

A 2-Meter Vertical Dipole Array

Build this 2 or 4-Element VHF repeater antenna with up to 9.7 dBi gain and 18° Vertical Beamwidth.

Most commercial 2-meter repeater antennas with gain fall into two categories: collinear arrays and stacked element arrays, with gains ranging from 3 to 9 dB¹. The higher gain antennas have a lower vertical beamwidth. For example, a typical 4-element exposed dipole offset array with 9 dB gain has a vertical beamwidth of 16°. This is the angle above and below the horizon at which the signal is half the strength (-3 dB) of the signal at the horizon. In general, high gain antennas work best from low level sites, or high elevation sites far away from the targeted area. For high sites near the target area, a lower gain antenna with a higher vertical beamwidth is used. This prevents the signal from passing over the target area.²

Exposed dipole arrays fall into the stacked element array category. They resemble folded dipoles and their construction often requires tube bending, welding, or special brackets. Coaxial collinear arrays (made from coax) are easier to build but do not break down into convenient lengths for transporting. Vertical dipole arrays built from individual and unconnected center-fed dipoles are among the simplest to construct but can be difficult to feed. Unless each feedline is routed a significant distance away from the antenna at a 90° angle, feedline coupling will distort the radiation pattern.

With these ideas in mind, I began modeling antennas in search of an easy to build, all metal, vertical dipole array. The antenna that emerged from these modeling sessions consists of four vertical dipoles, each centered on a 60 inch vertical section. While the array can be built using a variety of methods and materials, a copper pipe version is presented here. The array is offset³, with all elements and maximum gain on the same side of the mast. In addition to 9.7 dBi gain, each dipole is 50Ω, allowing the phasing harness to be built from readily available 75Ω coax. The phasing harness sections are strapped to each dipole, minimizing feedline coupling and pattern distortion. For high elevation sites near the target area, one-half of the array can be used to provide less gain (6.85 dBi) and a higher vertical beamwidth (36°).

Antenna Construction

The array can be built using four identical dipoles. However, the length and feedpoint impedance of each dipole is influenced by its location in the array. Inner sections are affected by the outer section on both sides and hence differ in impedance from the outer sections, which are affected on only one side. In order for the phasing harness to work correctly, each antenna in the array should be as close as possible to 50Ω at the resonant frequency⁴. For this reason, each dipole in the array has been optimized. (See individual SWR plots, attachment 2 of 9).

The array is built entirely from ½ inch copper pipe and fittings and is 20 feet tall. However, due to the weight of copper pipe it must be supported (or hung) from a tower or fastened to a non-metallic mast. To construct the 4-element array you will need 35 feet of ½ inch type L copper pipe, eight ½ inch copper tees, ten ½ inch copper caps,

three ½ inch unions, and 12 inches of ¼ inch PVC pipe (0.540 inch OD). The caps are optional and are for the prevention of mud dauber nests. If installed, drill a 1/8 inch hole in the bottom caps for moisture drainage. If they are not installed, increase the pipe lengths accordingly. Cut the PVC pipe into four, three inch pieces, to make the feedpoint isolators for each dipole.

One-half inch type L copper pipe has an actual OD of 5/8 inch and an ID of 0.545 inches. Copper pipe fittings now come in normal and pre-soldered⁵ varieties and the dimensions can vary. It is more accurate to cut the pipe slightly longer than needed, sweat the joint, and then trim to length with a tubing cutter and a file.

Centerline dimensions as well as cut pipe lengths (for pre-soldered fittings) are included on Drawing 1. Use 6-32 x 7/8 inch stainless steel pan head screws, washers, and locknuts for all feedpoint hardware. Drill the feedpoint screw holes using a drill press and then deburr the inside of the pipe with a round file. Next, insert the three inch length of PVC, align and tape the feedpoint assembly together, and then drill the PVC. This allows the PVC to be easily removed for sweating the pipe joints and prevents it from melting. Flag terminals are soldered to the coax and attached to the feedpoint screws. The exposed coax ends are sealed with Coax-Seal⁶ and the harness is secured to the pipe with cable ties. Male UHF connectors are soldered to the other ends of the coax.

Each 60 inch dipole section is secured to the mast with 10-24 x 1-¼ inch stainless steel screws and stop nuts. After drilling 3/16 inch holes at each end (see Drawing 1), match drill corresponding holes on the assembled mast sections. Insert a screw in each mast from the inside and secure it on the outside with a stop nut. Depending on where the mast holes fall this may require taping a string on the end of the screw and fishing it through the mast hole. Each dipole can now be fastened to the mast by placing it over the mast screws and secured with a stop nut.

Dimensional Changes

A larger diameter for the 60 inch vertical section is possible as long as the horizontal distance between the vertical section OD and the dipole OD is maintained. The ½ inch copper array centerline dimension between the vertical section and the dipole is 9 inches. This distance between outside diameters (for ½ inch copper pipe) is 8-3/8 inches (9 inches between centerlines minus 5/16 inch on each pipe). If, for example, the 60 inch vertical section is increased to 1-1/2 inches OD, you must maintain the 8-3/8 inches between outside diameters. This will increase the centerline dimension to 9-7/16 inches. The feedpoint dimension may also have to be moved slightly to obtain 50Ω at resonance. An aluminum clamp-on array, shown on Drawing 4, illustrates the use of different materials and construction techniques. The dipoles are made of 1-3/8 inch OD aluminum tubing and are clamped to a metallic 1-1/2 inch OD mast. I encourage the reader to use an antenna modeling program to model any changes before construction

Phasing Harness

The 4-element array phasing harness is based on feeding four 50Ω antennas from one 50Ω feedline. Likewise, the 2-element array uses two 50Ω antennas fed from one 50Ω feedline. Coax connectors and tees are used to aid in a faster setup. If your antenna installation is permanent, you may want to solder and weatherproof the coax junctions to minimize losses. Figures 1 and 2 show the 4-element and 2-element harnesses, respectively, with cable lengths and impedances at each point. Optimum coax lengths are necessary to prevent from having too much cable to strap to the antenna. When

cutting cable lengths, remember that the velocity factor applies only to that portion of coax where the center conductor insulation is still in place. The math involved for calculating coax impedance and length is as follows:

Lambda (λ) is the physical wavelength of coax and is defined as:
 $\lambda = (\text{Electrical Wavelength at } F_o) \times (\text{Velocity Factor of the Coax})$

Equation 1: $\frac{1}{4}\lambda = (2952/F_o) \times (VF)$

Where

$F_o = \text{Design Frequency} = \text{SQRT}(F_{\text{INPUT}} \times F_{\text{OUTPUT}})$

For this TNSG⁷ repeater, the frequencies are

$F_{\text{INPUT}} = 143.225 \text{ MHz}$

$F_{\text{OUTPUT}} = 149.800 \text{ MHz}$

$F_o = \text{SQRT}(143.225 \times 149.800) = 146.475, \text{ or } 146.5 \text{ MHz}$

Equation 2: $Z_o = \text{SQRT}(Z_{\text{IN}} \times Z_{\text{OUT}})$

Where

$Z_o = \text{Transforming coax}$

$Z_{\text{IN}} = \text{Input impedance}$

$Z_{\text{OUT}} = \text{Output impedance}$

Each antenna is 50 Ω at the operating frequency. Because we are combining four antennas in parallel at the connection point, the impedance of the connecting cables A, B, C, and D must be 100 Ω at the point of connection. Two 100 Ω impedances connected in parallel produce an impedance of 50 Ω . A quarter wavelength (and odd multiple) of cable that provides the proper characteristic impedance can transform the 50 Ω impedance of each antenna to 100 Ω at the connection point⁸ The required characteristic impedance of cables A, B, C, and D can be found from the formula in Equation 2. In this application, the calculation is shown as:

Cables A, B, C, and D:

$Z_o = \text{SQRT}(50 \times 100) = 70.7, 75\Omega \text{ coax}$

RG-11A/U, 75 Ω , 0.66 VF (Wireman 121)

VF was verified using an MFJ-259B: 0.6638

Vertical distance between Dipole 1 - 2, and 3 - 4: 60 inches

Minimum length needed for each cable: $60/2 = 30$ inches

Length needed for each cable (strapped to antenna): $29+8+3 = 40$ inches

$F_o = 146.5 \text{ MHz}$

$\frac{1}{4}\lambda = (2952/F_o) \times (VF) = (2952/146.5) \times (0.6638) = 13.376$ inches

Odd multiples of $\frac{1}{4}\lambda$: $1 \times \frac{1}{4}\lambda = 13.376$ inches (not long enough)

$3 \times \frac{1}{4}\lambda = 40.128, \text{ or } 40\text{-}1/8$ inches

Cables E and F:

The math for cables E and F is the same except for the distances involved.

$Z_o = \text{SQRT}(50 \times 100) = 70.7, 75\Omega \text{ coax}$

RG-11A/U, 75 Ω , 0.66 VF (Wireman 121)

Distance between Tees 1 and 2: 120 inches

Minimum length needed for each cable: $120/2 = 60$ inches

$F_o = 146.5 \text{ MHz}$

$$\frac{1}{4}\lambda = (2952/F_0) \times (VF) = (2952/146.5) \times (0.6638) = 13.376 \text{ inches}$$

Odd multiples of $\frac{1}{4}\lambda$:
1 X $\frac{1}{4}\lambda = 13.376$ inches (not long enough)
3 X $\frac{1}{4}\lambda = 40.128$ inches (not long enough)
5 X $\frac{1}{4}\lambda = 66.880$, or 66-7/8 inches

The phasing harness loss at 150 MHz is calculated to be 0.67 dB. Additional loss from 50 feet of RG-8 (Wireman CQ102) is 0.79 dB, for a total cable loss of 1.46 dB. The total cable loss for the 2-element array is 0.96 dB.

Antenna Coverage and Testing

Initial testing was performed with the 2-element array in my back yard. Using a GPS, latitude, longitude, and elevation data were fed into a HAAT⁹ calculator to obtain a value of 33 feet. This "Height Above Average Terrain" value represents an average of the terrain elevations within 10 miles of the transmitter site, and provides a single value on which general coverage calculations and regulatory requirements may be based. Using 5 watts, comparisons with a J-Pole at the same elevation indicated that the 2-element array was a major improvement for distant repeater access.

Subsequent testing was done with the assistance of NG4T, Communications and Electronics Officer for the Third Alvin C. York Regiment of the Tennessee State Guard. For this location, the 4-element array's HAAT was calculated to be 40 feet. Antenna coverage was tested using a Motorola Micor at 40 watts and a six cavity mobile duplexer. Using 5 watt HT's, communication ranges of up to 15 miles were established in residential areas with rolling hills and considerable ground clutter.

Portability & Assembly

The array was built with portability in mind. Each 60 inch section mechanically attaches to the next with a copper union and the array is clamped to a 44.5 foot fiberglass mast. This sectional surplus mast was used by the military for camouflage screening. Stainless steel screws (10-24 x 1- $\frac{1}{4}$ inch and stop nuts) installed from inside the top 6 mast sections secures the array to the mast. The array is offset about 10 inches down from the top guy ring to prevent interference with the guy lines. The 4-element array weighs 13 pounds (including phasing harness) and breaks down into a 1 by 5 foot bag. A second bag contains the harness, cable ties, Coax-Seal®, stakes, hammer, wrench, and guy lines. A third bag holds the 12 fiberglass mast sections.

When assembling the array, ensure that all dipole feedpoints are oriented in the same direction (i.e. all on the bottom or all on the top), and are lined up vertically. Failure to do this will result in a less than optimal radiation pattern. I recommend labeling each dipole and its associated position on the mast. Setup is accomplished with two to three people in under two hours. Install a tilt base vertically in the ground at the desired location. Lay the mast sections down with the large ends pointed toward the base and the screw sections at the top. Plug the mast sections together, adding guy rings at the top of the 3rd, 6th, and 12th mast sections. Attach each antenna section to the mast using 10-24 stainless steel stop nuts and connect the sections. Assemble the coax tee connections and feedline and secure to the mast using cable ties. Waterproof the coax tee connections using Coax Seal®. Next, attach the appropriate length guy lines to each guy ring using snap clips. Measure a 23 foot radius from the base of the mast and install three stakes, 120° apart, with one stake in the direction of the prevailing wind. Attach two sets of three guy lines to the closer two stakes and pull/push the mast upright. Finally,

secure the third set of guy lines to the last stake and adjust the guy line tension as needed to obtain a vertical mast.

Antenna Gain Comparison

The EZNEC¹⁰ modeling program displays gain in dBi, whether in free space or over ground. In an effort to present a fair comparison and to avoid confusion over gain figures, several vertically polarized antennas were modeled and compared to the 2 and 4-Element Vertical Dipole Array. The reference antenna is a 2-meter vertical dipole made of 5/8 inch OD copper, fed in the middle, and resonant at 146.5 MHz. The modeled statistics for free space and 45 foot elevations (over average ground) are summed up in Table 1.

<i>Table 1</i>					
2-Meter Vertically Polarized Antenna	Elevation: Free Space			Elevation: 45 ft.	
	Gain dBi	Gain over Vertical Dipole dBi (dBd)	Vertical Beamwidth °	Gain dBi	Gain over Vertical Dipole dBi
Vertical Dipole Reference	2.15	-	78.0	6.99	-
Collinear J-Pole	4.99	2.84	39.5	9.45	2.46
Vertical Moxon Rectangle	6.00	3.85	79.4	10.80	3.81
<i>2-El Vertical Dipole Array</i>	6.85	4.70	35.4	11.18	4.19
3-El Vertical Yagi	8.50	6.35	61.0	13.27	6.28
<i>4-El Vertical Dipole Array</i>	9.71	7.56	17.2	13.77	6.78

Transportable TNSG Repeater

With the recent addition of TEMA¹¹ responsibilities to the state guard, regiments are being asked to provide emergency communications during emergency and disaster situations. To assist the Tennessee State Guard in accomplishing its mission, I have donated this antenna and mast to the Third Alvin C. York Regiment for use as part of a transportable Tennessee State Guard repeater system.

Wrapping Up

Elevation is the single most important factor when choosing a repeater antenna site and it can be a challenging process to find the optimum location for a given target area. Attempting this with a portable system is even harder as the location will change from one setup to the next. The 2 and 4-Element Vertical Dipole Arrays presented here provide some flexibility for installations in different situations. The 2-element array would be the best choice for high elevation sites near the target area. The 4-element array should be used for high elevation sites far away from the target area, or low elevations sites near the target area. Portability combined with respectable gain has validated the 2 and 4-Element Vertical Dipole Array as an effective VHF antenna for emergency or general 2-meter repeater use.

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References

- ¹ The general practice among commercial antenna manufacturers is to express gain in dB (or dBd), where 2.15 dBi (Isotropic Gain) = 0 dBd (Dipole Gain).
- ² Paul Shinn, KAF8333, *What They Never Told You About Repeater Antennas*, GMRS Web Magazine; <http://www.popularwireless.com/gmrsrpt051599.html>
- ³ A 7 dBi omni version is possible, but the elevation pattern is somewhat distorted.
- ⁴ L.B. Cebik, W4RNL, E-mail correspondence.
- ⁵ EZ-Sweat™ pre-soldered copper fittings, Watts Water Technologies; http://www.wattsreg.com/pro/whatsnew/whatsnew_ezsweat.htm
- ⁶ Coax-Seal, <http://www.coaxseal.com/>
- ⁷ The Amateur 2-meter band plan is 144-148 MHz. 143-150 MHz is for a Tennessee State Guard (TNSG) repeater; <http://tsg3.us>
- ⁸ Harold Kinley, *Antenna Phasing 101*, Mobile Radio Technology, September 1, 2004; http://www.findarticles.com/p/articles/mi_m0HEP/is_9_22/ai_n6196620
- ⁹ Stan Horzempa, WA1LOU, *The Return of the HAAT Calculator*, ARRL Web, January 6, 2006, <http://www.arrl.org/news/features/2006/01/06/1/>
- ¹⁰ EZNEC Antenna Software, Roy Lewallen, W7EL; <http://www.ez nec.com/>
- ¹¹ TEMA, Tennessee Emergency Management Agency

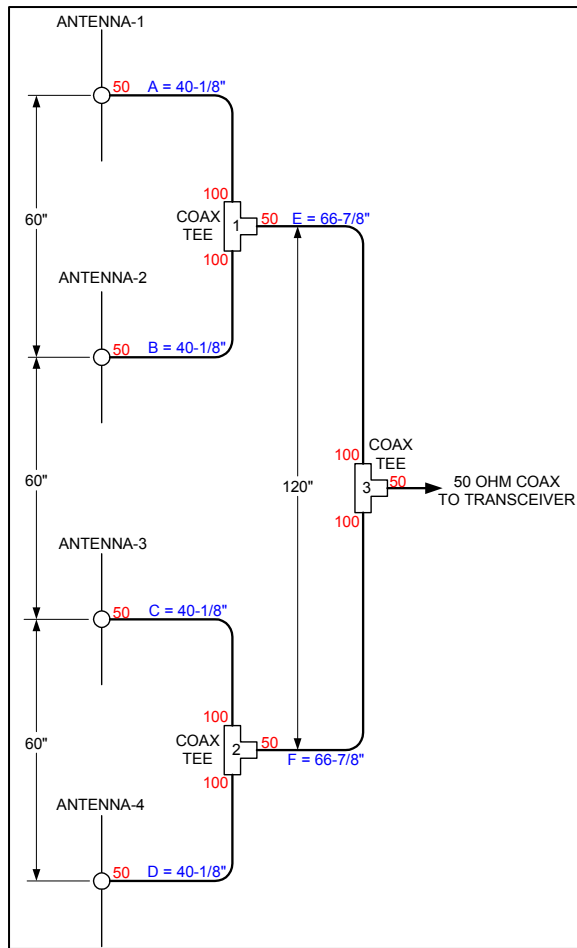


Figure 1
4-Element Array Phasing Harness
Impedances are shown in red and cable lengths in blue.

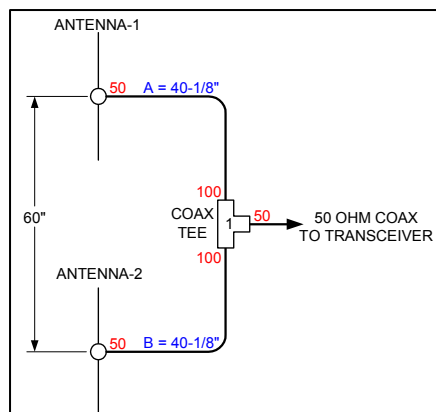
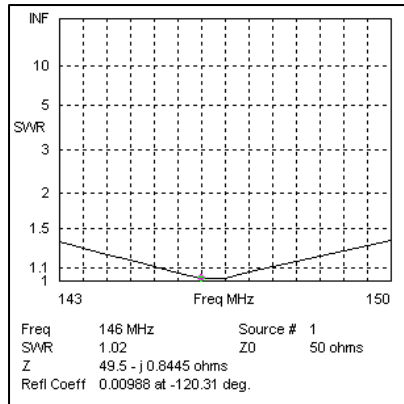
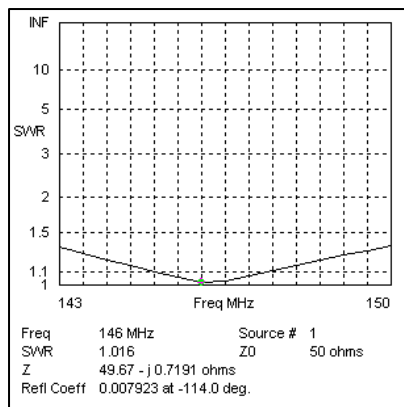


Figure 2
2-Element Array Phasing Harness
Impedances are shown in red and cable lengths in blue.

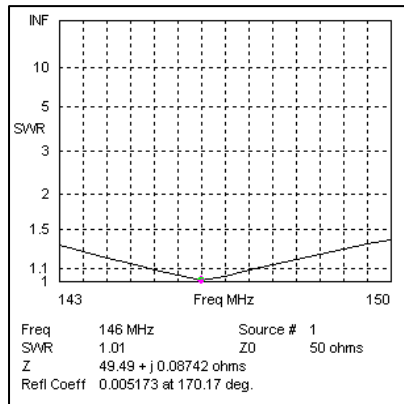
EZNEC SWR Plots for Individual Dipoles in the 4-Element Array



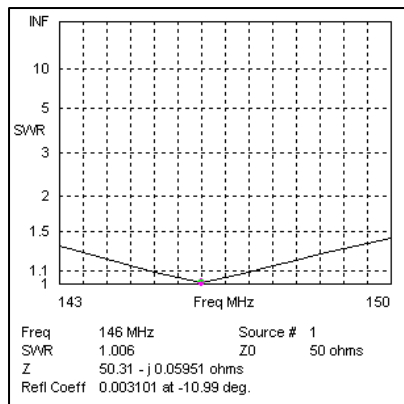
Dipole-1



Dipole-2

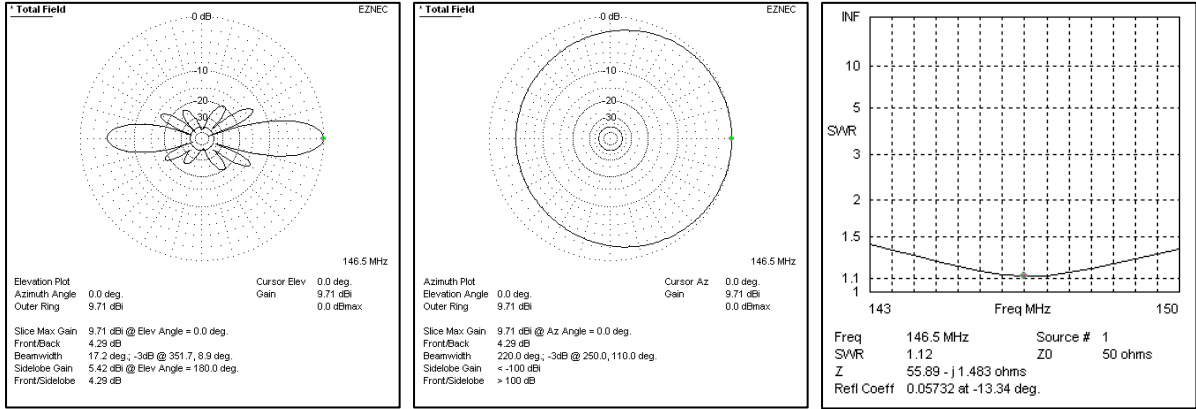


Dipole-3

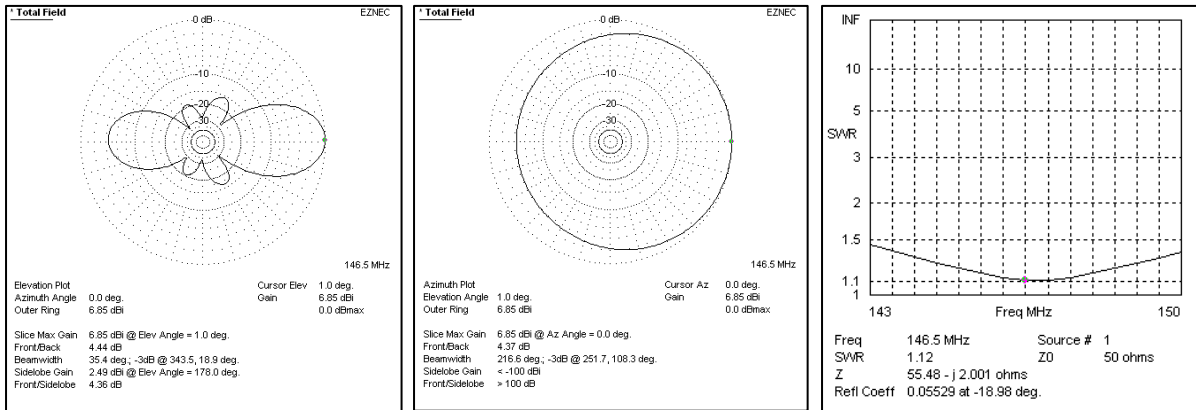


Dipole-4

EZNEC Plots for Free Space

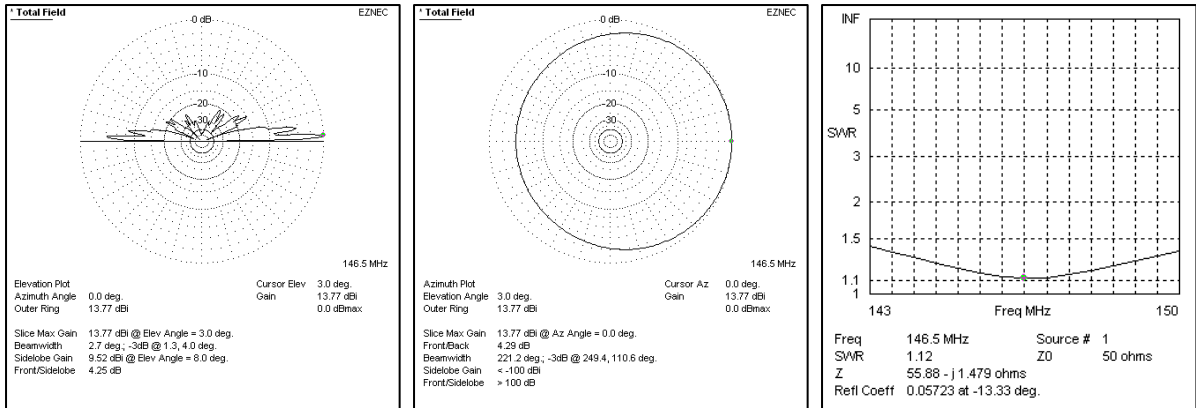


4-Element Vertical Dipole Array

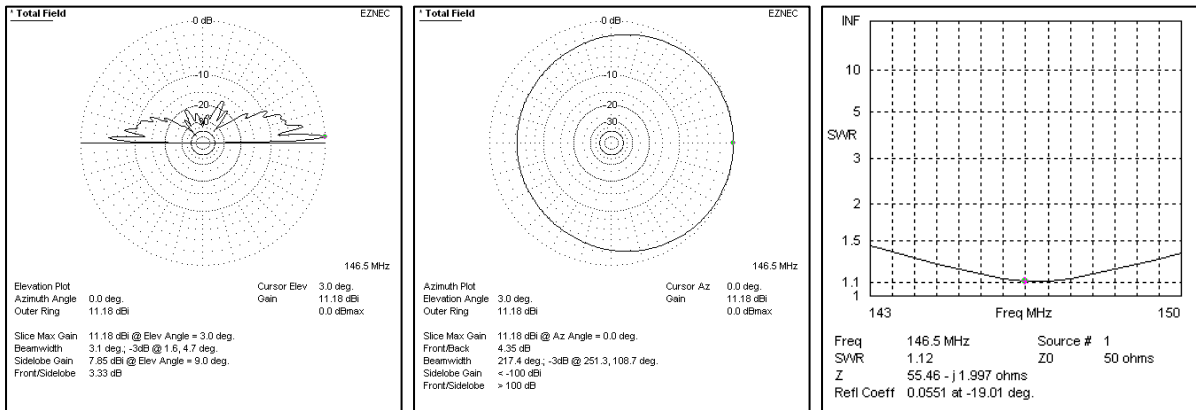


2-Element Vertical Dipole Array

EZNEC Plots @ 45 Feet



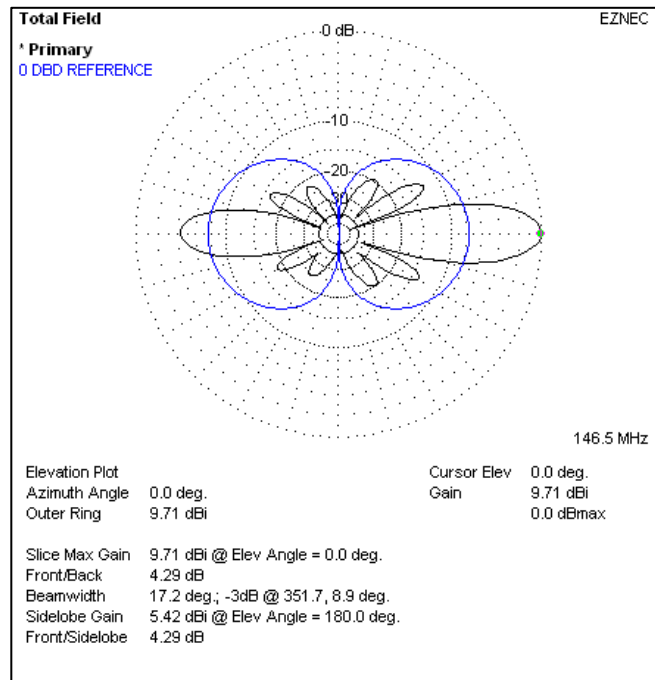
4-Element Vertical Dipole Array



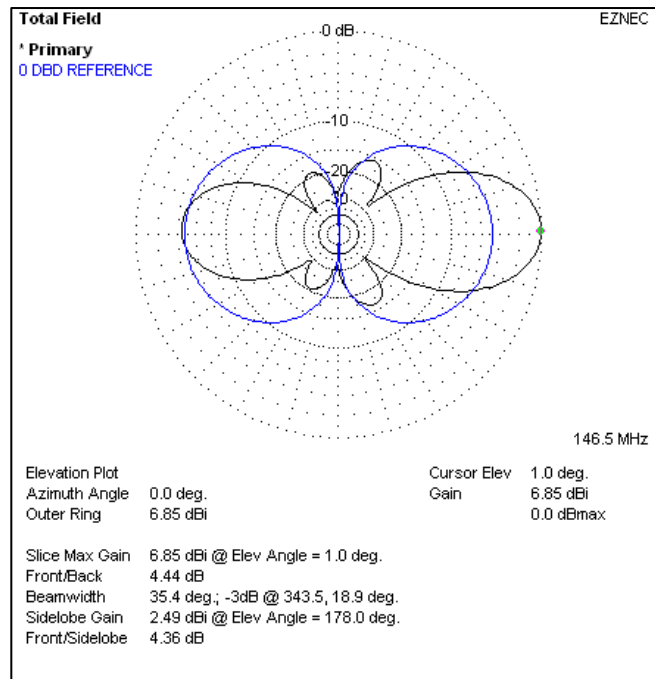
2-Element Vertical Dipole Array

EZNEC Plots for Free Space

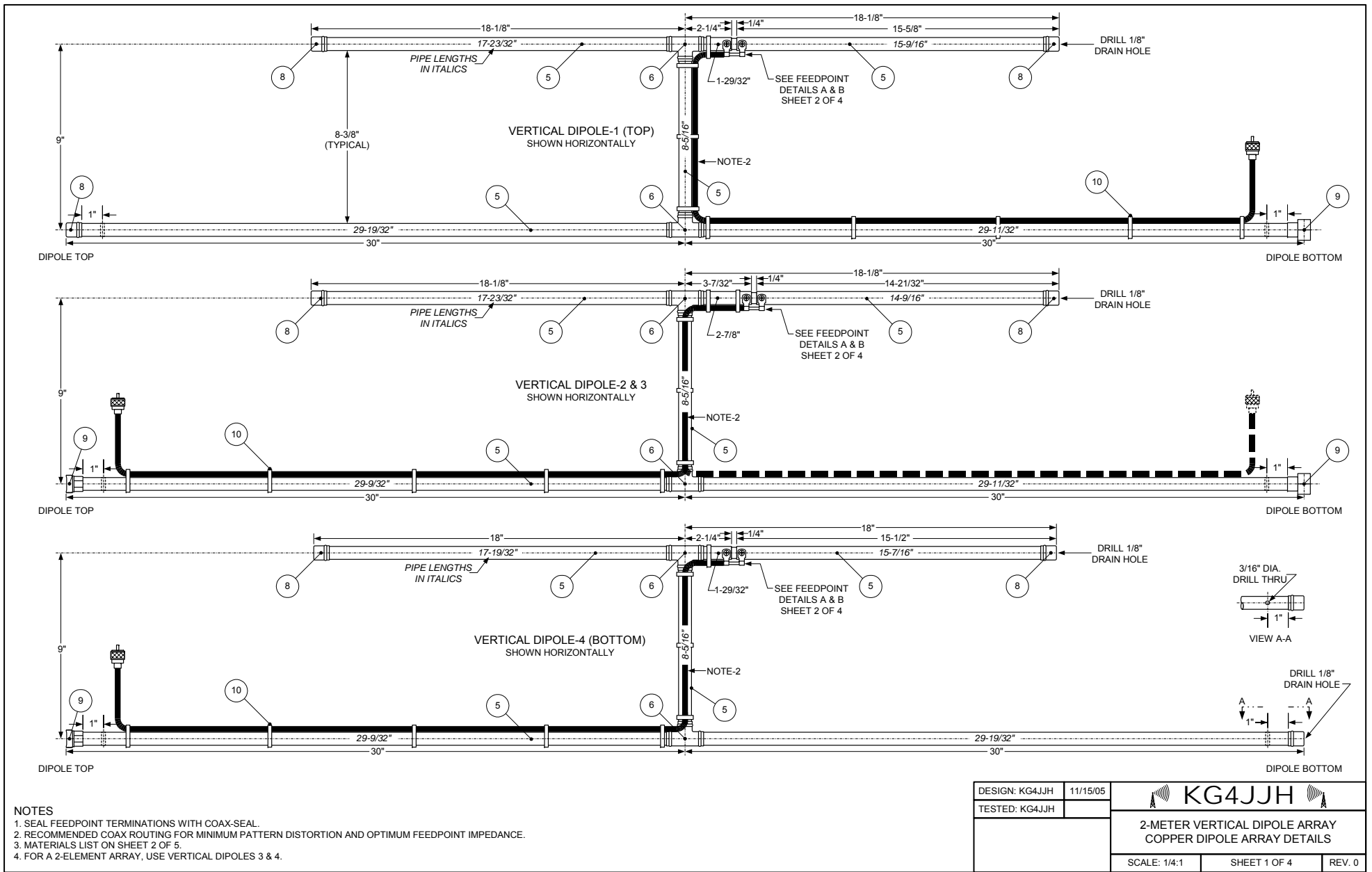
Elevation Plots with 2.15 dBi Vertical Dipole Reference

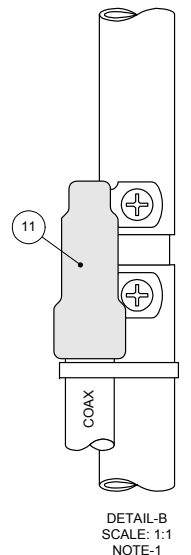
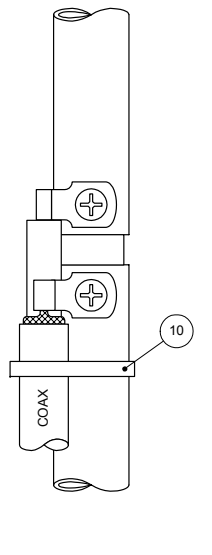
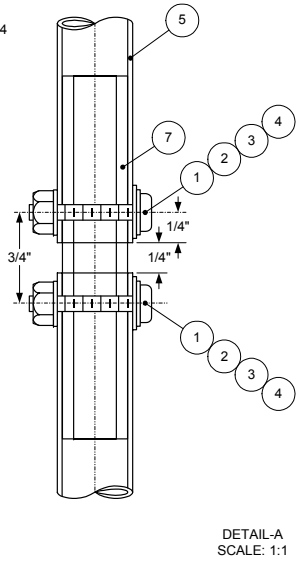
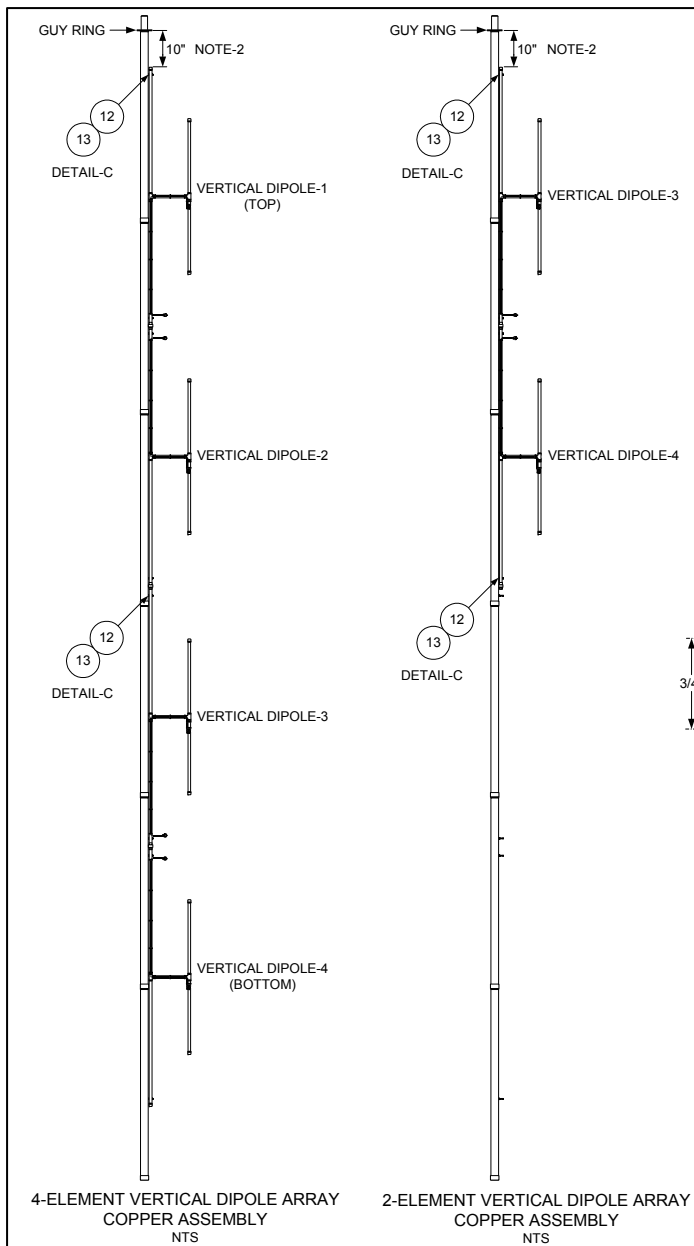


4-Element Vertical Dipole Array



2-Element Vertical Dipole Array

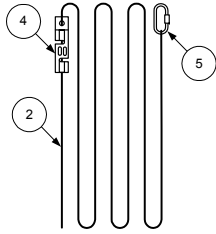




ITEM	QTY	DESCRIPTION	SOURCE
1	8	6-32 X 7/8", SS, PAN HEAD MACH. SCREW, McMASTER 95345A486	www.mcmaster.com
2	8	#6 FLAT WASHER, SS, McMASTER 92141A007	www.mcmaster.com
3	8	#6 LOCK NUT, SS, McMASTER 91831A007	www.mcmaster.com
4	8	FLAG TERMINAL, #6, MCMMASTER 73125K64 & 73125K61	www.mcmaster.com
5	35'	PIPE, COPPER, 1/2" TYPE L	www.homedepot.com
6	8	TEE, COPPER, 1/2", PRE-SOLDERED	www.homedepot.com
7	12"	PIPE, PVC, SCH 80, 1/4", McMASTER 48855K41	www.mcmaster.com
8	8	CAP, COPPER, 1/2", PRE-SOLDERED	www.mcmaster.com
9	3	UNION, COPPER, 1/2", McMASTER 5520K91	www.homedepot.com
10	AR	CABLE TIE	www.homedepot.com
11	AR	COAX-SEAL	www.coaxseal.com
12	8	10-24 X 1-1/4", SS, PAN HEAD MACH. SCREW, McMASTER 91400A251	www.mcmaster.com
13	16	10-24 LOCK NUT, SS, McMASTER 90715A011	www.mcmaster.com

NOTES
 1. SEAL COAX EXPOSED COAX ENDS WITH COAX-SEAL (DETAIL-B).
 2. DROP ARRAY DOWN APPROXIMATELY 10 INCHES FROM TOP GUY RING TO AVOID GUY LINE INTERFERENCE.

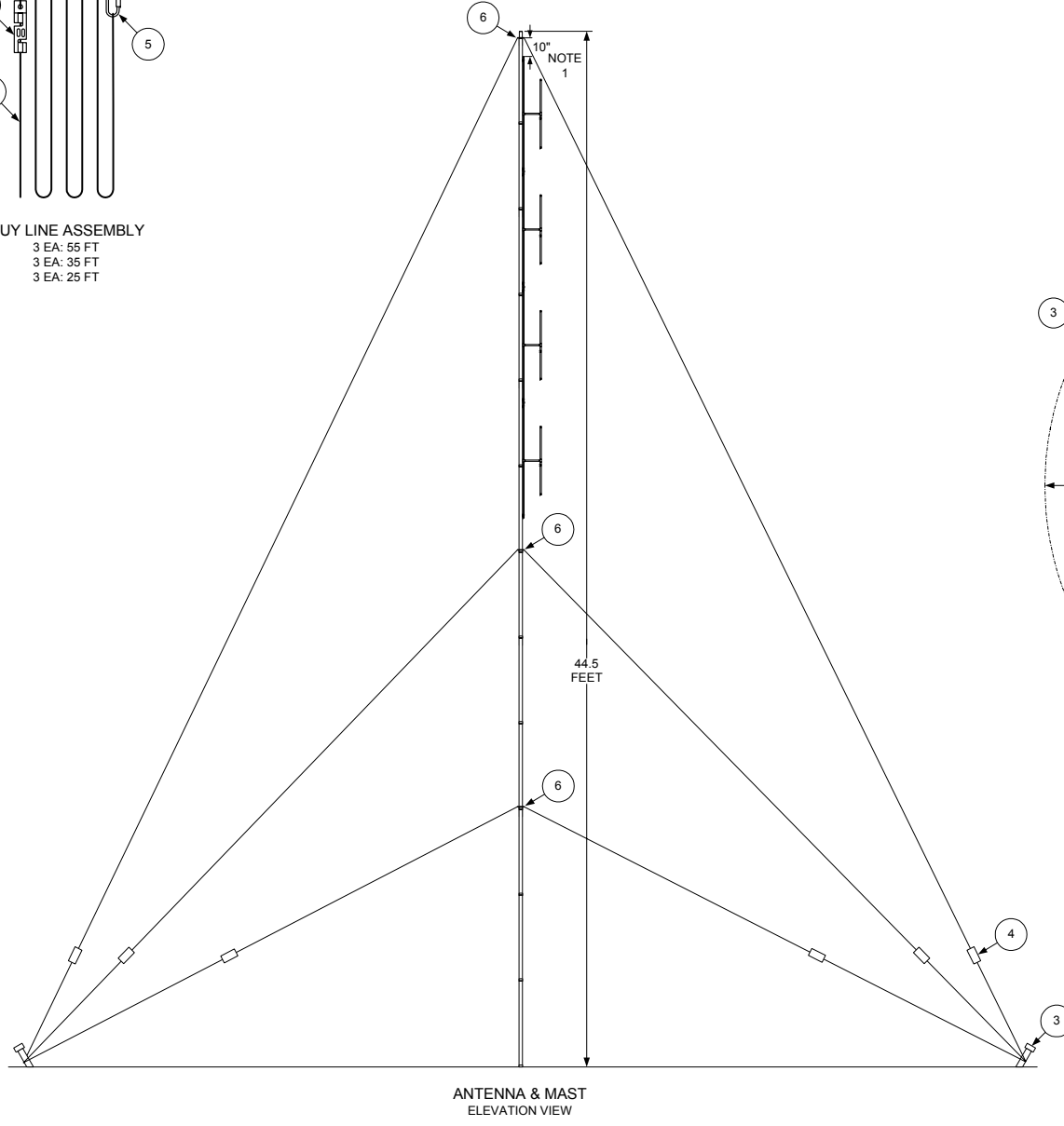
DESIGN: KG4JJH	11/15/05			
TESTED: KG4JJH				
		2-METER VERTICAL DIPOLE ARRAY FEEDPOINT DETAILS & ASSEMBLIES		
		SCALE: NOTED	SHEET 2 OF 4	REV. 0



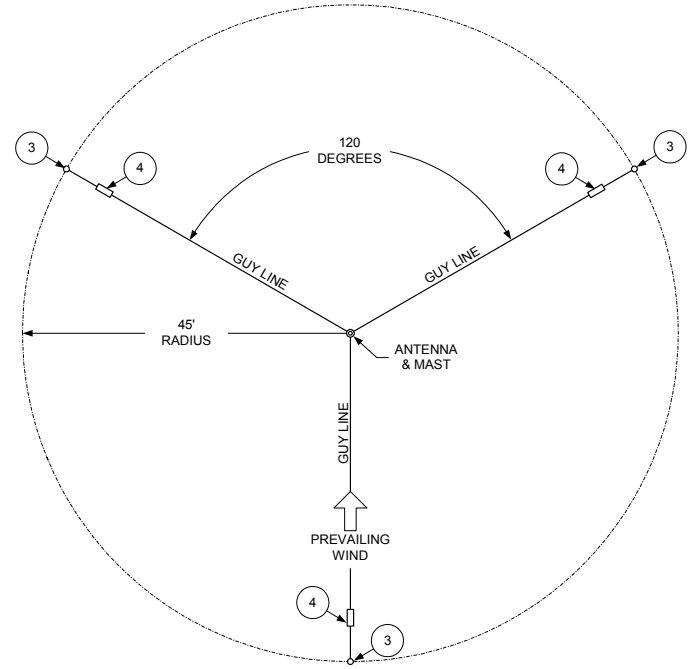
GUY LINE ASSEMBLY
 3 EA: 55 FT
 3 EA: 35 FT
 3 EA: 25 FT

ITEM	QTY	DESCRIPTION	SOURCE
1	1	MAST, 44.5 FT., FIBERGLASS	www.ebay.com
2	350'	GUY LINE, BLACK, 3/16", DACRON	www.ebay.com
3	3	STAKE, 18"	www.homedepot.com
4	9	LINE TIGHTENER, TAUT-TIE	www.campmor.com
5	9	SPRING SNAP, STAINLESS STEEL	www.homedepot.com
6	3	GUY RING	www.ebay.com

NOTES
 1. DROP ARRAY DOWN APPROXIMATELY 10 INCHES FROM TOP GUY RING TO AVOID GUY LINES.

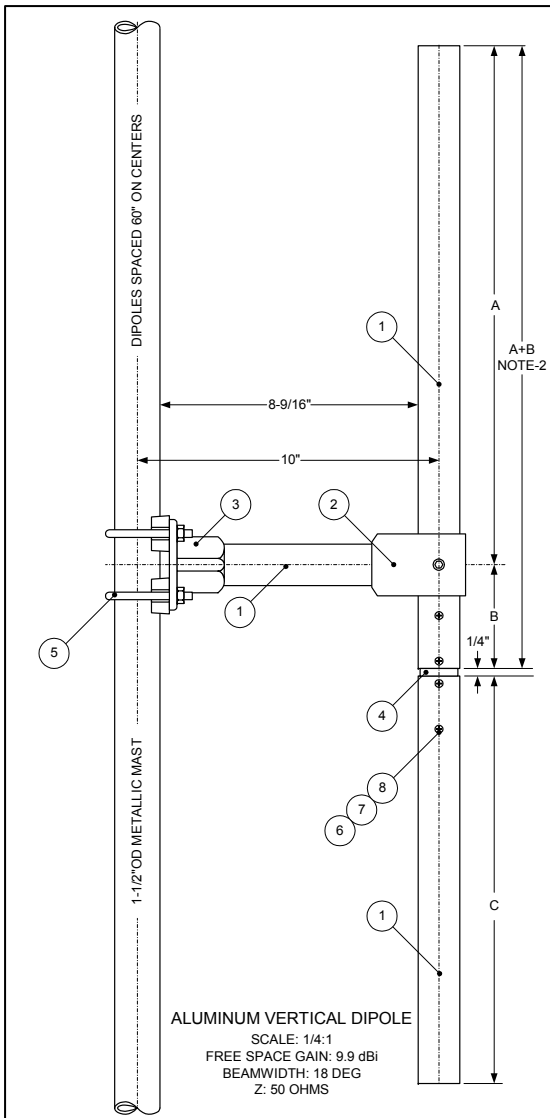


**ANTENNA & MAST
 ELEVATION VIEW**



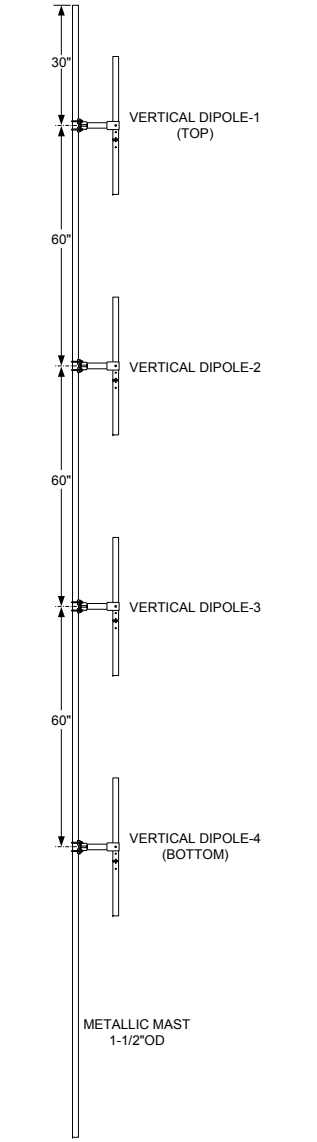
**ANTENNA & MAST
 PLAN VIEW**

DESIGN: KG4JJH	11/15/05	
TESTED: KG4JJH		
2-METER VERTICAL DIPOLE ARRAY FIBERGLASS MAST GUYING PLAN		
SCALE: NONE	SHEET 3 OF 4	REV. 0



ALUMINUM VERTICAL DIPOLE
SCALE: 1/4:1
FREE SPACE GAIN: 9.9 dBi
BEAMWIDTH: 18 DEG
Z: 50 OHMS

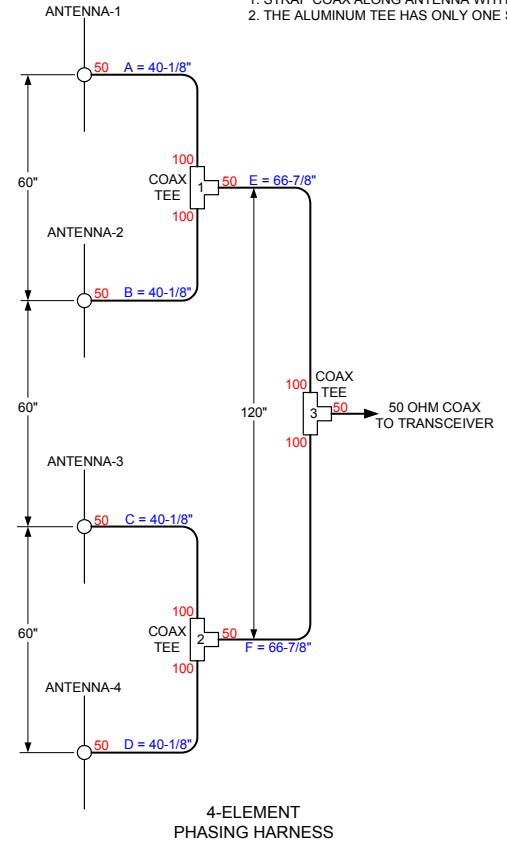
DIPOLE LOCATION	CENTERLINE DIMENSIONS			
	A	B	C	A + B
1 (TOP)	17-3/8"	3-1/2"	13-5/8"	20-7/8"
2 & 3	17-5/16"	3-15/32"	13-19/32"	20-25/32"
4 (BOTTOM)	17-3/16"	3-7/16"	13-1/2"	20-5/8"



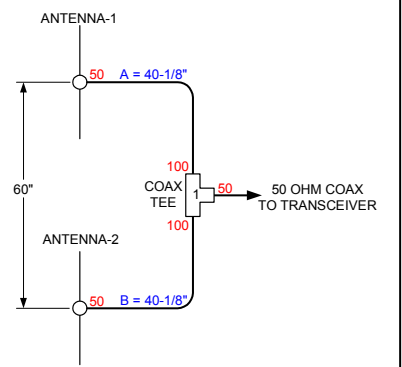
4-ELEMENT VERTICAL DIPOLE ARRAY
ALUMINUM ASSEMBLY
NTS

ITEM	QTY	DESCRIPTION	SOURCE
1	15'	ALUMINUM TUBING, 1-3/8" OD	www.texastowers.com
2	4	SINGLE SOCKET TEE, ALUMINUM, KEE LITE L10-6	www.keelite.com/us/
3	4	4-HOLE SQUARE FLANGE, ALUMINUM, KEE LITE L152-6	www.keelite.com/us/
4	24"	FIBERGLASS TUBING, 1-1/4" OD	www.mgs4u.com
5	8	V-BOLT SADDLE CLAMP, 1/2" TO 1-3/4", DXE-CAVS-1P	www.dxeengineering.com
6	16	6-32 X 1-3/4", SS, PAN HEAD MACH. SCREW, McMASTER 91772A158	www.mcmaster.com
7	16	#6 FLAT WASHER, SS, McMASTER 92141A007	www.mcmaster.com
8	16	#6 LOCK NUT, SS, McMASTER 91831A007	www.mcmaster.com

NOTES
1. STRAP COAX ALONG ANTENNA WITH CABLE TIES. SEAL TERMINATIONS WITH COAX-SEAL.
2. THE ALUMINUM TEE HAS ONLY ONE SET SCREW; COMBINE DIMENSIONS A & B TO MAKE ONE TUBE.



4-ELEMENT PHASING HARNESS



2-ELEMENT PHASING HARNESS

DESIGN: KG4JJH	11/15/05	KG4JJH
TESTED: KG4JJH		
2-METER VERTICAL DIPOLE ARRAY PHASING HARNESS & CLAMP-ON ALUMINUM ARRAY DETAILS		
SCALE: NOTED	SHEET 4 OF 4	REV. 0