Designing and Building Cross-Yagi Antennas for Working Amateur Satellites

Project Start: 10-29-2021
Project Completion: 3-8-2022
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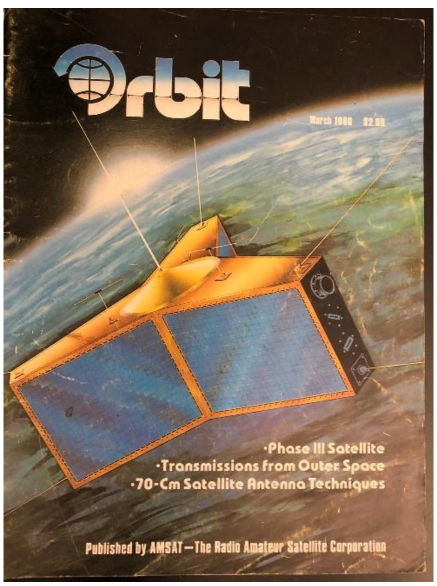
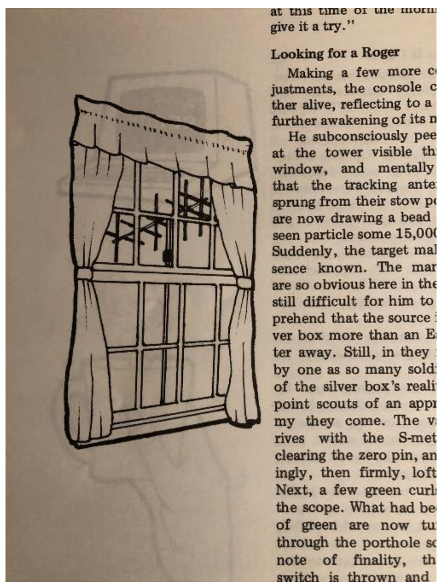
This document, additional images, antenna design spreadsheets, and EZNEC models can be downloaded from: https://github.com/jameshbaxter/AK2W-Satellite-Antenna-System

Introduction

It has long been a dream of my adult life to build an amateur radio station capable of HF and VHF/UHF and satellite operation – including a cross-Yagi 146 and 435 MHz antenna system on azimuth/elevation rotators to work amateur satellites.

Images are a powerful thing; the images and articles from the March 1980 Orbit magazine depicted below have stuck in my mind over the years – especially the cross-Yagi antenna out the window - nagging me not to forget to just do this one day. That day has arrived – it's time to build this, and this is the story of that journey.

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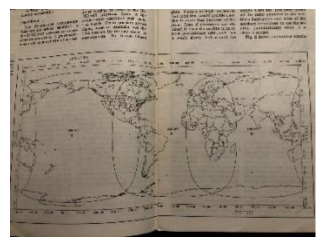
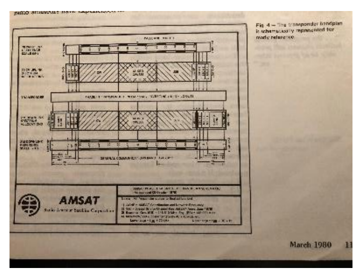




AMSAT P3A, P3B, P3C, P3E (Phase 3A, 3B, 3C, 3E / AO 10, 13 / AMSAT-OSCAR 10, 13): https://space.skyrocket.de/doc_sdat/amsat-p3a.htm OSCAR stands for Orbital Satellite Carrying Amateur Radio. A Brief History of AMSAT: https://www.amsat.org/amsat-history/

As of the start this document, I had completed building the basic HF/VHF/UHF amateur radio station, which I'll cover in a separate publication.

As I started researching articles on the Internet related to building Yagis in general, and cross-Yagis for satellite operation, I discovered there was a LOT to learn – which made the experience all that more enticing and rewarding. Let's get started.

Overview

At the time of this project, I am living in a house that is in a HOA-controlled community. There are no absolute restrictions against antennas if they are under 1 meter in diameter and not visible from the street. The homes in my community all have 'hip' roofs (peaked roofs with multiple sides), which offers some area on the back side of the middle peak for mounting an azimuth-elevation antenna solution (if the boom or elements don't extend too high) that isn't visible from the street. I had already mounted a VHF/UHF J-Pole, a small VHF vertical, and a HDTV antenna on a couple of poles mounted on the back eave and off to one side; only the tops of the J-Pole elements were visible on a side angle view from the street. This satellite antenna system was going to bust the 1-meter antenna size restriction, but my neighbors on both sides are reasonable people, aware of my hobby, and seemingly OK with the antennas I had up so far and would hopefully be equally accepting of the new satellite antennas if I did a clean construction job. I was also hoping the 'cool factor' of such an antenna array and satellite-tracking rotator system would help in this regard. Time will tell.

After reading several articles I determined that using the metric system for antenna work seemed to offer several advantages over the US imperial system of measurement as many of the design lengths in millimeters, which are easier to perform precise calculations with and making more accurate measurements, as opposed to dealing with fractions of an inch. After reviewing a metric system quick reference guide and working with the numbers in a spreadsheet for a while I soon began to wonder why we don't make the switch – until I realized that I still had a long way to go towards feeling comfortable creating mental pictures of length and such from metric values. I'm going to hope that doing some hands-on with antenna building will help grow those neurons. However, I also discovered during the build process that obtaining screws/nuts/washers in metric sizes in the US was not nearly as easy as getting other things (bushings, cable glands, etc.) in metric, so I had to mix the two.

The Process

The process of designing and building an effective satellite antenna solution consisted of three major activities:

- **Research on Yagi Antennas** – becoming aware of and then learning the details about Yagis, crossed-Yagis, along with all the factors that must be taken into consideration when designing and building any antenna system.
- **Designing the Antennas** – this includes selecting Yagi design criteria, finalizing design options, and modeling the antenna solutions in software.
- **Building the Antennas** – this is the act of turning an antenna design into physical reality – which isn't as easy as you might think – and installing / cabling the result.

  Once the antenna system was built and installed, there was another learning curve for using it:

- **Working Satellites** – although not part of the antenna design/build process, I found that working amateur satellites successfully required learning a few new techniques I'd like to articulate, with the caveat that I think I still have much to learn in this area that only experience can teach.

I'll cover these in the following sections, with some attempt at grouping – but since many of the research articles covered more than one aspect of antenna design the sorting is rather loose. The Building the Antennas section supplements some of the other topics with construction details and parts lists, including where to obtain most of the materials used in this project.

Research on Yagi Antennas

There are many things to learn about when designing and building crossed VHF/UHF Yagis, including factors I didn't initially know had to be considered. These include:

- Getting started
- Basic Yagi design
- Building materials and notes
- Boom length and diameter
- Element diameters, lengths, and spacing
- Folded dipole vs half-wave dipole for the driven element
- Feedline designs for impedance matching and polarization

Getting Started

Every project needs a seed article – this was mine, from Jim Kocsis, WA9PYH:

Circularly Polarized Yagi Antennas for Satellite Communications
http://www.arrl.org/shop/files/pdfs/Satellite%20project.pdf

In this article, Jim mentions where he obtained Yagi design information: "I used chapter 9 of The ARRL UHF/Microwave Experimenter's Manual, pages 9-3 through 9-8 to determine the element lengths and spacing along with the dimensions of the DE for a 70 cm CP Yagi…"

I ordered the ARRL Uhf/Microwave Experimenter's Manual: Antennas, Components and Design Paperback – December 1, 1990 book from Amazon: https://www.amazon.com/dp/0872593126

I also referenced several ARRL books that I had purchased through the years and never really read in depth, much less put to practice – it was a good feeling to finally be putting these to good use:

1. ARRL Antenna Book (Chapters 15, 17,
2. The Radio Amateur's Satellite Handbook
3. Antenna Modeling for Beginners

And, of course, dozens of articles on the Internet. There were a great number of articles available to review, and again, each typically covered several aspects of this topic.

Basic Yagi Design

From: https://en.wikipedia.org/wiki/Yagi%E2%80%93Uda_antenna

The Yagi antenna was invented in 1926 by Shintaro Uda of Tohoku Imperial University, Japan, with a lesser role played by his colleague Hidetsugu Yagi.

However the "Yagi" name has become more familiar with the name of Uda often omitted. This appears to have been due to Yagi filing a patent on the idea in Japan without Uda's name in it, and later transferring the patent to the Marconi Company in the UK.

Yagi antennas were first widely used during World War II in radar systems by the Japanese, Germans, British and US. After the war they saw extensive development as home television antennas.

At the start of this process, it felt like I had questions about more antenna topics than I could keep track of, including the question of whether I was even aware of all the pertinent factors. These questions generally ran the gamut of:

- How many elements can I get on an approximately 6-foot boom?
- What will be the gain? Will it be sufficient?
- What materials do I use to build the antenna?
- What is the spacing and length of the elements?
- What are the effects of running two sets of crossed elements on the same boom?
- I know that elements are spread out at differing distances and tapering lengths – why?
- How do you calculate the lengths and distance between the elements?
- How to you drive the driven element and match impedances?
- Will I need a balun or other matching devices?
- I would really like to better understand how a Yagi antenna works, and how it's designed.
- How do I model this antenna system?

I read through a lot of Internet articles and the pertinent sections of several antenna books trying to gain a solid understanding of the critical factors in Yagi antenna design - the more pertinent articles and books are listed below. I discovered that there are a handful of hams around the world that have published their optimized designs for VHF/UHF Yagis, including cross-Yagi designs for satellite work.

Upon comparing the data in these articles and books I also discovered that there doesn't seem to be a definitive set of formulas for calculating optimal Yagi element diameters, lengths, and spacings. I noticed that tables providing measurements of element spacings and lengths for otherwise similar antennas and frequencies varied, sometimes by quite a bit. I also became aware that these factors interact somewhat, that variations in design parameters can have varying degrees of effect on overall antenna performance, and most intriguing, that most of these designs are the result of extensive modeling and/or physical experimentation on the part of the authors versus any hard and fast formulas or rules of thumb.

I came to several conclusions regarding Yagi antenna design:

4. Foundational Yagi antenna design is based perhaps as much on empirical evidence from experimentation as it is on theoretical calculations, although these findings have since been captured in design formulas.
5. Final design parameters and subsequent construction measurements for a new Yagi antenna should be obtained by building software models based on rule-of-thumb and/or published values and then performing some trial-and-error tweaking of element spacings and lengths to obtain the optimal (or good enough) predicted performance.
6. In the end I mostly followed the design parameters outlined in the NBS Technical Note, which are reflected in DL6WU Yagi designs and further in the **Yagi Calculator** software by John Drew based on DL6WU criteria. I discuss this in more detail a bit further down this article.

The following is a list of articles I researched for this project:

Yagi Antenna Theory: Yagi Antenna Basics
https://www.electronics-notes.com/articles/antennas-propagation/Yagi-uda-antenna-aerial/theory.php

Yagi Antenna Gain, Directivity & Front to Back Ratio
https://www.electronics-notes.com/articles/antennas-propagation/Yagi-uda-antenna-aerial/gain-directivity.php

Folded Dipole Antenna – interesting discussion of using unequal conductors to affect impedance
https://www.electronics-notes.com/articles/antennas-propagation/dipole-antenna/folded-dipole.php

NBS TECHNICAL NOTE 688: Yagi Antenna Design by Peter P. Viezbicke
(National Bureau of Standards (NBS) is now the National Institute of Standards and Technology (NIST))
https://tf.nist.gov/general/pdf/451.pdf
https://ia601602.us.archive.org/26/items/yagiantennadesig688viez/yagiantennadesig688viez.pdf

"This work was carried out by the National Bureau of Standards at antenna test ranges located in Sterling, Virginia, and at Table Mountain near Boulder, Colorado."

Design and fabrication of crossed Yagi antennae for dual frequency satellite signal reception at ground
http://nopr.niscair.res.in/bitstream/123456789/27161/1/IJRSP%2043%281%29%20124-129.pdf

VK5DJ provides a free Yagi Calculator and other interesting articles
https://www.vk5dj.com/index.html
https://www.vk5dj.com/Yagi.html

http://dg7ybn.de/432MHz/dl6wu_lYagis.htm

https://www.elprocus.com/design-of-Yagi-uda-antenna/

Yagi Biquad Antenna Design for 4G LTE in 2100-2400 MHz Frequency Band
https://eudl.eu/pdf/10.4108/eai.20-1-2018.2281873

PA3GUO – DK7ZB Antenna Discussion
http://www.pa3guo.com/dk7zb.html

DK7ZB
https://www.qsl.net/dk7zb/start1.htm

DG7YBN - Scaling Yagi Elements by Hand
http://dg7ybn.de/Scaling/Scaling_Yagis.htm#Scaling_Frequency_EZNEC

Wisdom from L.B. Cebik, W4RNL (SK)
http://www.antentop.org/w4rnl.001/radio.html

http://on5au.be/content/ao/ao.html

QRZ.com: Yagi Element Spacing
https://forums.qrz.com/index.php?threads/Yagi-element-spacing.28641/

"… written by a small but finite set of aliens with a passion for spreading antenna knowledge. While this passion may seem strange, it is actually quite common outside the milky way. A human or two has contributed to this page (notably Peter Bevelacqua), but they are mainly kept on the team to understand the web-human interface."
https://www.antenna-theory.com/intro/authors.html
https://www.antenna-theory.com/antennas/travelling/Yagi.php
https://www.antenna-theory.com/antennas/travelling/Yagi3.php

General opinions about 'Spacing between elements on a Yagi antenna'
https://ham.stackexchange.com/questions/1782/spacing-between-elements-on-a-yagi-antenna

RF Wireless World 3 element Yagi Antenna Calculator
https://www.rfwireless-world.com/calculators/3-element-Yagi-Antenna-Calculator.html

Building Materials and Notes

The various sources and articles I perused to determine the proper antenna materials include:

Why build antennas out of copper and not aluminum or stainless steel
https://www.jpole-antenna.com/2012/07/03/why-build-antennas-out-of-copper-and-not-aluminum-or-stainless-steel/

DX Engineering's brochure on aluminum tubing:
https://static.dxengineering.com/global/images/instructions/dxe-at-aluminum-tubing-rev3.pdf

https://ea5nd.com/wp-content/uploads/2017/11/Home-Built-Antenna-Hardware.pdf

https://kimsen.vn/what-aluminum-grade-should-you-use-ne51.html

https://www.thomasnet.com/articles/metals-metal-products/types-of-aluminum/

Antenna Materials and Accessories
https://www.qrz.ru/schemes/contribute/arrl/chap20.pdf

https://www.thomasnet.com/articles/metals-metal-products/types-of-aluminum/

Online Metals
https://www.onlinemetals.com/en/buy/aluminum-round-bar

Yagi Antenna Elements Correction for Square Boom - Dragoslav Dobričić, YU1AW
https://qsl.net/yu1aw/Misc/Yagi_sq_boom_corr.pdf

Building Antennas That Last
https://www.seapac.org/seminars/2017/SEA-PAC2017-k7ja-building-antennas-that-last.pdf

Metric to Standard conversions
https://www.google.com/search?q=meters+to+inches

Findings and Selections

Antennas can be built out of copper or aluminum, with booms of metal or non-conductive materials. Copper has a conductivity of 90-100 vs 45 for aluminum, but copper can suffer from corrosive effects that may eventually erode antenna performance unless you coat the exposed surfaces with a clear lacquer or similar protectant, wherein aluminum resists corrosion and is apparently much more widely used for antenna construction. There are various grades and alloys of aluminum available; the 6061-T6 grade seemed to be the most popular for amateur antenna work.

I settled on 6061-T6 square aluminum tubing for the booms and ordered four ¾" x 6' and one 1" x 6' tubes from Texas Towers; I also ordered three 3/8" (.375) x 48" lengths of round aluminum tubing from TT to use for folded dipoles as driven elements. Finally, I decided to use ¼" solid aluminum rods for the reflectors and directors and ordered 22 48" rods from Home Depot.

I chose square vs round tubing for the booms because it is easier to accurately drill holes in a square tube, and I observed that the Arrow II Satellite antenna I had purchased previously uses ¾" square tubing with obviously good results. From what I read there doesn't seem to be any appreciable difference between square and round as far as electrical effects on antenna patterns are concerned. The longest tubing I could get delivered without exorbitant shipping costs was 6 foot lengths; since I was restricted in antenna size by the need to fully rotate them in all axes just above a sloping peak roof without being too obvious from the street, I decided that a 6 foot boom length was about all I could get away with anyway. This would reduce the amount of gain I could expect from the 2M antennas, but it should be more than sufficient for most LEO (Low Earth Orbit) satellites. There are eight-foot lengths of 1" aluminum tubing available at the hardware stores, but 1" seems too thick for shorter antennas and I couldn't readily determine what the grade and alloy was for that option, so six feet would have to suffice. In the end, I used some 5/8" outside diameter round tubing to join a short length of additional ¾" square tubing to the end of the 6' lengths to fit 6 elements on 2M and 11 elements on 436 MHz.

I chose ¼" solid aluminum rods because although I might have been able to find and work with small diameter hollow aluminum tubing, it didn't seem to be as readily available, and I was concerned about strength and durability – in numerous antenna articles I had seen pictures of antennas with bent antenna elements, which was just not appealing. Considering these antennas weren't going to be that large anyway, the added weight of solid versus hollow elements shouldn't be a problem. I ordered 48" lengths thinking I'd use most of a rod for 144 MHz elements (which vary from 35 to 40.5 inches) and could cut multiple elements for 435 MHz and perhaps 1296 MHz out of the others.

I planned to insulate the elements from the boom, so I ordered a package of nylon bushings with .375" inch mounting hole diameter, .25" inside diameter from Amazon. See the materials list in the Building the Antennas section for a detailed list including links for obtaining the materials I used.

Boom length and diameter

Boom length is determined by any external length restrictions (such as my need to limit the antennas to about six feet) and/or other physical and support limitations if you're building a longer Yagi, coupled with your gain requirements. Gain increases with boom length and number of directors; there are charts depicting this in most of the antenna books.

Boom diameter is not critical if it's not a significant portion of a wavelength at the design frequency, but the diameter does need to be figured into calculations of element lengths if you plan to run them through the boom – see the next section on element lengths.

The YU1AW article regarding corrections for square booms was insightful, but it focused on non-insulated elements, so it didn't apply well to my intended solution, but he does provide a discussion of using elements insulated from the boom – see the following:

YU1AW projects and articles library
https://qsl.net/yu1aw/Misc/engl.htm
https://qsl.net/yu1aw/Misc/vhf_ant.htm (list of all VHF/UHF Antennas articles)
https://qsl.net/yu1aw/Misc/yagi_sq_boom_corr.pdf
https://qsl.net/yu1aw/Misc/Yagi_boom_insul_corr.pdf

Element diameters, lengths, and spacing

Running elements through a conductive boom has the effect of shortening their effective length, so they will need to be cut longer. If the elements will be electrically coupled to the boom such as by attaching them to the top of the boom via a screw or clamp around the middle of the element or running them through the middle of the boom without insulators, this shortening effect is greater than if you insulate the elements from the boom by using plastic feedthroughs or a similar solution.

This article from YU1AW discusses insulated elements:
https://www.qsl.net/yu1aw/Misc/Yagi_boom_insul_corr.pdf

In this article he states: *"Element mounting methods, boom diameter and distance between boom and elements determine magnitude of the boom's impact and value of the necessary elements' length correction"*.

And: *"For elements passing through the boom but insulated from it, a general rule of thumb for boom correction is 15…25 % of boom diameter – for usual boom diameters (20…50 mm) due to lesser interaction between boom and elements."*

In the Conclusion of the above article, Dragoslav states that a "general rule of thumb correction of about 15…25% of boom diameter is quite accurate." I will go with 20% of element length adjustment (additional length) in element length calculations and confirm this with experimentation in antenna modeling software.

DG7YBN / 144 MHz / GTV 2-6M Antenna
http://dg7ybn.de/144MHz/144_GTV2_6m.htm

DG7YBN has built quite a few antennas, and provided several very informative articles on antenna Yagi antenna construction; the articles and updates seem to be recent:

DG7YBN / Practical Yagi Building
http://dg7ybn.de/Building/Building.htm#Elem_on_edge

DG7YBN / Scaling Yagi Elements by Hand
http://dg7ybn.de/Scaling/Scaling_Yagis.htm#Scaling_Frequency_EZNEC

DG7YBN / Boom Correction
http://dg7ybn.de/BC_numbers/BC.htm#DL6WU_online_calc

DG7YBN / 144 MHz / YBN 2-6m
http://dg7ybn.de/144MHz/144_YBN2_6m.htm

DG7YBN / 432 MHz / GTV 70-10w
http://dg7ybn.de/432MHz/GTV70_10w.htm#xpol

DG7YBN / 1296 MHz / GTV 23-25m
http://dg7ybn.de/1296MHz/GTV23_25m.htm

7arrays / antenna parts / insulators
http://7arrays.com/antenna_parts/insulators.htm

Other informative sources include:

DK7ZB: Cross-Yagis for Terrestrial and Satellite Work
https://www.qsl.net/dk7zb/start1.htm

PA3GUO has articles on building crossed-Yagi antennas for satellite and EME work – click 'Antennas'
http://www.pa3guo.com/

Folded Dipoles vs Half-Wave Dipole Driven Elements

The article below on folded dipole design was what inspired me to use plastic boxes and cable glands for my feed point solution, with which I am very pleased and grateful for the idea:

Folded Dipoles for VHF/UHF Yagis - from In Practice, RadCom (RGSB), April 1998
http://www.ifwtech.co.uk/g3sek/diy-yagi/dipoles.htm

The use of folded dipoles for VHF/UHF Yagis is very prevalent, but I struggle to understand why most of the solutions involved bending hollow tubing into a racetrack shape, which looked like it would involve a trial-and-error learning curve on how to a) bend the tubing without creases, and b) how to get the length and radius just right. After perusing some articles on HF folded dipoles, I observed that there was no call for rounded connections between top and bottom elements, so I started to question this approach - it seemed to me that just providing a shorting bar between the elements at the ends gets the job done and is adjustable. After discovering that M2 Antennas appears to be utilizing the shorting bar approach for their commercial offerings I decided to adopt this approach in my design – so far, it appears to be a solid solution.

https://www.m2inc.com/FG140CP14M

The other possibility for feeding Yagi driven elements is the use of T-matches and gamma matches on half-wave dipoles, both of which seemed like a lot of trouble. I was also under the impression that the folded dipole approach offered a bit more bandwidth, and since I intended to also use these antennas for point-to-point terrestrial communications (at higher frequencies than the satellite bands) I stuck with folded dipoles.

Feedline Designs for Impedance Matching and Polarization

Application Guide to RF Coaxial Connectors and Cables
http://f1chf.free.fr/fichiers/RF%20Connector%20Guide.pdf

"BNC connectors are generally rated for use in the DC-4GHz frequency range; however, they are rarely used above 500MHz. While they are capable of handling 80-100 Watts average power up to 1GHz, they typically do not have a maximum power rating but carry a maximum voltage rating of about 500V."

N-type Connector
https://www.electronics-notes.com/articles/electronic_components/rf-connectors/n-type-connector.php

"As a guide a new and clean connector with a perfect load (VSWR = 1:1.0) might be expected to handle 5000 watts at 20 MHz, but this could fall to 500 watts at 2 GHz."

The characteristic impedance of a folded dipole is reported to be on the order of 300 ohms, so in theory a 4:1 coaxial balun would provide a 300/4 = 75-ohm feed impedance. Since I wanted to utilize 50-ohm feedlines, I looked for a 75 to 50 transformation solution that didn't involve a balun (I was trying to keep the feed point boxes as small as possible); a 12^{th} wave transformer looked like an attractive possibility, since it would leverage generally available 50 and 75 ohm coax – but the physical manifestation was cumbersome, and much too small at 436 MHz to be practical. In the end I just accepted the mismatch and slight increase in SWR that would come with it – especially since I didn't see much attempt to address this in published designs and software calculators.

Matching 50 Ω to 75 Ω
http://ham-radio.com/k6sti/match.htm

Twelfth Wave Transformer Calculator
https://kc1kcc.com/twelfth-wave-transformer-calculator/

The Twelfth-Wave Matching Transformer
https://www.cv.nrao.edu/~demerson/cs/twelfth.htm

Matching with 1/12 λ (wave) Transmission Line
https://pa0fri.home.xs4all.nl/Ant/Eentwaalfde%20golf%20trafo/One-twelfth%20wave%20transformer.htm

Finally - the **ARRL Antenna Handbook** provides some examples of using various lengths and impedances of coax to achieve some control of polarization (pgs 17-8 & 9 of the 22nd edition), and this topic was discussed in several of the articles listed. In general, it comes down to leveraging a phase shift using ¼ or ½ wavelengths of coax and some impedance matching tricks, all of which I decided to alleviate with some commercial polarization control solutions.

The articles and links I researched on polarization control include:

PA3GUO – H-V-RH-LF Relays
http://www.pa3guo.com/

SM5BSZ
http://www.nitehawk.com/sm5bsz/polarity/simplesw.htm

Calibration
http://www.nitehawk.com/sm5bsz/polarity/polcal.htm

Digi-Key High Frequency (RF) Relays
https://www.digikey.com/en/products/filter/relays/963?ColumnSort=1000011&FV=-8%7C963&page=1&pageSize=25&quantity=0&s=N4IgjCBcoOwExVAYygMwIYBsDOBTANCAPZQDaIAHDBQGwUiFwAsAnAKy0gC6hADgC5QQAZX4AnAJYA7AOYgAvoTBMADC0QgUkDDgLEyIVWxY11PEAKGjJshUqZgVGrTryESkcnAAEAQW58gpAgAKpSEvwA8qgAsrjo2ACuYrgK8vJAA

RF Parts – Tuhtsu Japan Coaxial Relay
https://www.rfparts.com/cx520d.html

I didn't find any articles that provided what I considered to be a satisfactory solution for home-built polarization control.

Designing the Antennas

In this section I leverage the information from the research phase to make final design choices, model the antennas in software, and publish the specifications for building the antenna solution.

- Selecting Yagi design parameters
- Antenna modeling software
- AK2W Antenna Designs

Selecting Yagi design parameters

After comparing the various Yagi designs and related viewpoints offered in the books and numerous articles I researched, I initially thought I'd follow Jim Kocsis' (WA9PYH) lead and use the information in Chapter 9, pages 5-8 of *The ARRL UHF/Microwave Experimenters Manual*, with supplemental guidance from other applicable sources, but ***in the end, I used the Yagi Calculator by John Drew for my initial design parameters*** (see below). There were several conclusions I came to and reasons for this decision, as follows:

- I was initially concerned that the *Experimenters Manual* and other older books & articles may not reflect more recent discoveries and improvements in Yagi design; I did not find substantial evidence of this in my research – the tried and true still seems to be relevant.
- There seems to be only a few truly original Yagi antenna designs, with numerous variations around these by various authors designed to optimize gain, F/B ratio, bandwidth, or construction techniques.
- The DL6WU Yagi by Gunther Hoch seems to be the golden standard; he "spent decades of research and development … using cut-and-try experimental techniques, sometimes with the aid of a large reflection free test range owned by the German Post Office."
- Independent of work by radio amateurs (but with a few references to QST articles and the ARRL Handbook), there is also the 'NATIONAL BUREAU OF STANDARDS TECHNICAL NOTE 688' on 'Yagi Antenna Design' by Peter P. Viezbicke; the PDF provides numerous graphs and formulas for Yagi design based on, again, seemingly based on a lot of 'cut-and-try' experimentation – the results reportedly influenced the DL6WU metrics (I think I read that somewhere, but can't put my fingers on it so don't hold me to it).
- Many of the designs and discussions I found were centered around 'long' Yagi's whose published director lengths and spacings were for boom lengths of 2 wavelengths or more – since I was limited in boom length (six feet or so) due to my attempt not to overly antagonize HOA constraints, I was concerned that the provided data wouldn't be accurate for a shorter boom antenna, especially on 146 MHz. I initially decided to utilize the wavelength-driven formulas in the Experimenter's Manual to calculate initial element lengths and spacings in a spreadsheet, then enter and model the results in EZNEC and 'tinker' with the spacings just a bit to see if I could optimize the performance for a shorter boom solution. I later applied the design parameters from the John Drew Yagi Calculator in the same fashion, and found the modelled results to be similar.
- Lacking any substantial improvements or concerns discovered during modeling both of the above approaches, I would otherwise get on with building the antennas as this research phase has taken a lot longer than I thought it would and I still need to figure out driven element particulars, a phasing harness, and a reasonable polarity switching solution design, along with physical construction materials and techniques, and I would like to actually get this project done by the end of the year if possible.

The **Yagi Calculator** by John Drew (updated 7 October 2019) is based on the DL6WU Yagi design – **this is the software I used to derive some starting design parameters which I then modeled and modified somewhat in the EZNEC software:** https://wwww.vk5dj.com/yagi.html

I later found a spreadsheet that is reported to leverage the same DL6WU formulas – I haven't tried it however: https://www.worldwidedx.com/attachments/dl6wu-xls.1187/

More on DL6WU Yagi design by Gunther Hoch, and a few more reference articles:

DL6WU Yagi Design Page by Graham Selwod, VK4SG – has a bit of history about Gunther Hoch (DL6WU) and offered some valid concerns about the K1FO design, specifically the lower feed impedance (22 ohms) and the complexity of the driven element.
https://www.qsl.net/vk2kfj/DL6WU.html

There is another Yagi Uda Antenna Calculator based on DL6WU derived design formulas here:
https://www.changpuak.ch/electronics/yagi_uda_antenna_DL6WU.php

Practical Design of Very High Gain Yagi Arrays – SM 5 BSZ, Leif Asbrink
http://www.nitehawk.com/sm5bsz/antennas/cpudes02.htm#BOOMCORR

Building UHF Antennas – W6PQL - published in QST magazine (August 2006)

Good step by step process & pics – see the Back-Yard Antenna Range Story
http://www.w6pql.com/index.htm
http://www.w6pql.com/antennas.htm
http://www.w6pql.com/antennas/theplan.htm
http://www.w6pql.com/misc/range-story.htm

L.B. Cebik W4RNL (SK)

A wealth of information about a multitude of topics including antennas, modeling, & miscellaneous
http://www.antentop.org/w4rnl.001/radio.html

Antenna Modeling Software

The predominant antenna modeling software in use by many hams is EZNEC by Roy W. Lewallen, W7EL: https://www.eznec.com/

I am aware that there are two versions of EZNEC that use the modified NEC-2 (Numerical Electromagnetic Codes) calculation engine – EZNEC v. 6.0, and EZNEC+ v. 6.0. The EZNEC+ version offers additional features, including:

- 2000 segments vs. 500 for the standard program -- allowing very complex antennas to be analyzed.
- Circular polarization far field analysis in addition to the linear polarization capability of the standard program.
- Double-precision calculating engine in addition to the standard mixed-precision engine.
- Catenary wire creation for realistic modeling of sagging wires.

Roy stated on his website that he is retiring on January 1, 2022, after which he will offer EZNEC (PRO/2) free of charge. While I could have waited for the free version to be available, I wanted to start this project sooner than that, and I couldn't tell for sure from Roy's explanation if the free copy would be the EZNEC+ version – so I paid the $149 for a downloadable copy and got on with it.

After installing the program, I printed the EZNEC User Manual, perused the chapters, and worked through the Test Drive sections starting on page 20 to get familiar with the EZNEC features. I completed the various sections until I reached 'A Lap Around Track 5', for which Roy suggested getting more experience with basic EZNEC features before attempting to follow this and the remaining sections.

I then started reading through the 'Building The Model' chapter on page 59. I also read through the articles below, and then I just got on with creating and testing the models:

How to Start Modeling Antennas using EZNEC
http://www.arrl.org/files/file/Antenna%20Modeling%20for%20Beginners%20Supplemental%20Files/EZNEC%20Modeling%20Tutorial%20by%20W8WWV.pdf

EZNEC Antenna Design Example
Using EZNEC to design a compact 23 cm band Yagi array - Rick Campbell March 2015
http://web.cecs.pdx.edu/~campbell/EZNECexample.pdf

EA467 Antenna Design using EZNEC
http://www.aprs.org/labsats/labs08/EA467-EZNEC08cubeA.pdf

Note: By the time I finished this project in mid-March of 2022, **EZNEC Pro/2+ v. 7.0 was indeed available free of charge** – you can find it here: https://www.eznec.com/ ***Download EZNEC Pro/2+ v. 7.0***
I installed it after the fact; it appears to function just like the v6 copy I used for my design work.

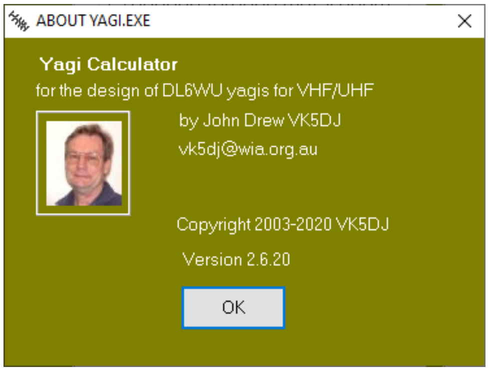
There is also a program available to iterate through various EZNEC design criteria to help find optimal design characteristics – I didn't experiment with this, but you may wish to:

AutoEZ: Collected Short Examples
https://ac6la.com/aecollectiontoc.html

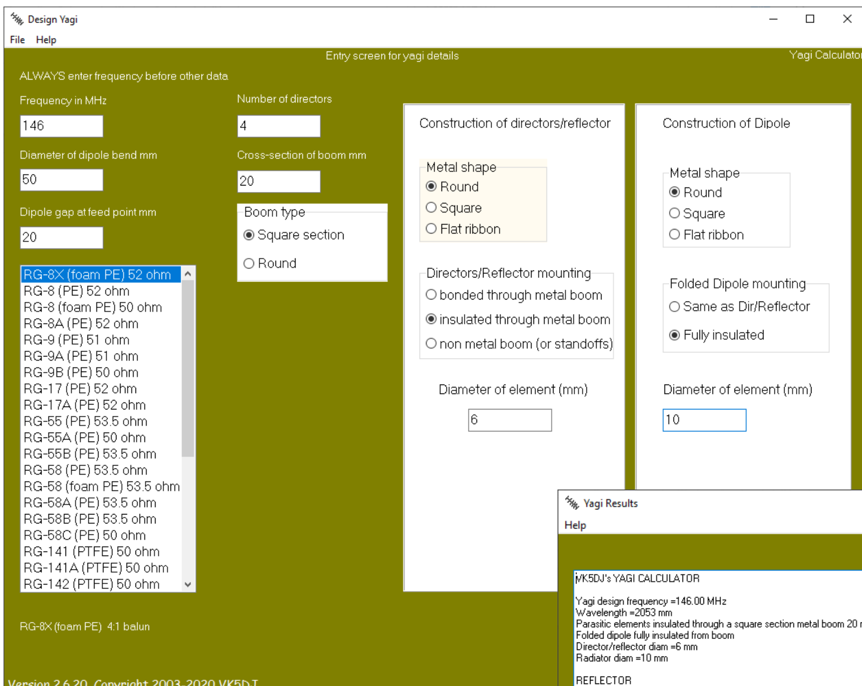
AutoEX v2
https://ac6la.com/autoez.html

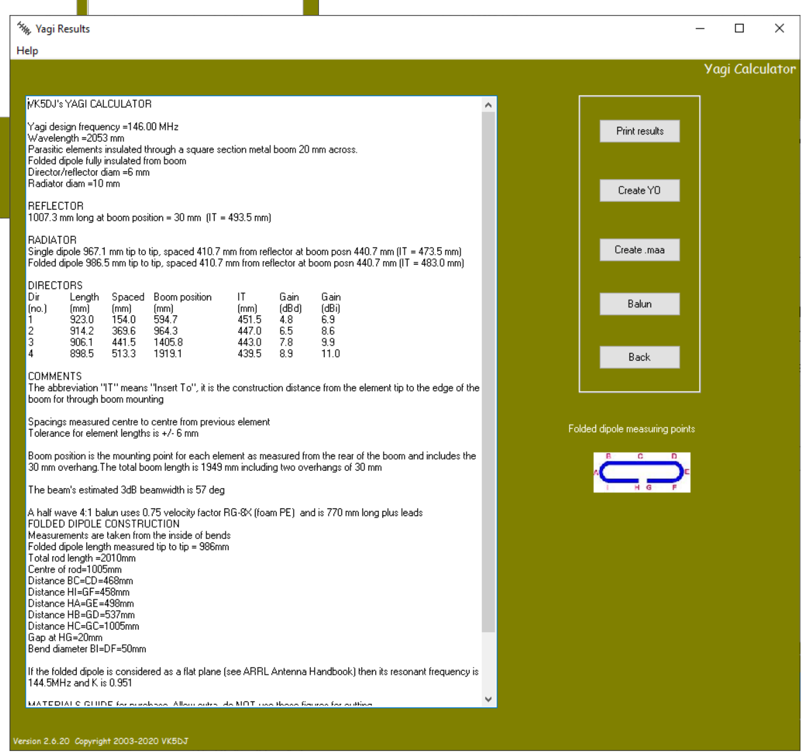
AK2W Antenna Designs

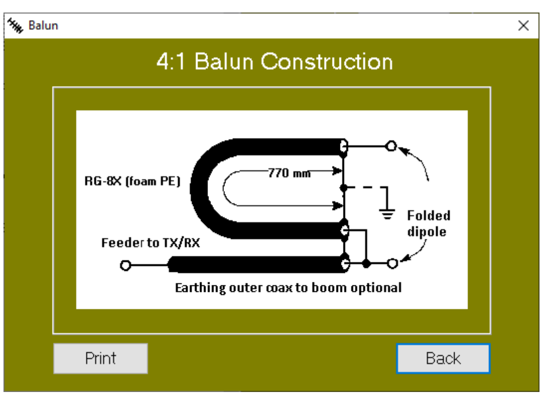
Yagi Calculator



As mentioned above, the Yagi Calculator by John Drew was utilized to obtain element length and boom position values based on provided design specifications in terms of size and type (square, round) boom, element dimensions, etc. The length of the 4:1 balun was also calculated based on the velocity factor of the specified feedline coax. I actually used RG-6, but that wasn't an option on the coax list, so I specified RG-8X foam as its velocity factor (.82) is similar to RG-6 (.81).

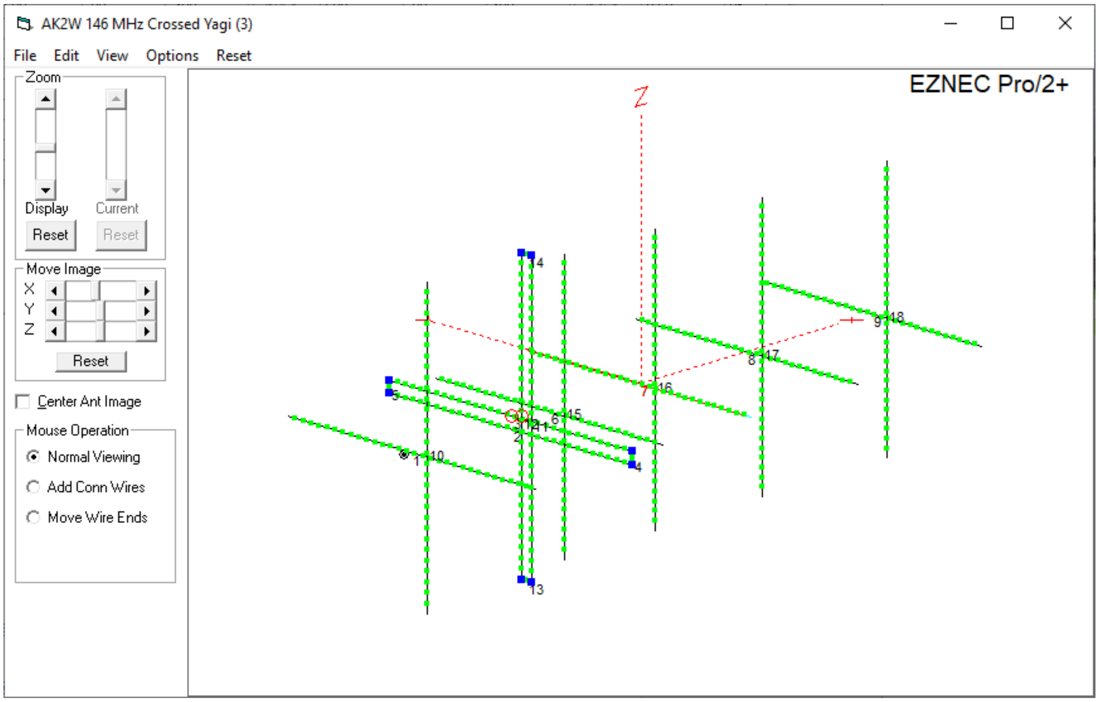






146 MHz Crossed-Yagis

The design criteria obtained from the Yagi Calculator was then input into a EZNEC model for both antennas. Selected windows and form data from the EZNEC model of the 6 element crossed-Yagi design for 146 MHz are given below so that you can see what's involved in creating and using an EZNEC model.



The 'Wires' form is where you input the dimensions and spacing of the antenna elements along the X, Y, and Z planes (see the image above) – this is how the model is basically built.

Wires

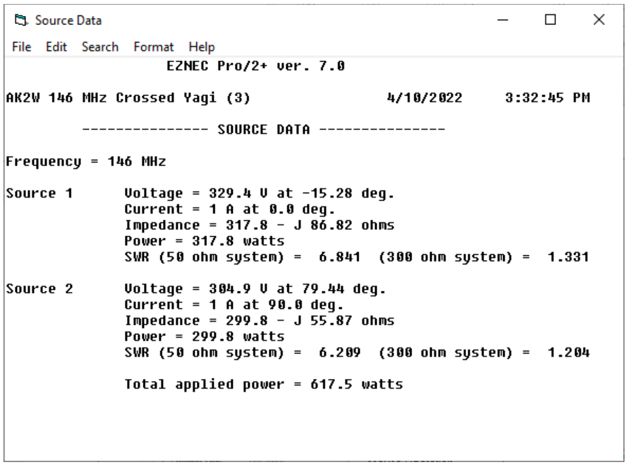
Wire Create Edit Other

☐ Coord Entry Mode ☐ Preserve Connections ☐ Show Wire Insulation ☐ Show Loss

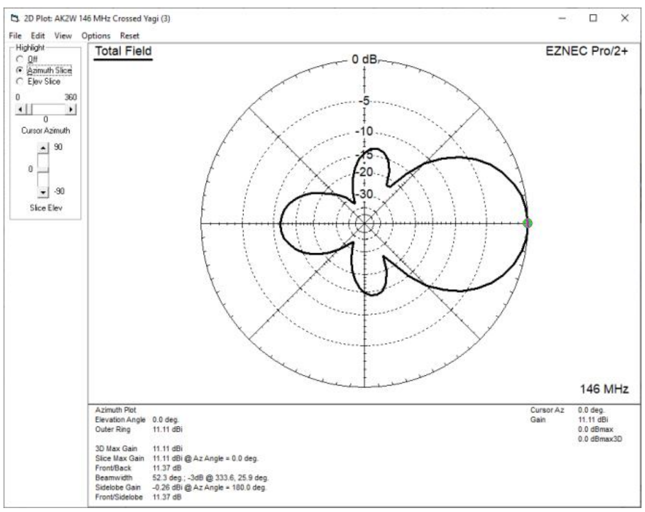
Wires

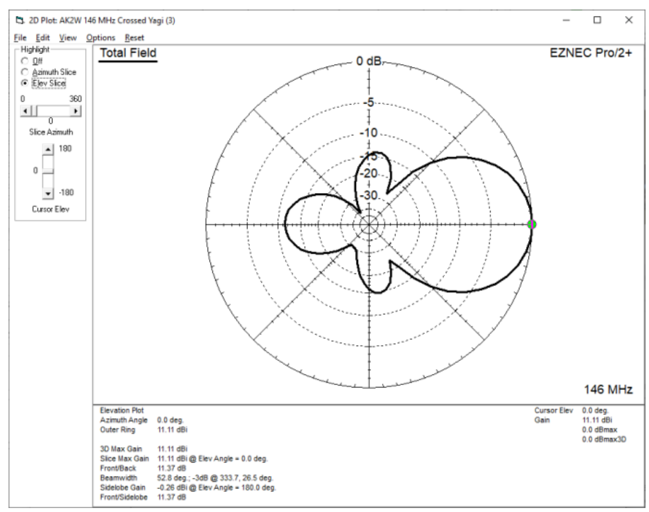
No.	End 1				End 2				Diameter	Segs
	X (mm)	Y (mm)	Z (mm)	Conn	X (mm)	Y (mm)	Z (mm)	Conn	(mm)	
1	30	-504	0		30	504	0		6.35	31
2	441	-493	-20	W4E1	441	493	-20	W5E1	9.53	31
3	441	-493	20	W4E2	441	493	20	W5E2	9.53	31
4	441	-493	-20	W2E1	441	-493	20	W3E1	9.53	3
5	441	493	-20	W2E2	441	493	20	W3E2	9.53	3
6	595	-462	0		595	462	0		6.35	31
7	965	-457	0		965	457	0		6.35	31
8	1407	-453	0		1407	453	0		6.35	31
9	1920	-449	0		1920	449	0		6.35	31
10	95	0	-504		95	0	504		6.35	31
11	506	-20	-493	W13E1	506	-20	493	W14E1	9.53	31
12	506	20	-493	W13E2	506	20	493	W14E2	9.53	31
13	506	-20	-493	W11E1	506	20	-493	W12E1	9.53	3
14	506	-20	493	W11E2	506	20	493	W12E2	9.53	3
15	660	0	-462		660	0	462		6.35	31
16	1030	0	-457		1030	0	457		6.35	31
17	1472	0	-453		1472	0	453		6.35	31
18	1985	0	-450		1985	0	450		6.35	31
*										

The Source Data form provides impedance information in ohms + reactance for both driven elements.

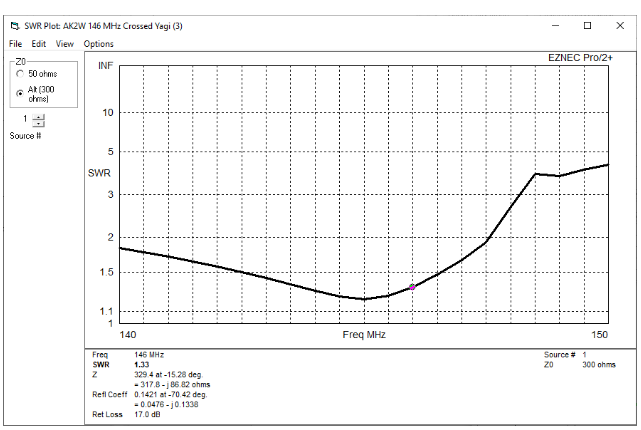

```
Source Data
File  Edit  Search  Format  Help
                 EZNEC Pro/2+ ver. 7.0

AK2W 146 MHz Crossed Yagi (3)              4/10/2022     3:32:45 PM

         --------------- SOURCE DATA ---------------

Frequency = 146 MHz

Source 1       Voltage = 329.4 V at -15.28 deg.
               Current = 1 A at 0.0 deg.
               Impedance = 317.8 - J 86.82 ohms
               Power = 317.8 watts
               SWR (50 ohm system) =  6.841  (300 ohm system) =  1.331

Source 2       Voltage = 304.9 V at 79.44 deg.
               Current = 1 A at 90.0 deg.
               Impedance = 299.8 - J 55.87 ohms
               Power = 299.8 watts
               SWR (50 ohm system) =  6.209  (300 ohm system) =  1.204

               Total applied power = 617.5 watts
```

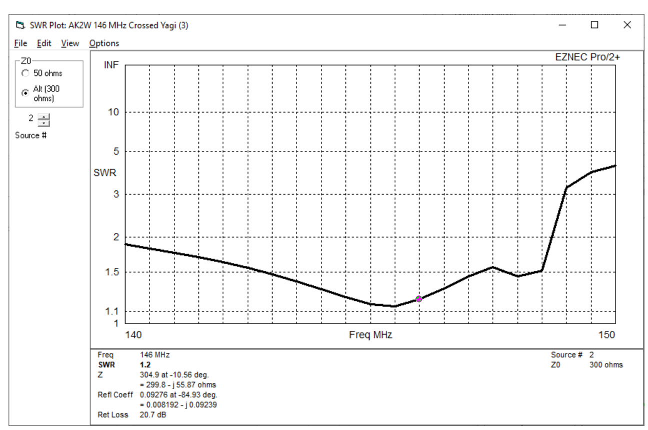
The Field Radiation plots show the calculated radiation patterns in both azimuth and elevation. The expected gain for this antenna is 11.11 dBi (11.1 – 2.15 = ~9 dBd – the gain over a dipole):



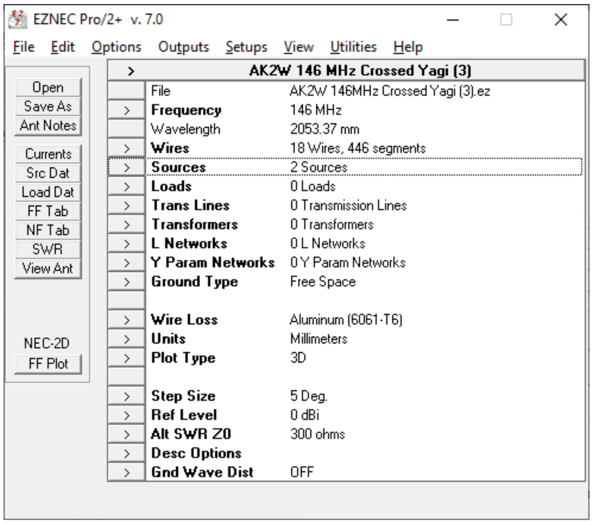


The SWR plots for this design suggest the minimal SWR is a bit lower than the design frequency – I'm leaving it because it's easier to reduce the driven and passive element lengths a bit than to replace them with longer ones, and these models don't correct for the shortening effect of thru-mast elements. The SWR was projected to be 1.33 / 1.2 at 146 MHz for the horizontal/vertical arrays respectively.

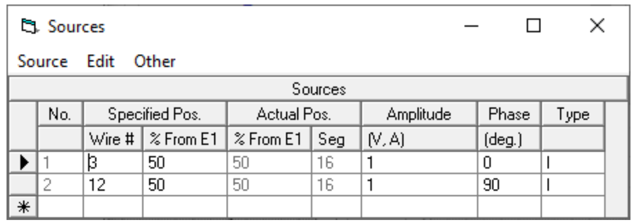




The main form of the EZNEC user interface allows you to specify options for Frequency, an alternate feed impedance, Ground Type, Power Level, etc.



The 'Sources' form allows you to specify where the driven elements for the two antennas are fed:



I combined the dimensions information and screenshots of the other EZNEC forms & plots into a spreadsheet tab for each antenna – the image below is the build specs for the vertical and horizontal planes.

146 MHz 6-Element Crossed Yagi Antenna Build Specifications

				Gain (dBd)	Gain (dBi)
VK5DJ Yagi Calculator Results - 146 MHz - Horizontal Elements				8.9	11.0
Element	**Spacing (mm)**	**Pos (mm)**	**Len (mm)**	**Len (in)**	**NEC (L/2)**
REF	30	**30**	1007	39.65	**504**
DE	411	**441**	986	38.82	**493**
D1	154	**595**	923	36.34	**462**
D2	370	**965**	914	35.98	**457**
D3	442	**1407**	906	35.67	**453**
D4	513	**1920**	898	35.35	**449**
End Allow	30	**1950**			
DE 1	2	50.80 mm	**1037**	**+ 2" for shorting bars & end caps**	
DE 2 (x 2)	1.5	38.10 mm	**512**	**+ 1.5" for short bars + caps - feed gap / 2**	
Balun Loop Length			770	30.31	

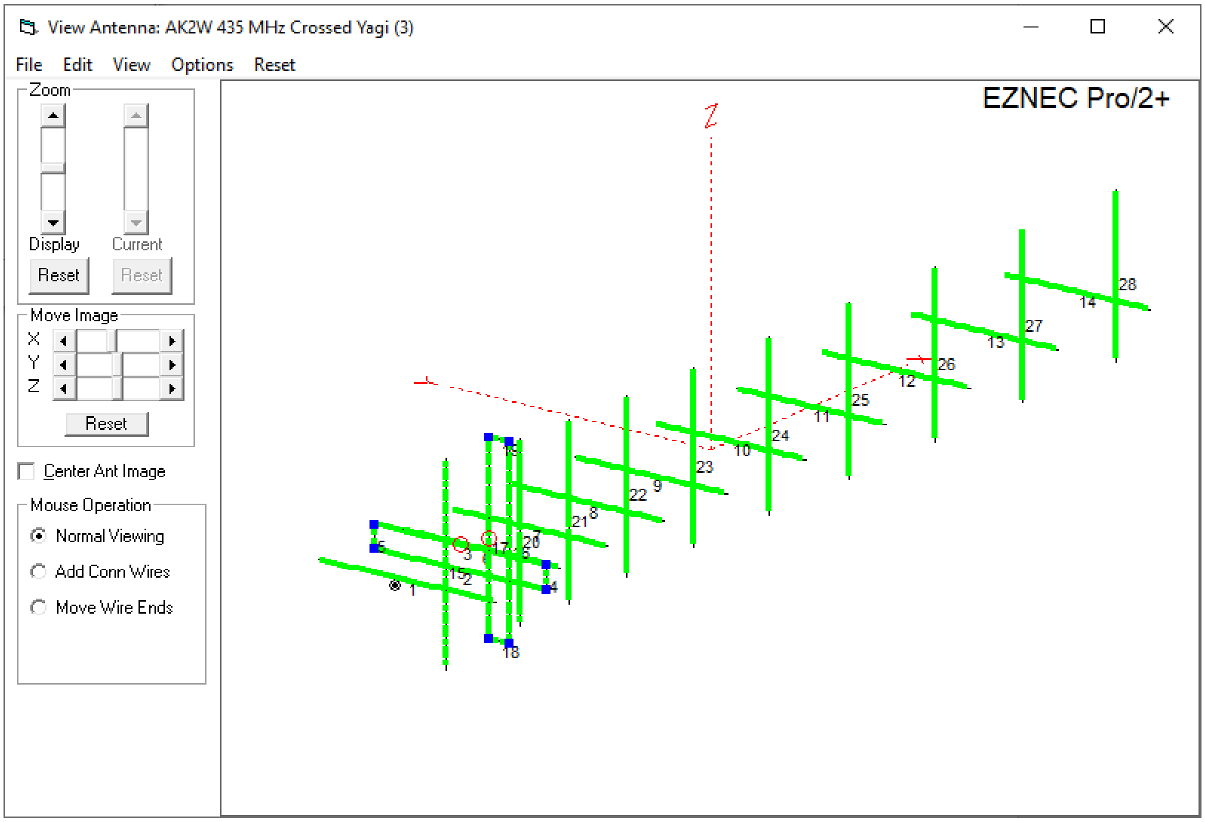
VK5DJ Yagi Calculator Results - 146 MHz - Vertical Elements					
Element	**Spacing (mm)**	**Pos (mm)**	**Len (mm)**	**Len (in)**	**NEC (L/2)**
REF	95	**95**	1007	39.65	**504**
DE	411	**506**	986	38.82	**493**
D1	154	**660**	923	36.34	**462**
D2	370	**1030**	914	35.98	**457**
D3	442	**1472**	906	35.67	**453**
D4	513	**1985**	899	35.39	**450**
End Allow	30	**2015**		**Boom Length (in):**	**79.3**

Element	**Insert to (mm)**
REF	**494**
DE	**483.5**
D1	**452**
D2	**447.5**
D3	**443.5**
D4	**440**

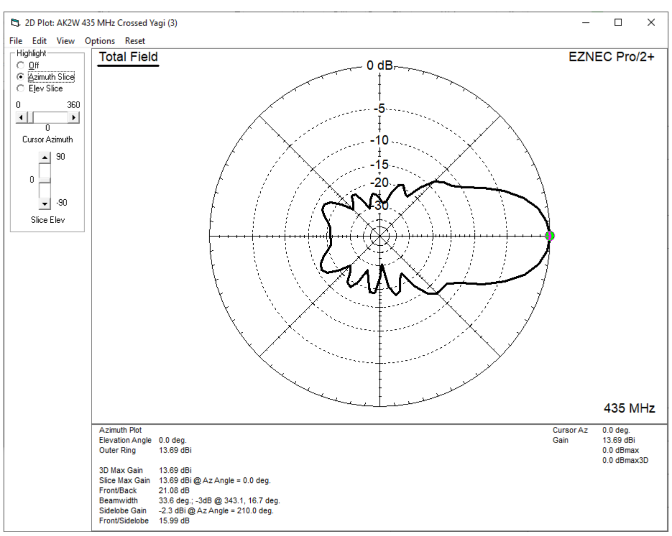
Balun Coax Loop Length	770	30.31

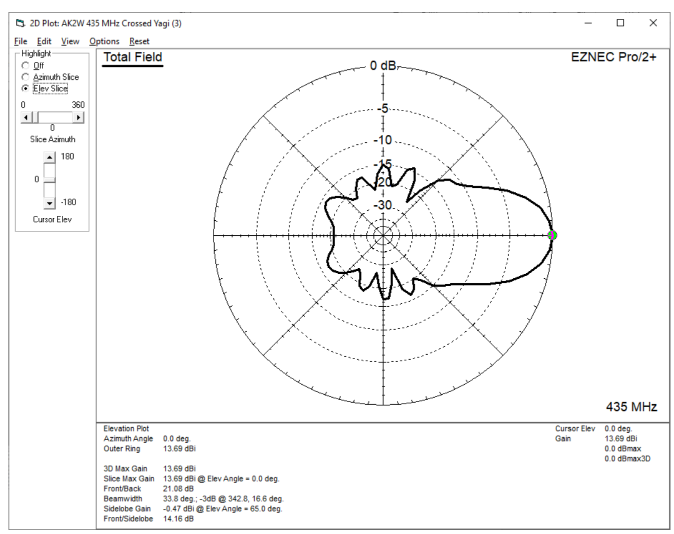
436 MHz Crossed-Yagis

Another EZNEC model was built for the 11 Element 436 MHz crossed-Yagi array – here are screenshots.

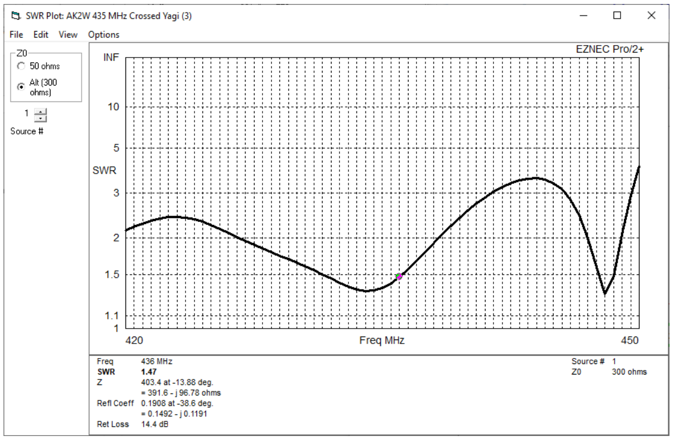


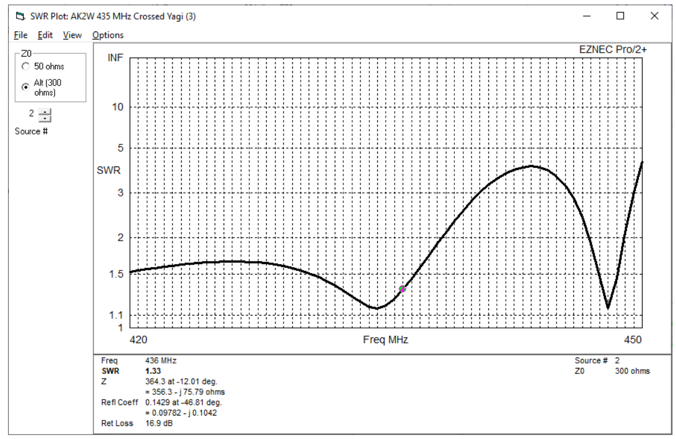
Azimuth and elevation Field Radiation plots – the expected gain for this array is 13.7 dBi = 11.6 dBd.





The SWR plots weren't perfect, but not too bad considering this was a 420-450 MHz plot. SWR at 436 was projected to be 1.47 and 1.33 for the horizontal/vertical arrays respectively.





The build specs for both antennas arrays include length adjustments for the driven element (DE1/DE2) that account for the shorting bars and vinyl end-caps that keep moisture out of the hollow 3/8" aluminum tubing.

435 MHz 11-Element Crossed Yagi Antenna Build Specifications

				Gain (dBd)	Gain (dBi)		
VK5DJ Yagi Calculator Results - 435 MHz - Horizontal Elements				12.2	14.4		
Element	**Spacing (mm)**	**Pos (mm)**	**Len (mm)**	**Len (in)**	**NEC (L/2)**	**Gain (dBd)**	**Gain (dBi)**
REF	30	**30**	341	13.43	**171**		
DE	138	**168**	325	12.80	**163**		
D1	52	**220**	301	11.85	**151**	4.8	6.9
D2	124	**344**	297	11.69	**149**	6.5	8.6
D3	148	**492**	294	11.57	**147**	7.8	9.9
D4	172	**664**	291	11.46	**146**	8.9	11.0
D5	193	**857**	288	11.34	**144**	9.8	11.9
D6	207	**1064**	286	11.26	**143**	10.5	12.7
D7	217	**1281**	283	11.14	**142**	11.2	13.3
D8	227	**1508**	281	11.06	**141**	11.7	13.9
D9	238	**1746**	279	10.98	**140**	12.2	14.4
DE 1	2	50.80 mm	**376**	**+ 2" for shorting bars & end caps**			
DE 2	1.5	38.10 mm	**182**	**+ 1.5" for short bars + caps - feed gap / 2**			
Balun Loop Length			258	10.16			

VK5DJ Yagi Calculator Results - 435 MHz - Vertical Elements					
Element	**Spacing (mm)**	**Pos (mm)**	**Len (mm)**	**Len (in)**	**NEC (L/2)**
REF	202	**205**	341	13.43	**171**
DE	138	**343**	326	12.83	**163**
D1	52	**395**	301	11.85	**151**
D2	124	**519**	298	11.73	**149**
D3	148	**667**	294	11.57	**147**
D4	172	**839**	291	11.46	**146**
D5	193	**1032**	288	11.34	**144**
D6	207	**1239**	286	11.26	**143**
D7	217	**1456**	283	11.14	**142**
D8	227	**1683**	281	11.06	**141**
D9	238	**1921**	279	10.98	**140**
End Allow	30	**1951**		**Boom Length (in):**	**76.8**
Balun Loop Length			258	10.16	

Building the Antennas

This is the culmination of the research and design efforts discussed thus far – it's time to construct the antennas and get this project done. I'll start with a brief overview of the tools used, materials lists, and some construction images and notes. Then I'll review some of the ancillary portions of the solution – rotator cables, polarization relays and controller, etc. Finally, I'll cover testing and installing the antenna system.

Workshop, Power, and Hand Tools

The following are pictures of the garage-based workbench (two Harbor Freight woodworking benches bolted together for more workspace and drawers) and power tools – drill press, grinder, and MITRE saw on stand.

One of the limitations on the antenna array size was to assure the ability to build the system in the garage – I mounted the antennas on the cross-beam at their center of gravity to keep wear on the elevation rotator at minimum; as it turned out I had about 1” clearance from the ceiling when the array was pointed straight up so I could store it back in the corner and still park my Jeep in the 2-car garage.

Between tools and materials, I spent a lot more money designing and building this antenna system than it would have cost to just purchase commercial units – but I learned a LOT, I have no qualms about building other advanced antennas, and I intend to leverage the tools and experience on some robotics projects in the future – so it was all a worthy investment. And a lot of fun!

Hand Tools

The hand tools that I ended up using the most for this project included those in the pictures below:

- Combination square with the protruding ruler length set to various depths to help mark the hole centers of connection boxes, masts, and attachment pieces.
- AFA Tooling Deburring Tool Kit - for cleaning the burrs out of holes drilled in both plastic and aluminum.

  https://www.amazon.com/gp/product/B07RM1D6WD
- Automatic center hole punch – you push down until it 'snaps' and makes a nice dent in plastic or aluminum for guiding a drill bit to the center for an accurate hole position.

  https://www.amazon.com/gp/product/B07DS7CMFX
- Several sizes of 'step' drill bits (for drilling large holes) – CO-Z Step Drill Bits, HSS 5PCS Titanium Step Drill Bit Set, 50 Sizes in 5 High Speed Steel Unibit Drill Bits Set for Sheet Metal with Aluminum Case, Multiple Hole Stepped Up Bits for DIY Lovers33
  https://www.amazon.com/gp/product/B0177PN6SI
- Good-quality 'normal' drill bits – Lowes or Home Depot.
- Fine point and ultra-fine-point Black & Blue Sharpie pens (I didn't use the scoring tool shown in the picture).
- Phillips and flat screwdrivers, various sizes of open and closed-end wrenches, sockets, pliars, cutters, etc.
- A 8'-25' tape measure that has inches on one side and millimeters/centimeters markings on the other – I used this for most of the mast and element measurements. CRAFTSMAN Tape Measure, Self-Lock, 8-Meter (CMHT37226S) https://www.amazon.com/gp/product/B07RCNHV5J

- VINCA DCLA-0605 Electronic Digital Vernier Micrometer Caliper for fine measurements.

  https://www.amazon.com/gp/product/B017KUC6XQ

Antenna Materials

The following is a list of the materials used in the construction of this antenna solution, quantities (estimates in some cases), what they were used for, and in most cases, where/how I got them so this work could be duplicated to some degree in the future.

Also be aware that this list represents what I actually used to build the antennas. I researched/ordered/tested and rejected quite a few different types and sizes of plastic boxes, for example, before setting on the ones I acually used. Same story with some of the other materials – nylon spacers, clamps, etc.

Antenna Mast & Elements

I settled on **6061-T6 square aluminum tubing** for the antenna masts and ordered **four ¾” x 6’ and one 1” x 6’** tubes from Texas Towers: http://www.texastowers.com/square-6.htm

I also ordered **three 3/8” (.375) x 48”** lengths of **round aluminum tubing** from TT to use for folded dipoles as driven elements: http://www.texastowers.com/aluminum-6.htm

I decided to use **¼” solid aluminum rods** for the reflectors and directors and ordered **22 x 48”** rods from Home Depot: https://www.homedepot.com/p/Everbilt-1-4-in-x-48-in-Aluminum-Round-Rod-800377/204604769

Also used in this project:

(2) **¾” x 1/16” aluminum angle** – driven element stabilizers, mast to muffer clamp adapters - Home Depot

(1) **¾” x 1/16” flat aluminum stock** – attachment plate for feeline support masts – Home Depot

(1) **½” x 1/8” flat aluminum stock** – shorting bars on the ends of the loop dipole driven elements - Hope Depot

Round aluminum tubing that just fits inside the ¾" square tubing for joining/extending the length of the mast a bit past 6 feet to accommodate the last passive elements - **Aluminum Round Tubing - 5/8" OD x 48"** https://www.amazon.com/gp/product/B06XPHH95Q

I planned to insulate the elements from the boom, so I ordered a package of nylon bushings with .375" inch mounting hole diameter, .25" inside diameter from Amazon: Heyco 2030 SB-375-4 Black **SNAP Bushing** (Package of 250) https://www.amazon.com/gp/product/B001BPV94E

Jocon Safety SF9000 PVC Flexible **Round End Caps** Shelf Organizer Tip Caps Wire Thread Protector Cover (inner diameter **6mm** (**1/4"**) – black plastic end caps for the ¼" reflectors and directors: https://www.amazon.com/gp/product/B06XQMPQMY

Jocon Safety SF9000 PVC Flexible **Round End Caps** Shelf Organizer Tip Caps Wire Thread Protector Cover (inner diameter **9mm** (**3/8"**) – black plastic end caps for 3/8" driven element tubing https://www.amazon.com/gp/product/B071W12W49

Prescott Plastics **0.75" Inch Square Plastic Plug Insert** (16 Pack), Black End Cap for Metal Tubing, Fence, Glide Insert for Pipe Post, Chairs and Furnitures – plugs for the ends of the ¾" square aluminum masts. https://www.amazon.com/gp/product/B07N6HRYJW

And for mounting the antenna mast to the fiberglass cross-beam:

(4) Ohio Diesel Parts Heavy Duty **Muffler/Exhaust Clamp 1-3/4" Inch** - Saddle Style with U-Bolt -Zinc (2-Pack) – attach the ¾" aluminum masts to the fiberglass cross-beam that goes through the elevation rotator https://www.amazon.com/dp/B079P9KX37

MATNIKS **Rubber Sheets**, Black, (Pack of 3) **6x6-Inch by 1/8** (+/-10%) Duro A60. Neoprene, Plumbing, Gaskets DIY Material, Supports, Leveling, Sealing, Bumpers, Protection, Abrasion, Flooring – cut to fit between the muffler clamps and the fiberglass cross-beam to provide a good grip without having to tighten the clamps down so hard that the fiberglass get crushed - https://www.amazon.com/gp/product/B06XFRJD56

Miscellaneous Hardware

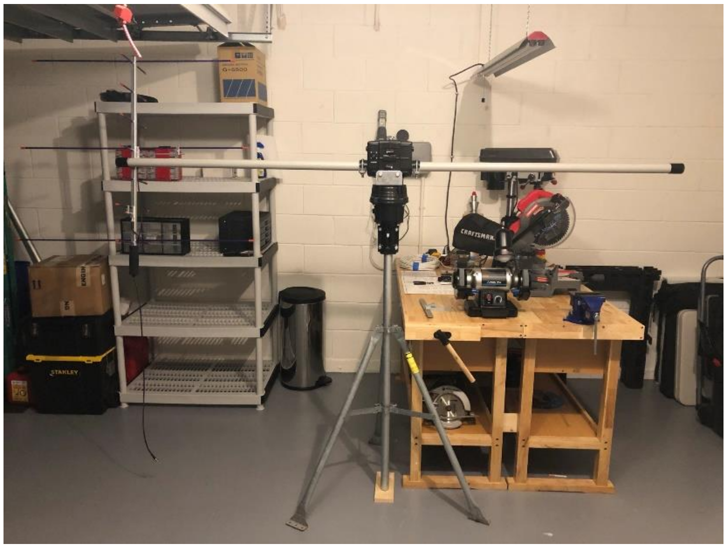
I used 6-32 round phillips-head screws of various lengths, with the associated washers, star lock-washers and nuts. I had to order some of these online as they weren't available in sufficient quanties at Lowes / HD.

#10-32 x ½" Phillips Truss Head Machine Screw (100 pc)

#10-32 X 1-1/4" Stainless Phillips Truss Head Machine Screw, (25pc), Fine Thread, 18-8 (304) Stainless Steel, by Bolt Dropper https://www.amazon.com/dp/B07D1L49NR

Steel Pan Head Machine Screw, Zinc Plated, Meets ASME B18.6.3, #2 Phillips Drive, #10-32 Thread Size, 2-1/4" Length, Fully Threaded, Imported (Pack of 25) https://www.amazon.com/dp/B00F2Y2F52

Azimuth-elevation rotators and crossbeam



I purchased the popular Yaesu G-5500DC azimuth/elevation rotator solution:
https://www.yaesu.com/indexVS.cfm?cmd=DisplayProducts&ProdCatID=104&encProdID=79A89CEC477AA3B819EE02831F3FD5B8&DivisionID=65&isArchived=0

And an eight-foot 1-1/2” OD hollow fiberglass crossbeam and vinyl end-caps from Max-Gain Antennas:
https://mgs4u.com/product/1-1-2-od-1-id-1-4-wall-round-tube/?attribute_pa_length=8-foot
https://mgs4u.com/product/vinyl-end-caps/?attribute_pa_id-nom=112-id

I mounted the rotator solution on an approximately 5-foot section 1-1/2” mast supported by a MFJ tripod and installed the fiberglass crossbeam so that a) I could learn how this all fitted together before putting the antenna system up in the air, and b) to have something to mount the antennas on after they were constructed and ready to be tested. View the Antenna testing pics to see the result.

Rotator Control Cables

I built a set of approximately 10-foot cables to go from the back of the G-5500DC control box to Molex connectors, and then another set of approximately 15-foot cables with Molex connectors on one end and the rotator connectors on the other. The 10’ cables will eventually go from the ham station table to the window feed- through panel, the 15’ cables will reach from the rotators to under the house eaves, and I’ll build Molex-to-Molex cables for the under-eave run at the needed length during installation. In the meantime, I can connect the two shorter sets of cables together to control the rotators during the build/test phases of the project.

Consult the Yaesu rotator controller manual for wiring specifics.

Molex -3 Complete Set - (6 Circuit) w/14-20 AWG, Wire Connector - 2.13mm D, Latch Lock, MLX
https://www.amazon.com/gp/product/B075R4RWV7

Alzatex 18ga Wires in a 6-Conductor, Stranded Cable with White or Grey PVC Jacket, Class 2 Approved for Low Voltage Applications (100ft)
https://www.amazon.com/gp/product/B07S7F188X

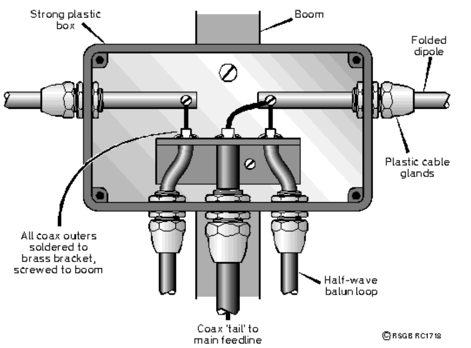
Constructing the Antennas

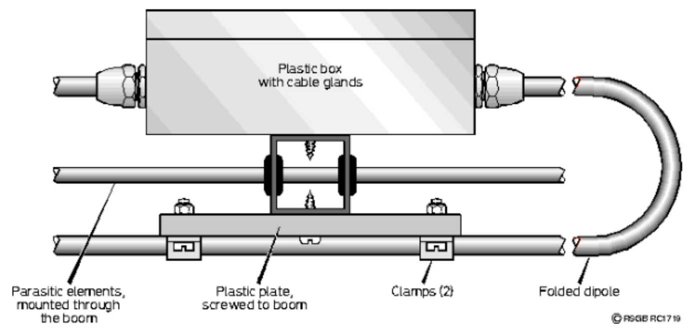
The following pages are a set of pictures and brief explanations of the various stages of the antenna build process; I've tried to include pics of and notes on the tools and materials used to serve as a guide to anyone wanting to duplicate some part of this process, as well as a reminder to myself of how this was done in case it's a while before I launch another similar project.

The construction process includes two major activities – construction of the driven element solution, and then cutting/drilling/assembling the reflector and directors along with the driven element solution on the mast.

Driven Elements Solution

Designing the physical aspect of the driven element solution was, by far, the most challenging aspect of this entire project.





As I mentioned before, I gained inspiration from these images in the In Practice, RadCom (RGSB), April 1998 article (http://www.ifwtech.co.uk/g3sek/diy-yagi/dipoles.htm) and decided to use a plastic box and appropriate size cable glands for supporting the 3/8" driven elements and getting coax runs into the junction box, while trying to keep the box as small as possible for astetic and size/weight purposes. I didn't do it exactly as depicted here; I think my solution of using a common binding post for the coax ground connections and an insulated clamp for supporting the middle of the folded dipole worked much better in my particular application.

I had to do a lot of experimentation with various sizes of waterproof plastic boxes that were available from Amazon (I didn't want to wait for the the delivery times from other suppliers, given the iterative process I found myself in), and finally decided to use the smaller boxes I had started out with. Because there wasn't enough room to mount two cable glands on one side of the box for the 4:1 RG-6 balun coax entries, I opted to use rubber grommets and hope that some waterproof sealant would work for keeping moisture out. Fitting the separation of the 3/8" aluminum tubing ends for the driven elements with an insulating spacer, clamps for attaching feedline and 4:1 balun coaxes, and mounting hardware in the small amount of space available was a challenge, but I finally found the right combination that worked.

Driven Elements Parts List

This is the final list of the materials used for construction of the driven element solution:

T Tulead 3PCS **Junction Box** ABS Enclosure Box Conduit Juction Box Waterproof Project Box Dustproof Electrical Box Case 2.52"x2.24"x1.38"
https://www.amazon.com/gp/product/B088R4T8JL

(4) **¼" x 48" wooden dowel** – - slid inside the 3/8" driven elements to provide additional strength and a mounting solution for the nylon spacer between the driven elements in the coaxial junction boxes - Home Depot

Nylon spacers - Swpeet 150Pcs Nylon Round Spacer Standoff Screw Nut Assortment Kit, Nylon PA66 Plastic Standoff OD 11mm and ID 6.2mm Length 3mm 4mm 5mm 8mm 10mm 12mm 15mm 18mm 20mm 25mm for M6 Screws Prototyping
https://www.amazon.com/dp/B07LDBB94B

Insulated 3/8" clamps - TICONN 80PCS Cable Clamps Set - Rubber Cushioned 304 Stainless Steel Hose Clamps Loop Clamps Pipe Clamps in 6 Sizes (80PCS combo, 1/4'' 5/16'' 3/8'' 1/2'' 5/8'' 3/4'')
https://www.amazon.com/gp/product/B094YP2F3D

3/8" metal clamps - Glarks 80Pcs 5 Size 1/4'' 5/16'' 3/8'' 1/2'' 5/8'' Stainless Steel Cable Clamp Assortment Kit
https://www.amazon.com/dp/B07Y372WMT

Sutemribor **Nylon Flat Washer Assortment** Set 600 Pieces, 9 Sizes - M2 M2.5 M3 M4 M5 M6 M8 M10 M12, Black
https://www.amazon.com/dp/B07KQTTXSY

CGELE **Cable Gland** 50 Pack Plastic Waterproof Adjustable Connector 3-16mm Strain Relief Cord Connectors Joints Nylon with Gaskets PG7 PG9 PG11 PG13.5 PG16 PG19 (for design experimentation)
https://www.amazon.com/gp/product/B0993CWBGV

Cable Glands - Lokman 20 Pack **PG11** Plastic Waterproof Adjustable 5-10mm Cable Glands Joints With Rubber Gaskets, Black (PG11) - https://www.amazon.com/gp/product/B06Y5F6G67

Cable Glands -Lokman 20 Pack **PG7** Plastic Waterproof Adjustable 3-6.5mm Cable Gland Connectors Cable Gland Joints With Gaskets, Black (PG7) - https://www.amazon.com/gp/product/B06Y5HGYK2

100 **Nylon Spacer Bushings .257 I.D**. 1/2 O.D. **Length ¼**
https://www.amazon.com/gp/product/B005C0L5O8

350 Pieces **Rubber Grommet** Assortment Kit Firewall Hole Plug Electrical Wire Gasket Rubber Ring Gasket with Plastic Box 15 Sizes for Automotive, Plumbing, PC Hardware Piano (2 Boxes) – grommets for sealing against moisture where the RG-6 coaxial baluns enter the junction boxes
https://www.amazon.com/gp/product/B08P8RTJ42

NEOPRENE **RUBBER SHEETS black, 8x8-Inch by 1/16** (Pack of 4), Gaskets DIY Material – used between the junction boxes and aluminum mast to keep water out of the boxes - https://www.amazon.com/dp/B08LQYLPXV

Building the Driven Element Junction Box

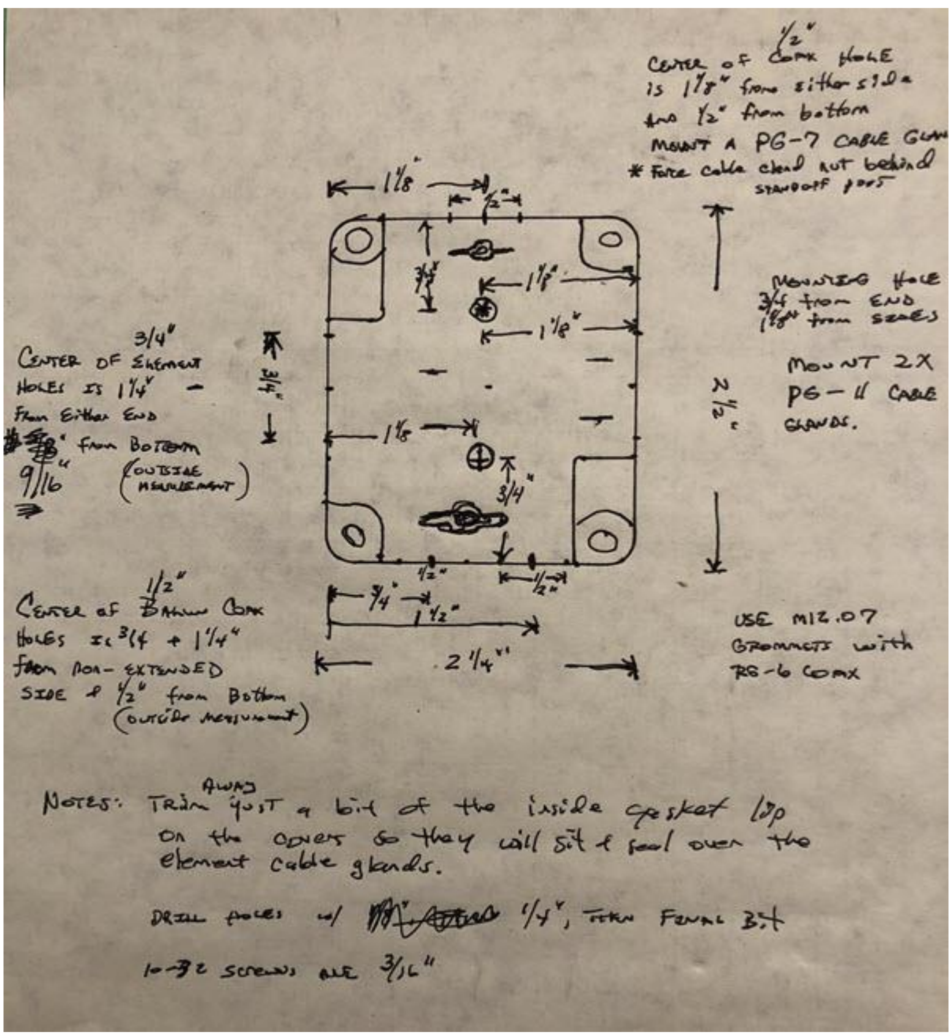
The junction box is 2.52" x 2.24" x 1.38", and is just large enough to mount the cable glands and accommodate the needed connections inside. I have included images of my hand-written notes below; I should probably do a proper drawing in Visio but this will suffice for now.

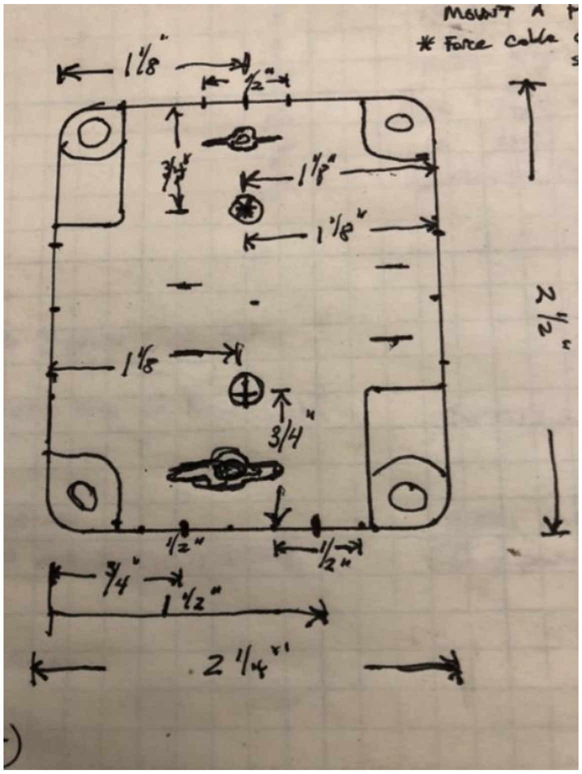
Following are the steps to prepare one junction box for one antenna. Note that in all hole drilling operations, you should measure and mark the hole center and then use the automatic center hole punch to create an indentation for guiding the tip of the drill bit so that the hole placement is accurate.

1. Drill the driven element holes in the sides of the longer edge of the box, centered 1-1/4" from either end of the box, and 9/16" from the bottom. Start with a ¼" drill bit, then use a ¾" step drill bit to slowly expand the

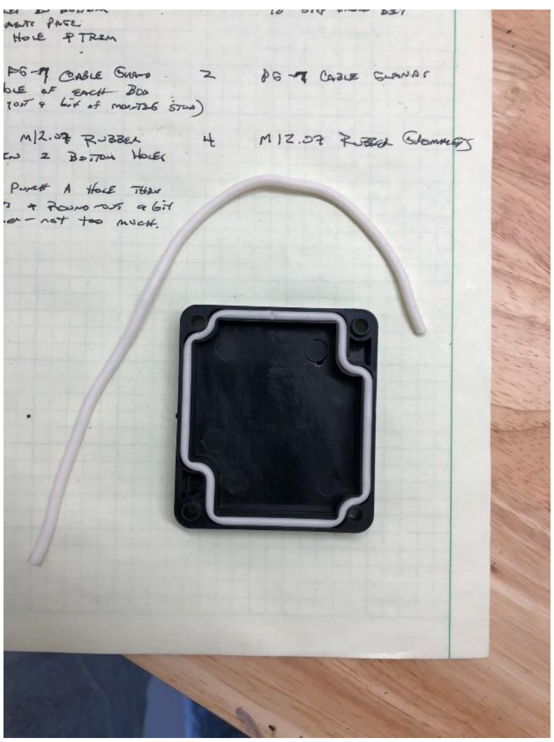
holes to the full ¾" diameter. Use the deburring tool to clean away the residual plastic from around the hole. These holes will be used with PG-11 cable glands for holding the 3/8" driven elements.

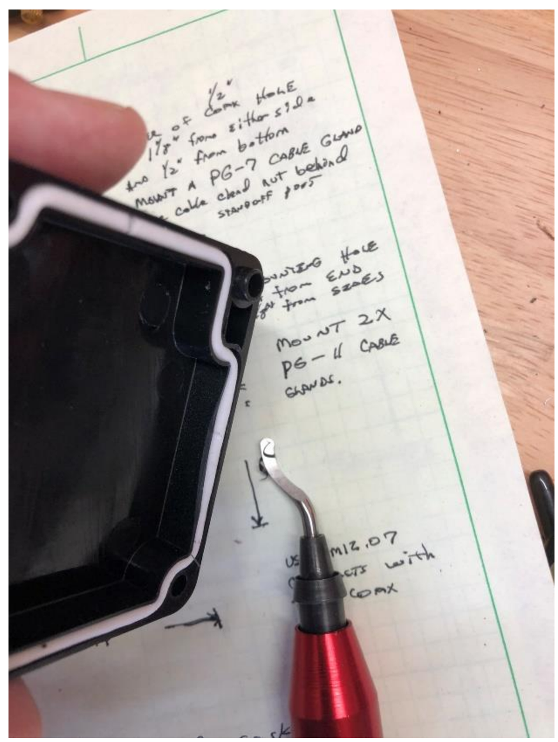
2. Starting with a ¼" drill bit and then using a ½" step drill bit, drill one ½" hole in the center of one end of the box (also centered 1/2" from the bottom), and two ½" holes in the other end with their centers ¾" and 1-1/2" from the side of the box where the mounting area is not extended – see the diagram and notes images below. These holes will be used with a PG-7 cable gland for the feedline coax, and two m12.07 rubber grommets for the 4:1 coaxial balun entries.
3. Drill two 3/16" holes in the center of the bottom of the junction box that are centered ¾" from each end and 1-1/8" from either side. These are for mounting the junction box to the antenna mast.
4. Mount two PG-11 cables glands in the ¾" holes, and a PG-7 cable gland in the top ½" hole, finger tight. Mount two m12.07 rubber grommets in the bottom ½" holes and punch a hole through the center if they have a thin solid center. You may opt to use two PG-7 cable glands and RG-8X coax for the 4:1 balun instead of the rubber grommets and RG-6 coax – if I build another set of these that is probably the option I'll try.
5. At any point in this process, you may need to use a drill bit and/or deburring tool to trim away some of the mounting masts located inside the box near either long end so that other things fit. We won't be using these mounting masts.





6. The mounting nuts of the PG-11 cable glands will extend just a tiny bit below the lip of the junction box. Using the deburring tool (and without the rubber grommet material in place), trim a small amount of the inside edge of the rubber grommet guide from the lid of the box so that the lid will seat and fit properly on the top of the junction box while still allowing the rubber grommet to provide a waterproofing barrier.





7. Cut the two shorter lengths of the driven element 3/8” hollow aluminum tubing (which will mount into the junction box) and the longer 3/8” tubing length which serves as the other side of the folded dipole. Note that the lengths of this aluminum tubing is longer than antenna calculations indicate to allow for the width of shorting bars and plastics caps that go over the ends of the 3/8” tubing.

8. Cut two lengths of ¼” wooden dowel just long enough to fit inside the longer 3/8” tubing. The wooden dowels will serve as a) strengthing and kink protection for the 3/8” hollow tubbing, and b) as a mounting solution for the nylon spacer that separates the ends of the driven elements inside the junction box.

9. Insert the ends of the short 3/8” tubing into the PG-11 cable glands, and then slide the wooden dowel into one end far enough to extend just past the end of one of the tubes – see the image below. Slide the ¼” width nylon spacer over the wooden dowel, then push the wooden dowel through the other 3/8 tube and all the way to the other end. Tighten the outer cable gland nuts just slightly so things stay together.

   We will seal the outside ends of the 3/8” aluminum tubes with rubber caps so that the dowels don’t soak up water and affect antenna operation before we’re done.

10. Install two JT-9 mm (3/8”) metal clamps over the 3/8” driven element ends, with the flat side of the clamps facing up. You can pre-install 10-32 x ½” screws, flat washers, star lock washers and nuts at this point just to see how it goes together and fits, but these will come out to install coax terminals so don’t tighten much.



11. Cut four 1-1/2” lengths of 1/8” thick x ½” wide aluminum stock, and after installing 3/8” metal clamps around the outer ends of the driven elements, align and mark and drill 3/16” holes in both ends of the stock to make shorting bars for the ends of the folded dipole. Assemble the bars using 10-32 x ½” screws, flat and lock washers and nuts, and tighten slightly, leaving room to slip 9 mm (3/8”) black plastic tips over the ends.


12. Slide a rubber-insulated 3/8” metal clamp over the middle of the longer folded dipole element.
13. Cut two ¾” lengths of ¾” aluminum angle to serve as mounting hardware for the clamp in the previous step.

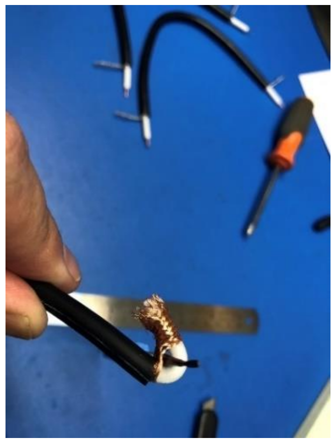
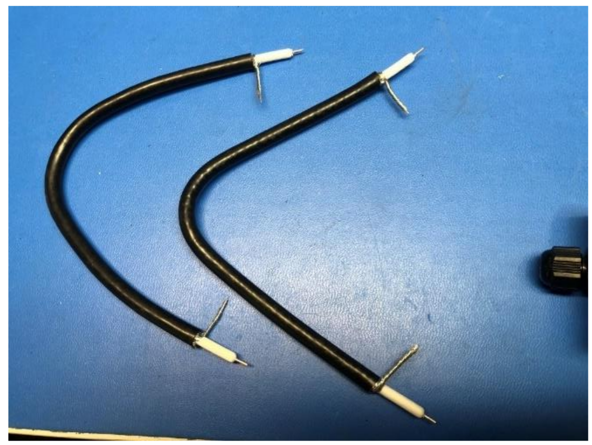
NOTE: When cutting any aluminum material, but *especially* small/short pieces, be sure to firmly secure the material on both sides of the cut. The image below depicts what will reliably happen if you don’t – about the time I had this short end-piece of aluminum angle cut from a longer length of stock the blade of the saw grabbed and ripped this piece off and sent it flying across the shop at very high speed. ALWAYS WEAR A FACE SHIELD, stand out of the line with the cutting blade and be aware of where your body is in relation to the potential path of any shrapnel. Try not to work with power tools when you are alone – just in case.

14. Assemble the ¾” angle with the 3/8” insulated clamp using 10-32 ½” screws, washers, nuts as depicted in the images. If you wish, you can mount the insulated clamp using a 10-32 x 1-1/4” screw through the feedline coax end mounting hole of the junction box, secure to the junction box with a flat washer and nut, allow ¾” inches of space that will be consumed by the square antenna mask, and mount the insulated clamp as seen the in picture below – again, just to see how things fit together, which way the clamp needs to be turned to line up the folded dipole elements, etc. We will disassemble this and mount the box and driven elements to the antenna mast permanently when we’re a little further along.

4:1 Coaxial Balun and Feedline Construction

At this point we're ready to build and assemble the 4:1 coaxial baluns and feedline coax into the junction box.

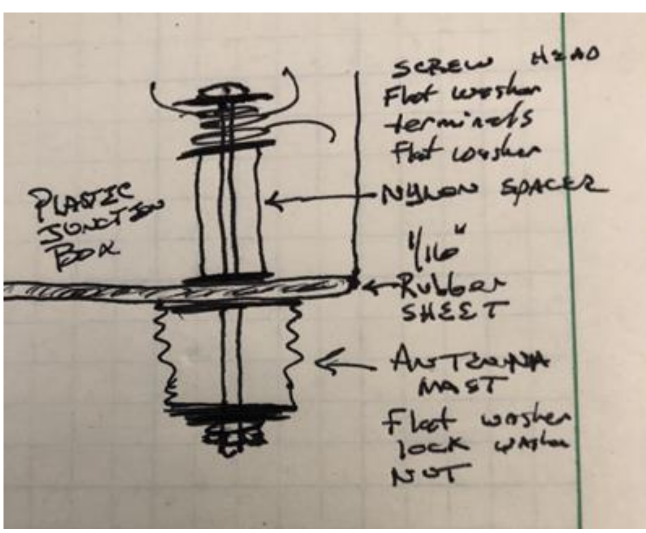
1. Using a small knife or stripping tool, cut away 1-1/4" of outer braid and ¼" of inner conductor insulation from the proper lengths of RG-6 (or RG-8X foam) coax (279 mm, for this 435 MHz implementation). Loosen the outer braid by pushing it up a bit, bend into a loop, and use a pointed tool slipped between the braid and center insulator to pull the center out of the braid. Then twist the braid together to form a separate conductor at a right-angle to the coax.

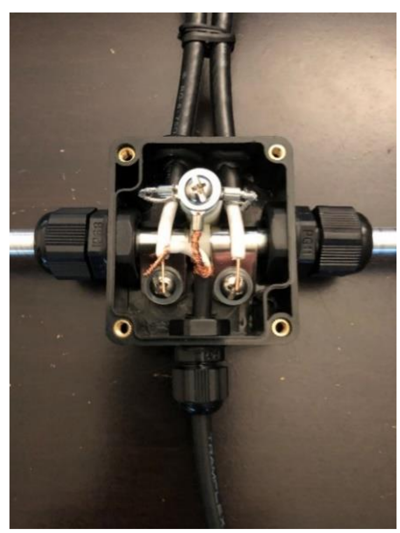




2. Prepare one end of the RG-8X foam feedline in like fashion as the RG-6, leaving a ~1" outer braid and 1-1/4" center conductor with ¼" of the insulation stripped off.

3. Push each end of the 4:1 balun coax through the rubber grommets on the junction box, and the RG-8X coax through the PG-7 cable gland. Crimp and solder a round terminal connector to each of the coax and center conductor ends (six terminals total).

4. Assemble a braid ground connector support using a 10-32 x 2-1/4" screw, flat washers, and ½" nylon spacer as seen in the hand drawing. Run the screw through a flat washer, then the three coax braid terminals, another flat washer, a ½" nylon spacer, and through the bottom of the junction box (mounting hole nearest the two ½" grommets). This screw is one of two used to mount the junction box to the antenna mast.

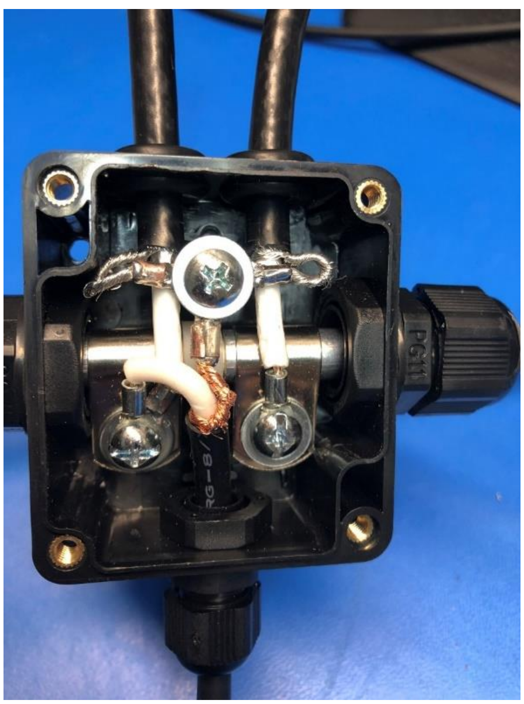




5. Route the feedline center conductor and its terminal around and push a 10-32 x ½” screw through it and one of the 4:1 balun coax terminals and secure to a 3/8” metal clamp with flat & lock washers and a nut. Secure the 2nd end of the 4:1 balun coax to the other 3/8” metal clamp on the other driven element. See pics below. Make sure the outer braid of the feeline coax is well separated / insulated from the driven elements and routed over the center of the nylon spacer. It may be prudent to place a small piece of 1/16” rubber sheet between the coax braid and the driven elements area. Tighten the driven element clamps, but only snug the ground mounting screw with a place-holder nut until ready to mount on the antenna mast.

6. Cut the feeline coax for each junction box to an appropriate length for your implementation and mount a N-type connector on the other end (see [Attaching RG-8X Foam Coax to N-Type Connectors]). **When cutting these feedlines to length, consider the difference in distance between where the driven element junction boxes will be mounted on the antenna mast, and add that distance (corrected for the velocity factor of the feedline coax) to the driven element that will be ‘forward’.** For example, if the driven element for the vertical array is 60 mm forward of the horizontal driven element, and you’re using RG-8X Foam coax with a velocity factor of .82, then add (60 mm x .82 = 49.2 =) 49 mm to length of the feedline coax for the vertical array. The idea is that from the coax feed points the two antennas will be electrically equivalent in distance in terms of the phase of the radiated signal.

   These images depict the completed connections within the junction boxes for 435 MHz driven element solutions. The 146 MHz solutions are identical except for the length of the 4:1 coax baluns. Note that the braid grounding connection screw also mounts the junction box to the antenna mast; the other mounting screw (10-32 x 1-1/4”) isn’t visible under the feedline coax - you can push the coax aside far enough to tighten the screw when the time comes.

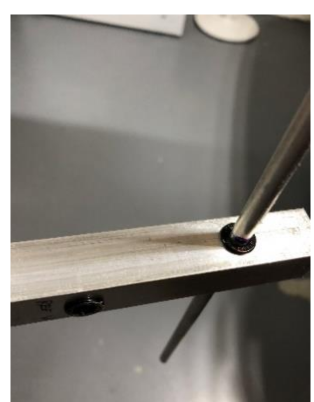


Passive Elements

Preparing and assembling the passive elements – reflector and directors – into the antenna mast is relatively straightforward, with the only significant challenge being the need for accurate measurements, and to take care not to drill holes in the wrong plane for mounting the junction boxes and antenna mast to crossbeam supports.

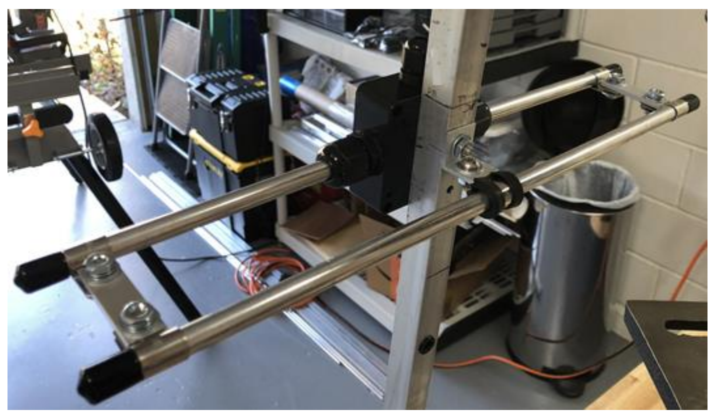
1. Carefully measure and cut the elements for the 146 MHz and 435 MHz arrays out of ¼” aluminum rod to the appropriate lengths for the reflectors and directors. For the 435 MHz elements, tend to err on the side of a bit too long (if anything) and grind down as needed.
2. Use a sharpie to mark each element with an indication of where it goes in the array – REF, D1, D2, etc. – in case they get mixed up.
3. Measure and mark the middle and about ½” on either side of middle on each element with a fat Blue sharpie so they’re easy to see – these outside marks will just be visible on either side of the plastic insulators that go through the antenna mast to guide and ease the centering of each element through the mast.

4. Measure, mark, center punch, and re-measure – then drill ¼” holes in the antenna mast for the reflectors and directors in each plane (horizontal and vertical).
5. Re-measure to ensure the holes are in the right place and reasonably centered in the mast width. Then re-drill those holes to 3/8”.
6. Insert the plastic feed-through insulators into each hole. Experiment with inserting a passive element through the insulators, but I recommend not installing the passive elements until further along in the project as they just get in the way of other activities and might get bent in the process.



7. Mark the locations of each hole as V(ertical) or H(orizontal) and it's designation: REF, D1, D2, etc. on one side of the mast.

8. If you need to extend the ¾" square aluminum mast beyond six feet, cut a 6" length of 5/8" OD round aluminum tubing and the additional length of square mast that you need and join them with 10-32 x 1" screws – I used 2 per plane (horizontal & vertical) for a total of 4 – two on each end. Take care to properly align the mast sides when drilling – this is easier if you drill the holes in the masts first, and then drill through the round tubing with the two masts and round aluminum tubing all put together and secured on top of the drill press platform. After drilling through one mast and tubing end, insert a screw in the hole to keep the round tubing from turning when the additional holes are drilled.
9. Mark and drill the holes for mounting the driven element junction boxes. Take care to get the orientation correct – the junction box mounting holes will be drilled 90 degrees turned from the orientation of the driven elements.
10. Install the driven element junction boxes, taking care to note the orientation and routing of the 4:1 balun coax – one balun will need to point to the front of the antenna, the other towards the rear, and may be looped around a passive element. The feedline coax will need to be routed directly towards the back of the antenna from one box or looped around and routed towards the back of the antenna from the other. Secure the balun and feedline coax to the mast in a few places with ty-wraps (not too tight).



11. As an optional step, slide the ¼" black plastic ends onto the passive elements. These don't lend any technical advantage, but I think it makes the antenna look more professional and can help avoid cuts or more serious damage if you accidentally poke your skin or eye with the end of a passive element.
12. Insert ¾" black plastic caps on both ends of the antenna masts to help keep water out.

Mounting the Antennas on the Crossbeam

The antennas are mounted on an eight foot hollow fiberglass cross-beam that goes through the elevation rotator portion of a Yaesu G-5500DC azimuth/elevation rotator system.

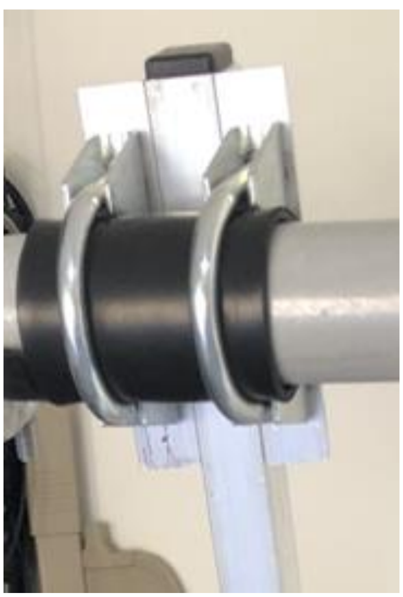
1. After you have attached the driven element junction boxes to the antenna mast and installed all the passive elements, support the feedline such that it doesn't affect the balance of the antenna to any great extent, and then find the point on the antenna mast where the center of gravity resides – where the antenna will balance on the edge of your finger. Identify and mark a location as near to that point as possible where you can install two 4" lengths of ¾" aluminum angle to serve as brackets for mounting the antenna to the fiberglass crossbeam using a couple of 1-3/4" muffler clamps.

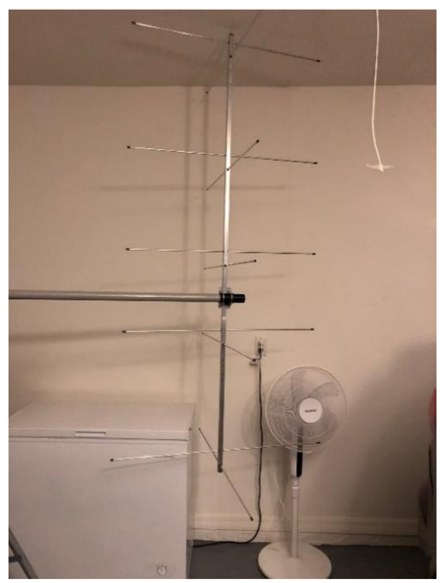
2. Cut the 4" lengths of ¾" angle (two per antenna mast), and mark/drill the brackets to accommodate the muffler clamps on one edge (staying a bit outside of center to allow room for the muffler clamp nuts to reside inside the angle). Then mark & drill holes through the other side of the angle and the antenna mast for mounting the brackets to the mast. I apologize that I didn't take any close-up pictures of this area before putting my antennas up.

3. Mount the antenna brackets to the antenna mast with 1-1/4" screws/flat & lock washers/nuts.

4. Cut two 3" x 5-1/8" pieces out of 1/8" rubber sheet. If you're mounting two antennas, you'll need four.

   Attach the antenna mast to the round hollow fiberglass crossbeam with two 1-3/4" muffler clamps, inserting the 1/8" rubber sheet between the round parts of the muffler clamps and the fiberglass crossbeam. This will allow you to tighten down the clamps enough to accomplish a good grip on the crossbeam so that the antenna won't slip, without having to tighten so much that you risk crushing the hollow fiberglass. The picture on the left below illustrates the use of the rubber sheeting, but this image is of the feedline support mast – the mounted 2M antennas are depicted on the right, minus the driven elements.



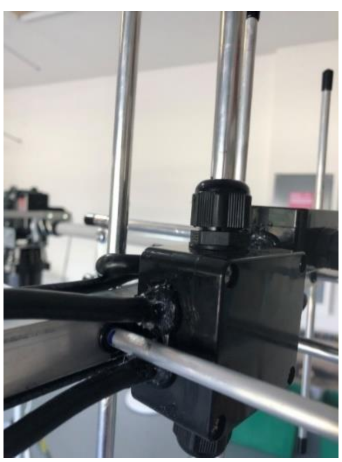


5. Assuming you are routing the feedline coax to the back of the antenna mast, measure the length from the crossbeam to the end of the back of the antenna, add 4", and cut a piece of ¾" square mast to that length. Insert ¾" black plastic caps on both ends. This is going to serve as a feedline support mast.

6. Build two more antenna mounting brackets out of ¾" aluminum angle, mark and drill the mounting holes, and attach the mounting brackets to the feedline support mast.
7. Cut a 4" length of 1/16" x ¾" flat aluminum and drill two holes for mounting the flat strip to the ¾" feedline support mast, leaving 1-1/2" of the flat strip sticking out beyond the end of the support mast.
8. Drill a 1/8" hole in the middle of the protruding end of the ¾" flat aluminum. This will be used for mounting a couple of plastic clamps to secure the feedlines to the feedline support mast – see the pics.
9. Attach the feedline support mast to the fiberglass crossbeam in the same fashion as was used for the antennas. It should be mounted close to the elevation rotator and in the same plane as the antenna mast.
10. Route the two coax feedlines around the far side of the back reflector, secure to the antenna mast with a ty-wrap, and then route them to the feedline support mast and secure with two plastic cable clamps (Lowes).



11. Rotate the antenna system so that you can visually inspect and align the mounting of the antenna mast, feedline support mast, and the elements with a known elevation angle for the rotator - straight up should be 90 degrees, and at 0 or 180 degrees you can visually sight down the antenna, and everything looks square.
12. Before putting the antennas up in the air, I applied some Loctite clear silicone around the grommets where the 4:1 coax baluns enter to try to keep moisture out of the driven element connection boxes.
    Henkel 908570 2.7 oz Tub Clear Silicone Waterproof Sealant: https://www.amazon.com/dp/B0002BBX3U

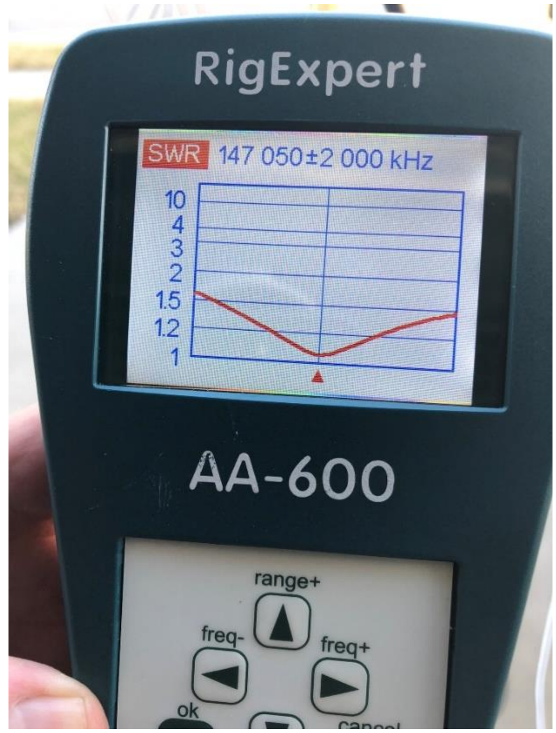


Testing The Antennas

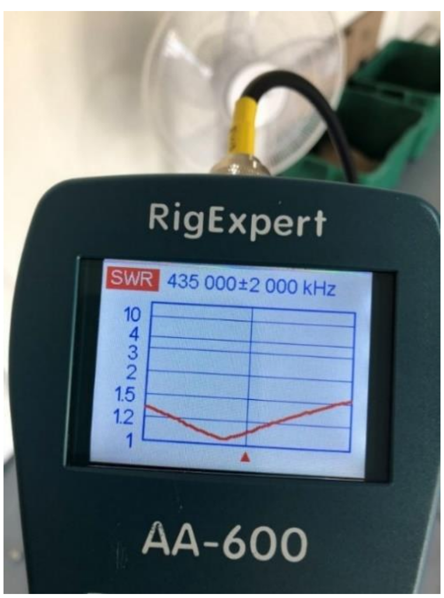
I didn't find a lot of useful articles on how to test VHF/UHF antennas for gain and polarization and knowing I didn't have the real estate and other antennas/test equipment that would likely be necessary, I resorted to moving my array outside of the garage, pointing it somewhat skyward, and taking SWR & reactance measurements with a RigExpert AA-600 antenna analyzer on the horizontal and vertical sections of the antennas – this was just to ensure the electrical connections seemed correct and the antenna exhibited something near expected SWR parameters. The results of this testing were acceptable, except for cutting some longer elements for the vertical section of the 435 MHz antenna to improve the SWR, so I didn't pursue this effort further.

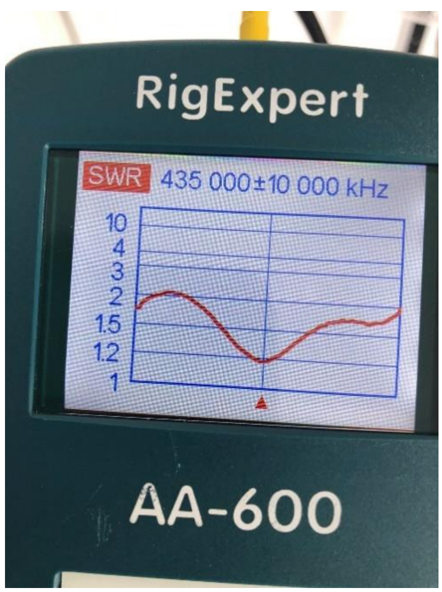
The following images are of on-the-ground testing of the antennas just after the build process was completed.

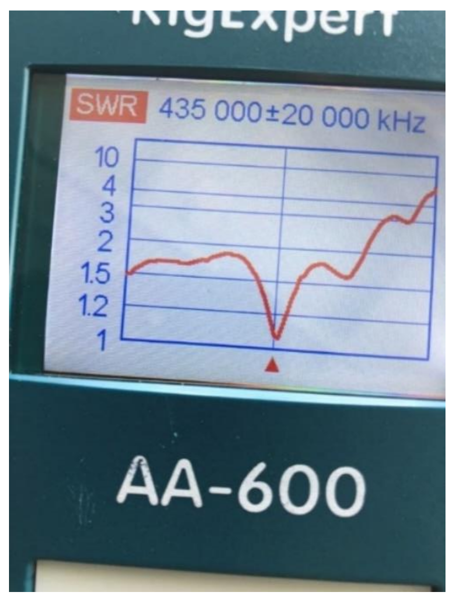
The SWR on the 146 vertical array was minimal at 147.05 MHz, and less than 2:1 across the band – not centered on the 146 MHz portion for satellite work, but I was OK with that given that I intended to use these antennas to increase my terrestrial reach as well and the SWR was acceptable regardless.



The SWR on the horizontal 435 MHz array was acceptable for satellite use, but intial measurements of the vertical part of the array showed minimal SWR at several frequencies quite a bit higher than desired. I cut 3 new elements 5 mm longer than the design specs to replace the reflector and D1/D2 directors, and rotated the longer elements to replace shorter ones along the rest of the array and got an SWR I was happy with.







Installing the Antennas

The satellite antennas and az/el rotators are supported by approximately 16 feet of 1-1/2" steel fence pole (a 10' + 6' length connected by a coupler further down). This is high enough to clear the roof but still keep the antenna hidden behind the center peak of the hip roof and not visible from the street to hopefully avoid HOA issues (I have understanding/accommodating neightbors)(so far). The two grey polarization control relay boxes can be seen mounted to the mast – one for 146, one for 435 MHz. The two coaxes that feed each (vertical & horizontal) antenna are routed back and behind the reflectors and then towards the middle of the array, supported by feedline support mast attached to the fiberglass cross-beam.

The two coaxes are secured to the end of the separation beam with two ¼"plastic clamps, and the appropriate length of coax is allowed to droop such that the antennas can be rotated through their entire range of travel without getting hung up on anything. This took a bit of trial-and-error adjustment of coax lengths and attachment points (with TyWraps) on the mast – the right balance can be seen in the images.

The other antennas visible in the above picture are:

Left-hand pole attached to the eve - a small vertical for monitoring aircraft frequencies.

Middle pole: HDTV antenna pointed towards Orlando, topped by an Arrow OSJ 146/440 Open Stub J-Pole.

The wire seen extending from the satellite antenna mast clamp and off to the left is a 40-10 meter End-Fed Half-Wave fed from a 49:1 balun in the grey box barely visible just behind the mast under the eave of the roof. The insulator on the other end of the wire is attached to a rope that routes through a pulley mounted to a tree limb by a metal hook just large enough to go around the tree limb (for ease of mounting/dismounting with an extended pole versus having to climb the tree) and then drops toward the ground; there are several round concrete sprinkler guards attached to the end of the rope that serve as weights that keep the antenna wire taut but allow it it self-adjust when the wind blows. The wire is black and the rope is camoflauge and in front of trees, so this HF antenna system isn't terribly obvious in most lighting conditions.

The following are more views of the satellite antenna array from various vantage points. I love looking at this antenna system! And it's not just builder's pride; I enjoy looking at pics of other's satellite arrays as well (and especially the large EME arrays). There's just something 'spacey' about the whole thing that I find intriguing.

Outside Connections and Details

This outside image shows the routing of the various coax and control cables down the wall from the eaves, a drip loop, and on to the MFJ window feed-thru panel. The plastic rain guards were cut out from the bottom of a clear plastic storage container (cut + crack & several attempts – the brittle plastic doesn't lend itself to being cut easily). The ground braid is connected to a 4 foot copper ground rod driven into the ground next to the wall.

The coax and control cables are supported under the eaves by plastic cable clamps and machine screws screwed into the air-flow holes in the eaves.

Polarization Switching Relays

I initially thought I'd try to build a polarization switching solution myself, but I could not find any articles or ham-built solutions with significant detail and determining/sourcing relays was difficult as well – so I ended up purchasing a set of polarization switches from WiMo Antennas & Electronics (http://www.wimo.com) that would a) get the job done, and b) offer some educational opportunity.

VHF: https://www.wimo.com/en/18080
UHF: https://www.wimo.com/en/18082

These are working very satisfactorily, and after sneaking a peek under the covers I'm not in any hurry to try to duplicate the design.

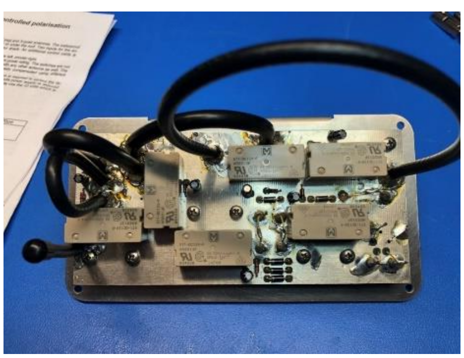
I wasn't sure how the polarization switching boxes were designed. I had assumed the use of relays and lengths of coax to achieve the needed phase offsets, but I wasn't sure what kind of relays were used, or if there was another method of doing this I wasn't aware of. An Internet search for RF relays was disappointing – nothing but surplus RF relays at ridiculous prices and dubious replication / replaceability if they were available at all.

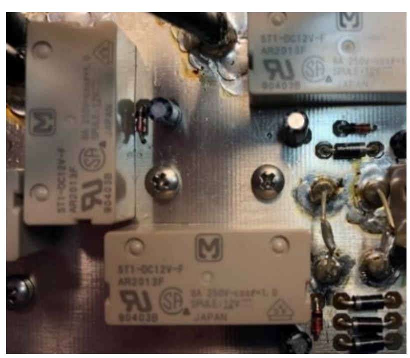
I had also assumed that PC-mounted relays on well-shielded boards were the ticket – but how do you determine which relay provides the needed power handling along with acceptable insertion loss & reactance characteristics?

So, of course, when the relays arrived, I took the covers off to find out how they worked – pics below.

I'm recording this information not with the intent of duplicating this product, but simply to understand how this was done in case I want to build any RF switching solutions of any kind in the future.

The relay used is a ST1-DC12V-F, DPST NO/NC with contacts rated at 8 Amps, readily available from DigiKey and other suppliers: https://www.digikey.com/en/products/detail/panasonic-electric-works/ST1-DC12V-F/2217934





You can tell which is the 146 MHz polarization switch (on the left in the pics below); the coax runs used to achieve the phase shifts are much longer than for the 435 MHz solution. These boxes work very well, and the price wasn't too bad.

Polarization Controller

There is a polarization relay controller for 146 MHz, and another for 435 MHz; I had to build the control box which has a rotary switch for both to allow setting polarization to vertical (off/default), horizontal, left-hand and right-hand circular polarization. Polarization is controlled by simply applying 12 VDC to the appropriate connector pin. Here's the parts list:

Eightwood Aluminum **Electronic Project Box** Enclosure Split Body Case DIY 4.72 x 3.82 x 1.57 inch (LxWxH)
https://www.amazon.com/dp/B010DHQPVW

SWITCH ROTARY 4POS 2.5A 125V – DigiKey - PART: CKN10614-ND - MFG : C&K / A10405RNZQ

mxuteuk 12pcs **12V LED Light Round Rocker Switch** Toggle SPST On-Off Switch 20A 3Blue + 3Green + 3Yellow + 3Red for Car Auto Boat KCD2-102N-2W-4C
https://www.amazon.com/dp/B07VNBTZBD

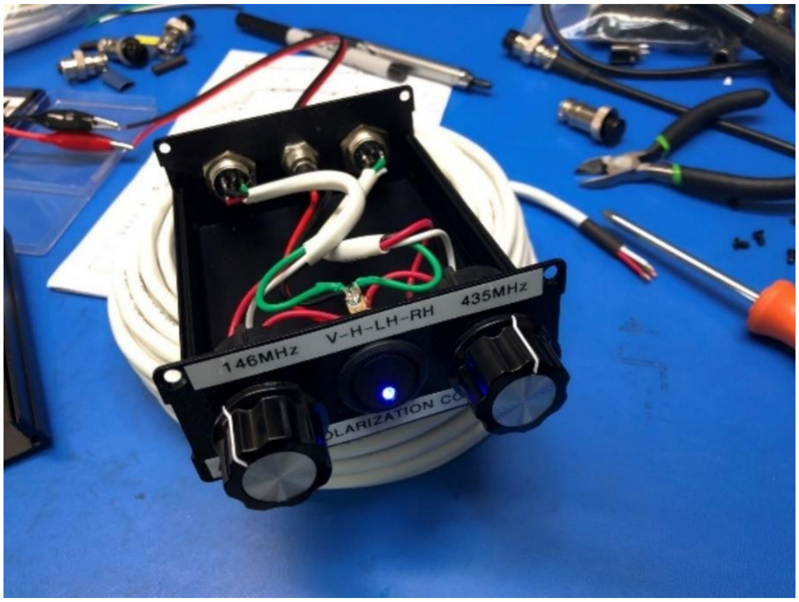
Lsgoodcare 30PCS 16mm **6 Pin Aviation Connector Plug Female Male** 5A with Aviation Caps, GX16-6Pin Metal Aviations Socket AC 200V
https://www.amazon.com/dp/B01GA0VI72

FPC **18/4 Stranded Conductor Cable 50ft** Wire for Access Alarm Control Unshielded 18 Gauge Security Burglar Station Wires
https://www.amazon.com/dp/B01MTCGJDQ

5.5 x 2.1 mm DC Power Jack Socket Threaded Female Panel Mount Connector Adapter with Dustproof Plug 6Pack
https://www.amazon.com/dp/B08SJM2G52

Taiss / 10pcs **Silver Tone Top Rotary Knobs** for 6.4mm / 0.25" Dia. Shaft 3590s Potentiometer, Switch Knob Top Diameter: 23mm Black A03-6.4mm
https://www.amazon.com/dp/B07F2CB3DC

Consult the 6-pin connector and relay control wiring diagrams in the documentation that comes with the relays to determine the polarization control box wiring; basically, you apply 12VDC to the appropriate pins to get horizontal, left-hand, and right-hand polarization; the default (no voltage) condition selects vertical polarization.

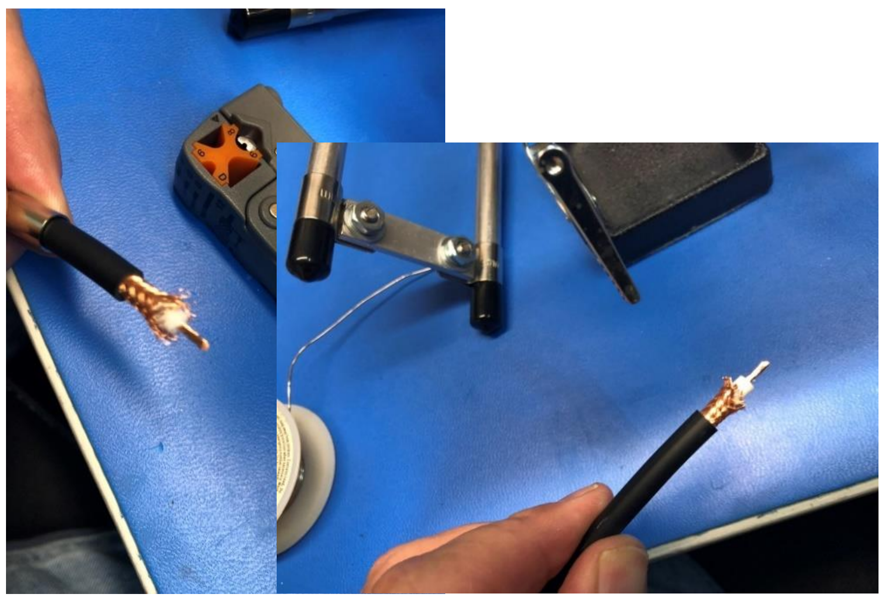


Attaching RG-8X Foam Coax to N-Type Connectors

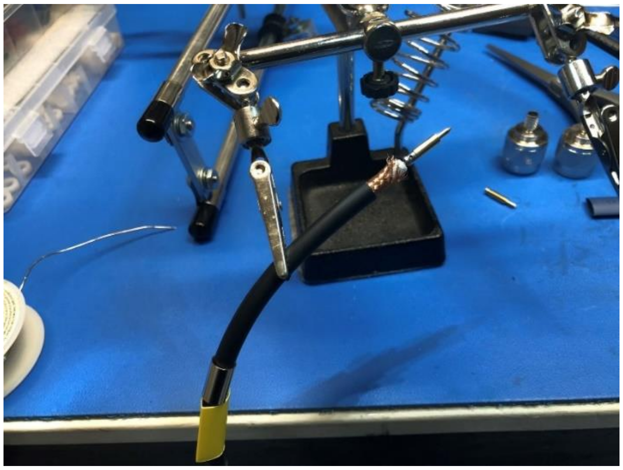
These are some pics and notes on attaching N-Type connectors to RG-8X Foam coax. I have found it very helpful to use a coax kit that includes a stripper tool and crimper with various sized crimp heads. You must experiment and adjust the stripper to get the depth of cut just right and learn where to place it on the coax to cut the correct length of braid and center insulation (just a turn and a half of the stripper around the coax is about right, usually) - but after that it's a snap to use and helps ensure professional, reliable results. ***Let me just state here: having the right tool(s) for any job makes a huge difference in the quality of the result, the ease of achieving and repeating it, and the relief and pride you'll experience from a job well done. Don't scrimp on tools.***

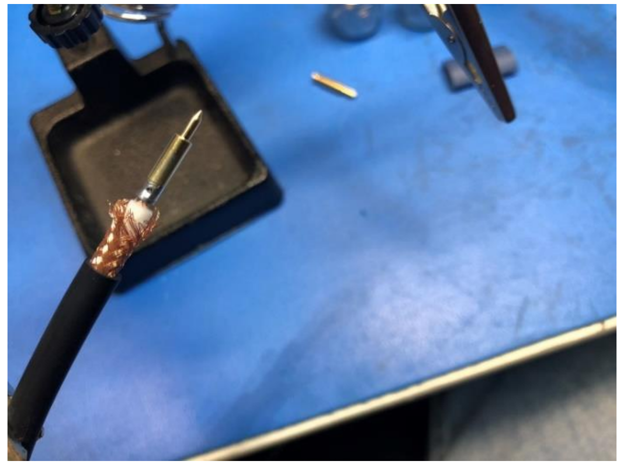
Remember to thread any heat-shrink (I like to seal and color-code my connectors) along with the sleeve that will be crimped over the coax braid onto the coax BEFORE starting the stripping/soldering/assembly process – otherwise you'll forget until it's too late and have to take things apart or do it over.

After using the stripper to cut the center insulation and score the outer protective covering over the braid, I remove the outer covering (if your stripper is set just right, you can just pull it off), then use a dentist's tool to lift the braid up and away from the center conductor insulation a bit – then use a pair of scissors to cut off about 1/8" so the braid is just a bit shorter than the end of the center insulation to help avoid a braid-to-center short.



Slide the center pin over the center conductor of the coax and ensure the length is correct – the pin should sit right up against or very near the center conductor insulation with sufficient wire protruding into the pin to ensure a solid physical and soldered connection. Using something to hold the coax steady, turn the pin so that you can see and reach the little solder hole. Using a fairly hot (650 degrees or so) and slightly tinned soldering iron, heat the pin from underneath and poke the solder into the hole. When the solder starts to flow, a reasonably small amount will be drawn into the center conductor by capillary action and then the hole will fill – don't over solder this connection such that a blob is sitting around the center pin; re-heat and 'flick' the extra solder away if needed (but don't let the pin fly off). A sufficiently hot iron and a little practice will allow you to make this solder connection quickly, correctly, and with little or no melting of the center conductor insulation.





When the coax has cooled, inspect to make sure no braid is or can get near the center conductor, then insert the center pin into the back of the N-connector and push the connector onto the coax such that the outer braid rides up and over the connector's shield section protrusion. When the coax braid is flush with the back of the connector, ensure that the tip of the center pin reaches to the end of the metal inner shield and is straight. Slide the metal sleeve over the braid such that there is a snug fit of the sleeve over the coax braid and connector body. If needed use a pair of pliar jaws turned sideways to help push the sleeve up until it rests all the way up against the connector body. After another inspection to ensure everything looks to be where it's supposed to be (coax braid & sleeve, center pin), use the crimper tool to crimp the sleeve to the connector body (I usually crimp twice). Finally, slide the heat shrink into position and heat it with an hot air gun or hair dryer until it's shrunk and sealed the connector sleeve.

Finally, test the conductivity of the center pin and shield with a VOM, and check that there are no shorts.

ConnectoRF Heavy Duty Quick Change Ratchet Crimping Tool Kit for Coaxial Cable With Crimper Cutter Stripper and 4 Die Sets
https://www.amazon.com/gp/product/B076TN118K

MOOKEERF **N Male Crimp Connector**, N Male Plug Adapter RF N-Type Connector **for RG8X/LMR240** Coax Cable(Pack of 10) -
https://www.amazon.com/gp/product/B099J81QWT

Preamps and Switching

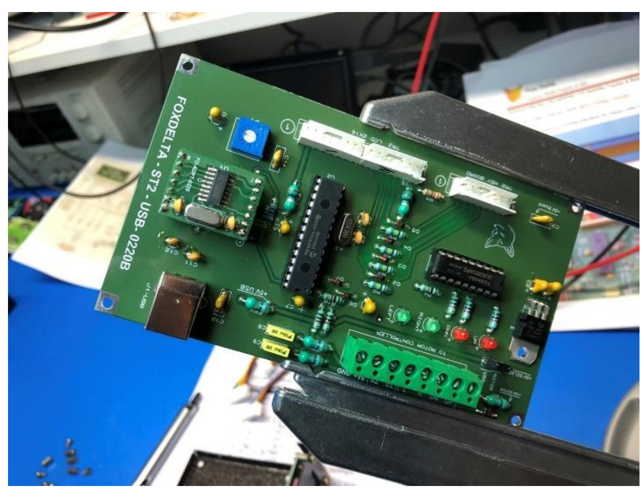
I didn’t find much in the way of discussions and examples of building switching preamps for VHF/UHF satellite work on the web; I recall there was some material in some of the antenna books. At this stage of the project I wasn’t sure if I needed preamps, and the only commercial source I found that received high marks in reviews no longer sells these products:

High Performance 160 Watt Mast Mounted Amateur Preamplifiers
http://www.advancedreceiver.com/page10.html

I will do more research on preamps if I determine I need them after getting this solution up and working.

Rotator control software

I initially purchased and assembled the Fox Delta ST2-0417 Satellite Antenna Controller for use with the Yaesu G-5500 rotators: https://www.foxdelta.com/products/st2-0417.htm



I started my career doing component-level electronics repair and alignments on military and commercial radio and satellite equipment, as well as building a lot of Heathkit gear – but my path eventually led to computers, software, and data analytics. At the bench, building this controller took me back to a happy place.

I'm going to start some robotics projects soon that should let me blend electronics and sensors along with my software and data skills in a fun and rewarding way.

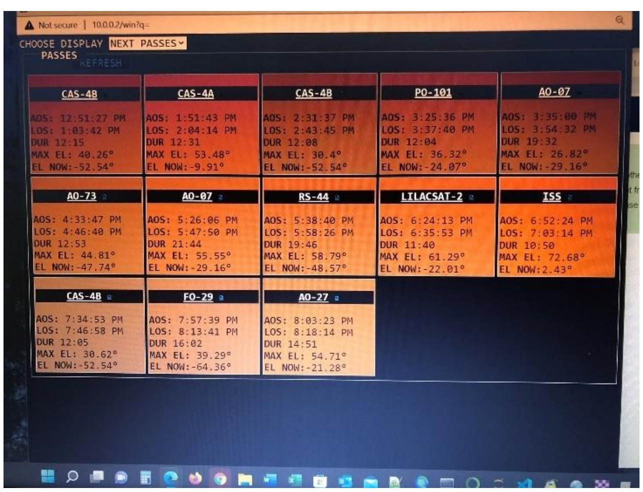
CSN Technologies S.A.T. Satellite Controller

I had initially thought I would use Ham Radio Deluxe for satellite antenna tracking and rotator control, but my entry-level experience with HRD hadn't been very satisfactory – it just seemed like too much complexity and wasn't very intuitive. If I was a dedicated contester I imagine the integration of radio controls, digital modes, logging, and all the other consolidated features HRD provides would be a boon – but I prefer simplicity when possible, so I abandoned HRD, at least for now, along with trying to use the Fox Delta controller with it.

During the final stages of the antenna build, I discovered the S.A.T. (Self-Contained Antenna Tracker) by CSN Technologies, which was advertised as:

"A self contained antenna rotator and radio controller. Natively controls Icom radios, Yaesu rotators and can interface with PSTRotator. The S.A.T. works with any modern web browser on any device. No software, no apps and no com ports."

The S.A.T. group page on Facebook was giving it very positive reviews and comments, so I decided to try it as I was interested in a fully self-contained solution that didn't require patching together various hardware and software solutions, and the web-based interface looked clean and intuitive. So far, I've been very impressed and satisfied with this solution and have no interest in trying other solutions: http://www.igatemini.com/sat



The S.A.T. controller allows you to open a 'Window' and select 'Next Passes' – clicking Refresh provides a list of upcoming satellite passes, with AOS/EOS times, pass duration, maximum, and current elevations. Clicking on a satellite name link activates the controller to load the information for that satellite, show it's path over the globe in the Map view, it's positional information in the Polar and Ground views, and provides a list of clickable radio modes in the Radio view. Clicking on a mode activates the radio controls to set the frequencies and modes and start the doppler shift adjustments – couldn't be easier!

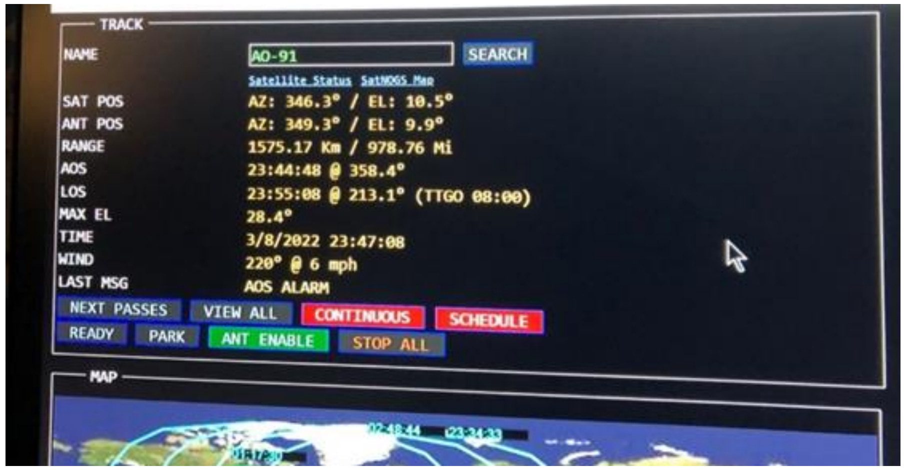
This is a view of the main CSN Technologies S.A.T. satellite controller screen, which manages tracking the satellites, pointing the antennas, tuning the radios, and adjusting for doppler shifts during a satellite pass – significantly reducing operator workload and allowing you to focus on simply tuning around the satellite passband and talking to other hams. The S.A.T. display (within a computer browser display) includes a world map, tracking, and various other views described along with the following images – all from a little box!

The world **map** view shows the current satellite position (Yellow triangle) as compared to your station location (Yellow ‘+’ over Florida for me), a green circle around the satellite depicting the range where it should be heard/accessible, and the (selectable) next 3 passes around the Earth in Blue.

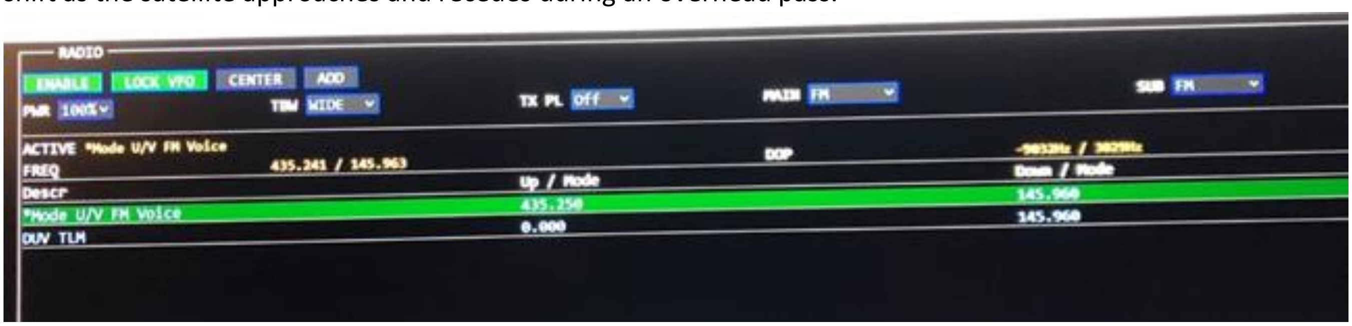
The satellite location is updated in near-real-time (every several seconds).

You can see from the range circle that the possible range of use of this satellite covers most of the US.

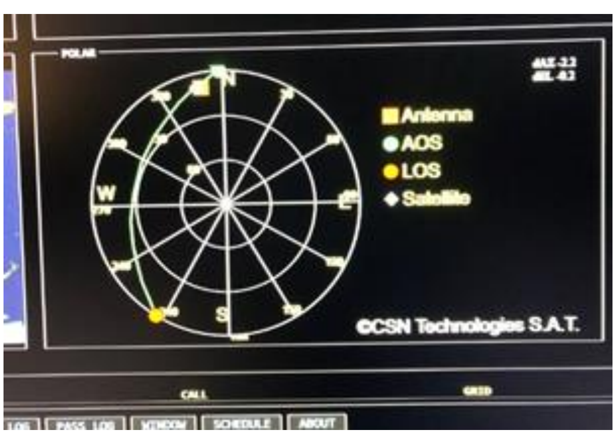
The **Track** view shows satellite tracking data. It displays the satellite which has been selected, current satellite and antenna azimuth and elevations, satellite range in kilometers and miles, the AOS (Acquisition of Signal) and LOS (Loss of Signal) times, degrees, and TTGO (Time To Go), as well as the expected maximum 'elevation' above the Earth's horizon the satellite will achieve on this pass. If the satellite will not be 'rising' very high above the horizon the signal strength and usable access time will be reduced.

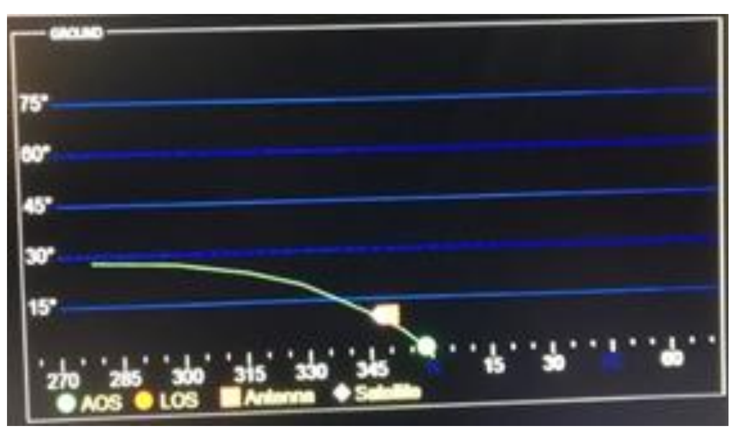


The **Radio** view displays the various 'transponders' (repeater channels, beacons, etc.) available for the selected satellite. Clicking on one of the entries causes the S.A.T. controller to configure the ICOM-9700 radio for the appropriate uplink and downlink frequencies, modulation mode (FM or Upper/Lower Single Sideband (SSB) for voice, or several digital/beacon modes), and any FM tone frequencies needed. The controller also shifts the uplink and downlink frequencies periodically based on calculated offsets to accommodate the effects of doppler shift as the satellite approaches and recedes during an overhead pass.



The **Polar** and **Ground** track views show the satellites position from the viewpoint of how it would pass overhead (**Polar** view) or if viewed from the side as it rises and sets above the horizon (**Ground** view). These are useful for establishing the satellite's relative position (and accessibility) to your location. The satellite is again represented as a triangle, and the antenna position as a square; you can watch the antenna positioning follow the satellite as it tracks it over the Earth.





Working Satellites

My Satellite Station

This is the AK2W Amateur Radio Station as of 3/9/2022, ready to work satellites with the new antenna system!

The left-hand side of the station is mostly for HF work, consisting of an Icom 7300 (not powered on in this view), a MFJ Versa-Tuner II, and a SignalLink USB for digital modes. There is also a Yaesu FT-857D (HF, VHF, UHF) that can serve as a back-up radio for either side of the station – I typically have the VHF/UHF side connected to a small vertical and leave this radio on to listen to aircraft communications around the local airport in Deland.

Also visible on the left is a set of (Blue-Green) antenna switches for routing the 40-10 EFHW HF antenna between the Icom and Yaesu radios, as well as switching the VHF/UHF side of the FT-857D between the small vertical and a path to the 2m/440 J-Pole (via another switch on the right-hand side).

There are two toggle switches on the middle shelf support for switching the Vibroplex keyer between the radios, as well as a switch that turns on DC for the meter lights in the Versa-Tuner and the SWR/PWR meters.

Just below the weather station display is a small PowerWerx DC power meter and analyzer for monitoring DC voltage and amperage for the station. The entire station is run on 13.8 VDC supplied by a 50 Ah Lithium Iron Phosphate (LiFePO4) battery managed by a BuddiPole solar charge controller; the battery is trickle-charged from a wall socket but can be connected to my Jeep battery and/or a set of solar panels during longer power outages. The laptop, monitors, and anything else needing 120VAC are powered from a 150W Samlex pure sine wave inverter running on battery DC as well. I intend to add a redundant battery/charge controller/inverter soon.

This is the VHF/UHF side of the station, consisting of an Icom 9700 VHF/UHF transceiver, MFJ SWR/PWR meters for VHF/UHF, and a CSN Technologies S.A.T. satellite controller controlling the Yaesu G-5500DC azimuth/elevation rotator controller.

The small vertical box with black knobs between the SWR/PWR meters and the S.A.T. controller controls the polarization of the VHF & UHF cross-Yagis between vertical (default/power off), horizontal, left-hand, and right-hand circular polarization, which does seem to make quite a difference on some satellite passes. The MFJ SWR/PWR meter on the top left is in-line with a J-Pole vertical for 2m/440, which is used for local repeater work.

The bottom two antenna switches on the right allow switching between the cross-Yagi satellite antennas and the diplexer-driven J-Pole vertical for the VHF & UHF bands from the IC-9700; the top switch selects feeding the J-Pole from the ICOM-9700 (via the diplexer) or the Yaesu FT-957D HF/VHF/UHF transceiver (not visible on left).

The little 'remote' with all the colored buttons just to the right of the S.A.T. controller and above the antenna switches controls LED lighting strips that run under the top shelf of the station to light all the equipment and controls. Another strip runs under the middle of the tabletop above the keyboard/mouse drawer so you can see to type. In the case of a power outage, this station remains fully operational, and you can see what you're doing. The lighting level and color is adjustable.

HitLights LED Strip Lights 3 Pre-Cut 12Inch/36Inch LED Light Strip Flexible Color Changing 5050 LED Accent Kit with RF Remote, Power Supply, and Connectors: https://www.amazon.com/gp/product/B07NWFVRY4

4pcs black 1M 3.28ft 4 Color RGB Extension Cable LED Strip Connector Extension Cable for SMD 5050 3528 2835 RGB LED Light Strip (4 PCS): https://www.amazon.com/gp/product/B072MLLF3P

Notes on Working Satellites

I finished building and testing the antennas, mounted them on the mast behind the house, and completed the control and coaxial cabling on March 8, 2022. Now it was time to work some amateur satellites! The first step is knowing what satellites are available, and their uplink/downlink frequencies. The S.A.T. controller has an internal list of all the satellites, but you can select your preferred birds from a list.

Here's some satellite lists and reference material:

AMSAT Live Oscar Satellite Status Page
https://www.amsat.org/status/?fbclid=IwAR3eknj19JLLn6s3htu3HcJR6HwFC7fb-GqaU4yf2-GTVN-GI1pTUJRJD-I

AMSAT list of Communications Satellites
https://www.amsat.org/two-way-satellites/

AMSAT Linear Satellite Frequency Summary
https://www.amsat.org/linear-satellite-frequency-summary/

JE9PEL Satellite Frequency List – very comprehensive list of all kinds of satellites
http://www.ne.jp/asahi/hamradio/je9pel/satslist.htm

Get Started with Amateur Satellites
https://stationproject.blog/wp-content/uploads/2020/06/Get-Started-with-Amateur-Satellites-v2.pdf

ARISS – Amateur Radio on the International Space Station
https://www.ariss.org/

These are a few notes about working satellites from what I've learned so far; I still have much more to learn, and if you spot any glaring errors in my comments or processes, constructive criticism is always appreciated:

1. I configured several options in the S.A.T. controller: beep when a selected satellite is about to come into range, where to 'park' the antennas after a pass or clicking the park button, and my list of favorite satellites (so the Next Passes list isn't cluttered with unusable birds). See the manual for instructions on these and other options you may want.

2. You will want to use headphones for listening so that you don't get a feedback loop from your own transmitted signal coming back down on the receive side.
3. You'll also want to wire a footswitch into the Aux connector of your transceiver so you can control transmit with your foot and not tie up one of your hands during a pass. I like to tune with one hand and do written notes with the other.
4. After selecting the satellite from the Next Passes list and the transponder you want to use (usually the FM or Linear transponders), the controller will select the appropriate bands and modes on the Icom-9700 and start making frequency adjustments for doppler shifts, even before the satellite is over the horizon. Now is a good time to note the up & downlink frequencies and modes, the time, and any other preparations for logging as the passes usually don't last too long and you'll be too busy to do these things during the pass.
5. When possible, I select the CW beacon frequency before the voice transponder so I can listen for the beacon to know when the satellite is coming into range, and to set my receive antenna polarization for optimal downlink signal level. I will then click the listed voice transponder on the S.A.T. controller and start listening.
6. When I'm sure the satellite is close enough that I should be able to communicate through it (strong CW beacon and/or hearing other hams on the transponder) I tune to an unused part of the passband, key the transmitter and start making short 'Test' or 'CQ' calls, and tune the RIT on the receive radio until I hear my voice, and then fine tune until the voice frequency is pretty close to correct. I'll also switch antenna polarizations on the transmit side to determine the optimal setting and double-check the receive polarization. Only then do I start making short CQ calls: "CQ Satellite this is Alpha Kilo Two Whiskey – AK2W" and listen for a response or tune the passband for another ham with a clear signal.
   Note: RIT tuning seems to be a crucial element of properly aligning your station with transponder and doppler frequency shifts before trying to make contacts – otherwise other hams responding to your signal will always seem off-frequency and you'll chase each other up and down the band and never get it right.
7. I have found that my 6 elements on 2M, 11 elements on 435 is more than sufficient for a strong, clear signal during passes that are at relatively high elevations, and I've received quite a few good signal reports from contacts. I haven't had opportunity yet to explore the edges of my station's capabilities since I'm still honing my skills and don't have a lot of time to devote to my hobby daily. The nice thing about full-duplex satellite operation is that you can hear your own signal – you don't have to rely on interpretation and reporting from another operator (whose station capabilities vary) to determine how your station is operating.
8. Be aware of linear transponder passbands and don't transmit on top of beacon/telemetry channels.
9. I've observed that some satellite transponders will operate for a bit, then cut out, then come back – I don't know if this is a response to too strong a signal, or some other anomaly. I intend to start adjusting my transmit power in future passes to see if this makes a difference – I don't want to be responsible for adversely affecting the operation of the transponder to my and other's detriment.
10. Satellite operators seem to be a very friendly, helpful, elite group. I'm proud to now be amongst their numbers.

Next: EME

Sometimes I think I'd like to build an Earth-Moon-Earth antenna system – but I'll need more real estate and no HOA issues – maybe a bit further down the road. Hopefully someday we'll have amateur radio repeaters on the moon… better yet, let's get some permanently manned lunar colonies with amateur radio stations!

END