Doug DeMaw (W1FB), in "QST", August 1981, pp. 32-35

Ref. 3: "5-Band Yagi (20M/17M715M/12M/10M)", product brochure of JK Antennas. Note: I cannot endorse this antenna, as I have no experience with it. The manufacturer is welcome to contact me, to donate such an antenna for trials.

Ref. 4: "The KJ5VW 20 Meter Mini Yagi" by Gary Hanson, KJ5VW

Ref. 5: "Build a high-performance low-profile 20-meter beam", Cornell Drentea WB3JZO), in "Communications Quarterly", Spring 1993, pp. 85; retrieved 5-July-2019. [pdf]

Ref. 6: "Monoband Yagi for 20 meters - more dBs for the buck" by Ken Kemski, AB4GX (aluminum tubing instead of wires; still center-loaded but the director and reflector are about 1m2 / 4 ft longer).

Ref. 7: "The G3YCC 'Shorty' Dipole for 14 MHz" by Frank Lee (G3YCC, SK)

Ref. 8: "Shortened Dipole Study for Conditions On BVARC's Rag Chew Net", Larry Jacobson (K5LJ), Rick Hiller (W5RH), expanded from same-title article in "Newsletter of the Brazos Valley Radio Club", September 2009

Ref. 9: "Element Loading to Achieve Dipole Resonance", part 3 of "Half-Length Dipoles (for 40 Meters)", L. B. Cebik (W4RNL, SK)

Ref. 10: Dipole loading calculators

- **Ref. 10A:** "On-line short Off-Center-Loaded dipole calculator by Martin Meserve (K7MEM)
- **Ref. 10B:** "Shortened dipole calculator (.exe)" by Alexander Stirling (VE3KSK)
- **Ref. 10C:** "Loaded dipole calculator (.exe)" by Al Legary (VE3SQB). Note: the GUI of this calculator shows inductance as "mH" instead of "μH"!

Ref. 11: Coil calculators

- **Ref. 11A:** "Helical coil calculator" on pages of the Tesla Coil web-ring.
- **Ref. 11B:** "K1QW Inductor Calculators"
- **Ref. 11C:** "ON4AA Single-layer Helical Round Wire Coil Inductor Calculator"

Ref. 12: "Measurements of an antenna loading coil" by Frank Dörenberg (N4SPP), 13 August 2008

Ref. 13: "Turns-length calculator for ferrite and iron powder core toroids"

Ref. 14: "A family of wire beams" by Steve Hunt (G3TXQ), May 2008 [pdf]

Ref. 15: NEC model of my half-size 2 elem 20m beam antenna by Frank Dörenberg (N4SPP), 3 September 2018.

Ref. 16: "Short Beams and Operating Bandwidth - The Evolution of a Modeling Design", L. B. Cebik (W4RNL, SK), version 10-5-97. Retrieved 1-Jul-2019. [pdf]

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Ref. 18: articles about Uda / Yagi antenna background

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