K3LR 160m 2024 Revisit

Greg Ordy, W8WWV

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Version 1.01

This note revisits the tuning of the K3LR 160m transmit array. The array is described in the ON4UN Lowband DXing book. The array is centered around a full size 160m quarter wavelength driven vertical antenna. The center vertical is surrounded by 4 parasitic verticals with slanted T top loading wires. All 5 verticals are located over extensive ground radial systems with literally miles and miles of radial wire. In the models used in this note a MININEC ground will be used with zero added series resistance.

The EZNEC Antenna View of the array is:

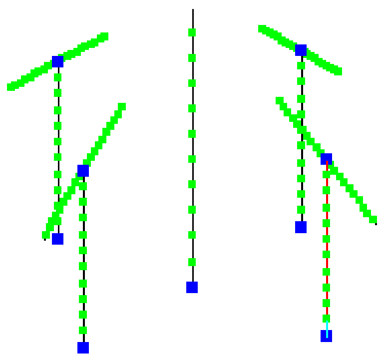


Figure 1 - EZNEC Antenna View of the Array

The T top loading wires run along support ropes that attach to the ground on one end and the top of the center full size vertical on the other end. With the top loading wire the parasitic verticals are electrically ¼ λ long even though physically shorter.

Each parasitic vertical is in one of three modes controlled by relays on the ground:

1. Floating (making it invisible on 160m)
2. Grounded (making it a parasitic director)
3. Grounded through a small inductor (making it a parasitic reflector)

With all 4 parasitic verticals floating the array is in omnidirectional mode.

A unidirectional mode with 4 direction choices is created by floating two side parasitic verticals while making the forward vertical a director and the rearward vertical a reflector. This means that the directional array mode is a 3 element end-fire array with two floating and invisible side verticals. For the purposes of modeling, with the two floating parasitic verticals removed, the array picture is:

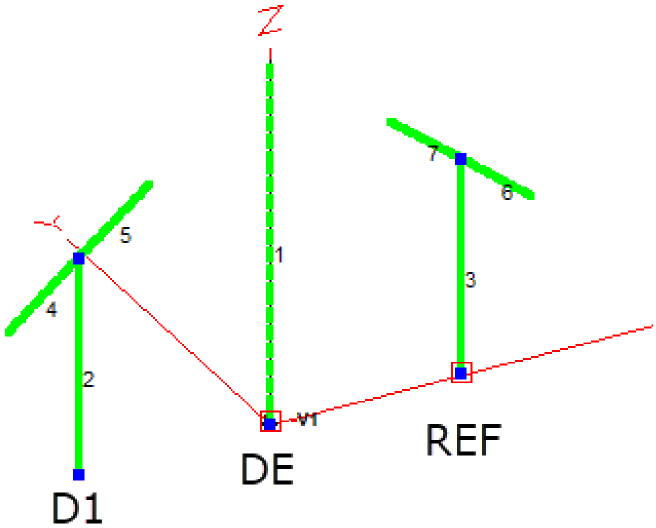


Figure 2 - Directional Array Model

With parasitic arrays like the Yagi, the tuning of the elements is usually specified by the physical length of the element. In this case it is more convenient to characterize the front and rear verticals by their resonant frequency when grounded as either a director or reflector. As expected, a director (D1 or DIR) resonates at a higher frequency and a reflector (REF) resonates at a lower frequency.

The earliest models I have of the array date back to 2007. Although the array comes up from time to time it's time to do a more detailed look at its tuning and a recently updated impedance matching scheme to 50 Ohms.

The four combinations that will be modeled are:

160m Array Tuning			
Mode	**Target Freq.**	**DIR Freq.**	**REF Freq.**
CW	1.822 MHz	1.904 MHz	1.800 MHz
CW	1.827 MHz	1.909 MHz	1.805 MHz
SSB	1.845 MHz	1.927 MHz	1.823 MHz
SSB	1.850 MHz	1.932 MHz	1.828 MHz

It is believed that these frequencies came from previous modeling. Unfortunately, the models can't be found, so it's time to do it again.

Tuning the Parasitics

The highest frequency parasitic is resonant at 1.932 MHz. I will adjust an isolated model parasitic to resonate on that frequency without any additional loading. Inductive loading will then be added at the base to arrive at all of the other needed frequencies. The table of needed frequencies and loading inductance values is:

Parasitic Tuning			
Target	**Parasitic Frequency**	**Inductance**	**Resistance**
1.822 MHz	REF 1.800 MHz	5.25 uH	22.05 Ω
1.827 MHz	REF 1.805 MHz	5.05 uH	22.21 Ω
1.845 MHz	REF 1.823 MHz	4.27 uH	22.80 Ω
1.850 MHz	REF 1.828 MHz	4.07 uH	22.96 Ω
1.822 MHz	DIR 1.904 MHz	1.05 uH	25.61 Ω
1.827 MHz	DIR 1.909 MHz	0.87 uH	25.79 Ω
1.845 MHz	DIR 1.927 MHz	0.20 uH	26.47 Ω
1.850 MHz	DIR 1.932 MHz	0.00 uH	26.65 Ω

Note that an array is composed of one director frequency and one reflector frequency. The pairs are highlighted with the same color background.

Using a model from several years ago as a starting point I had to reduce the length of the T top wire by about 1 foot on each end to raise the resonant frequency to 1.932 MHz. The impedance at the feed point is 26.65 – j 0.13 Ohms. The dimensions of the parasitic resonant at 1.932 MHz are:

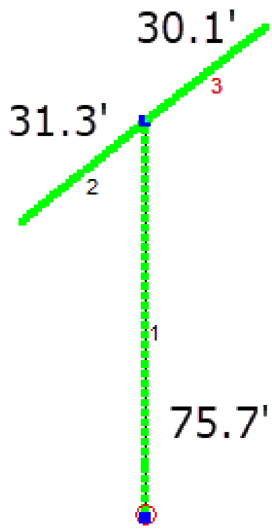


Figure 3 - 1.932 MHz Parasitic Dimensions

I then started adding inductance at the base to lower the resonant frequency until the reactance was zero. The resulting inductance and resistance at resonance are stored in the table.

The parasitic termination PCB that has been in use for a few years includes an inductor that is shown as **~ 4 uH**. The maximum value shown in the table is 5.25 uH. I suspect that having to remove 1 foot of wire from each end of the T top wire to push the unloaded resonance up to 1.932 MHz has required a bit more inductance to drag the lowest resonance down to 1.800 MHz. Whether this gap between modeled and measured is significant is not clear at this point.

The two different target frequency ranges correspond to best use in a CW contest and an SSB contest. The SSB targets are 23 KHz above the CW trargets.

1.822 MHz Target

The 1.822 MHz model has the REF at 1.800 MHz and the DIR at 1.904 MHz. With those settings the gain and F/B sweeps from 1.8 to 1.9 MHz are:

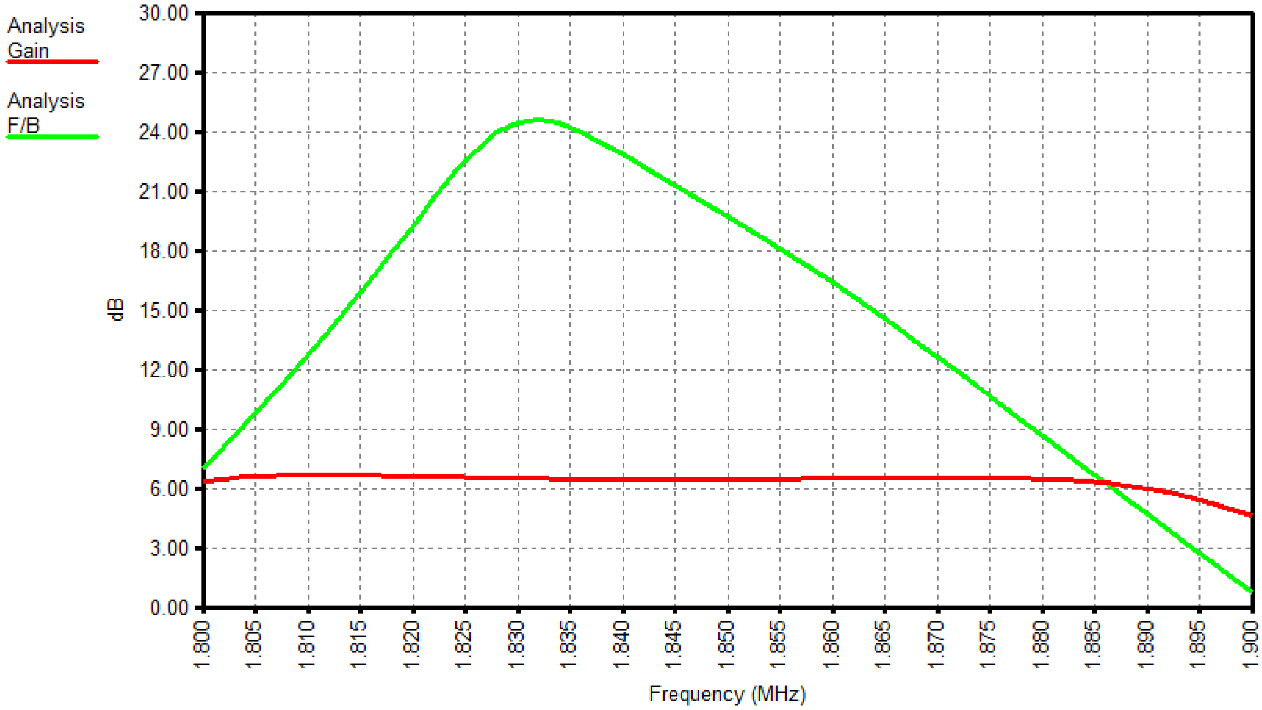


Figure 4 - 1.822 MHz Gain and F/B

Gain is the red trace and green is the F/B. The gain is close to flat, around 6.6 dBi maximum which happens around 1.812 MHz. F/B peaks at 24.7 dB around 1.832 MHz.

NOTE: when the gain is starting to dip on either end of the frequency span it is a sign that the array is going to reverse direction.

Typical Azimuth and Elevation Patterns

Using the maximum F/B frequency of 1.832 MHz the typical elevation pattern is:

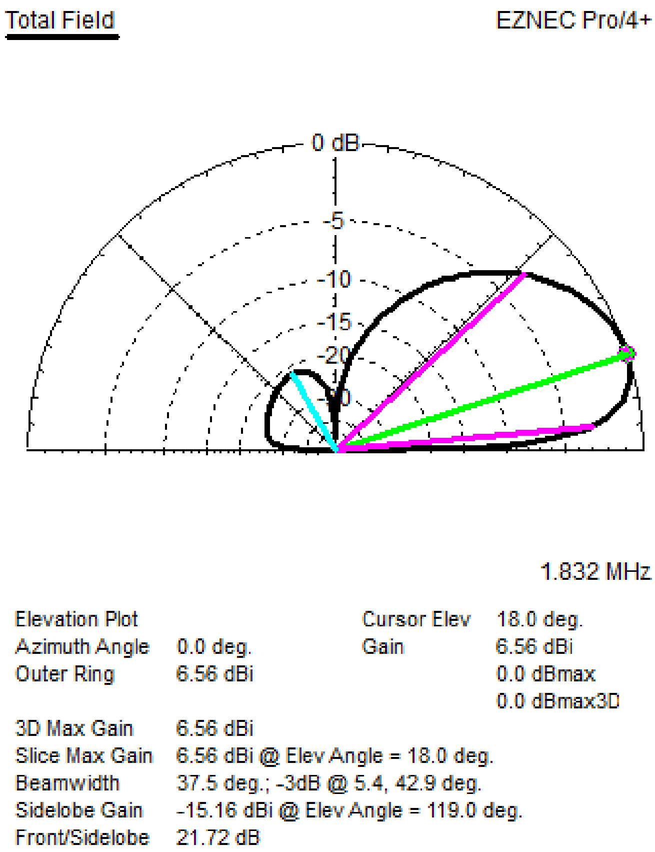


Figure 5 - Typical Elevation Pattern (1.832 MHz)

The take off angle of maximum gain is around 18 to 19 degrees. At the 18 degree take off angle the azimuth pattern is:

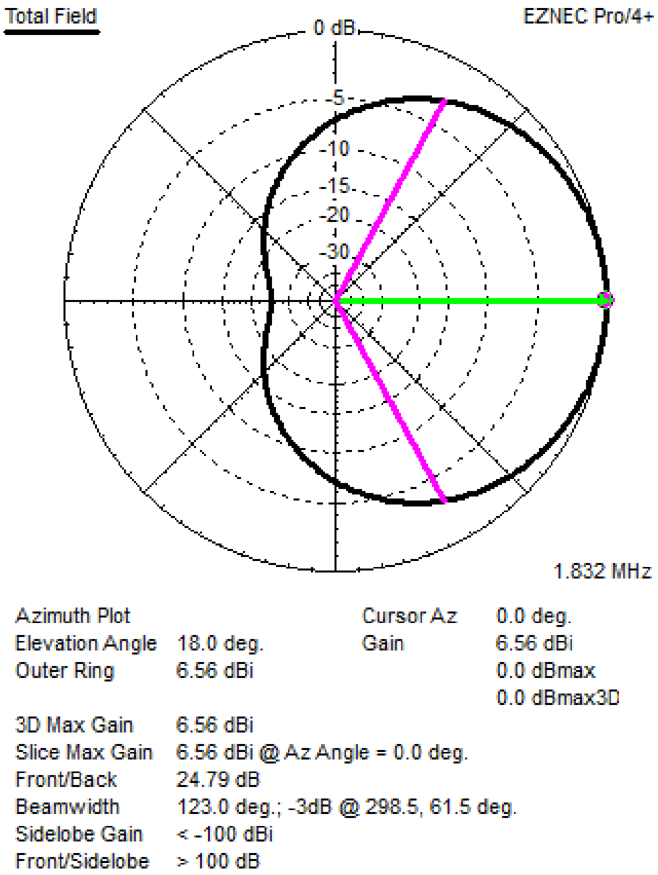


Figure 6 - Typical Azimuth Pattern (1.832 MHz). 18 Degree Take Off Angle

1.827 MHz Target

The gain and F/B sweeps at the 1.827 MHz target are:

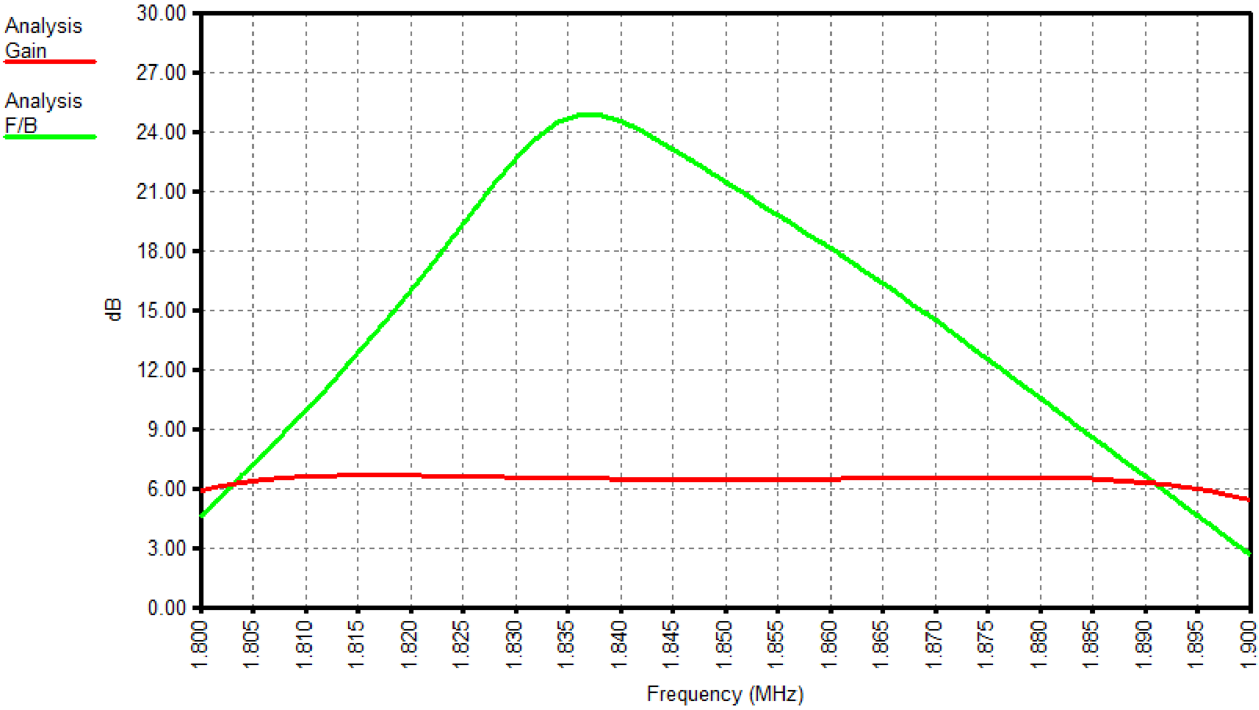


Figure 7 - 1.827 Gain and F/B

As expected, both curves have shifted up in frequency by about 5 KHz.

1.845 MHz Target

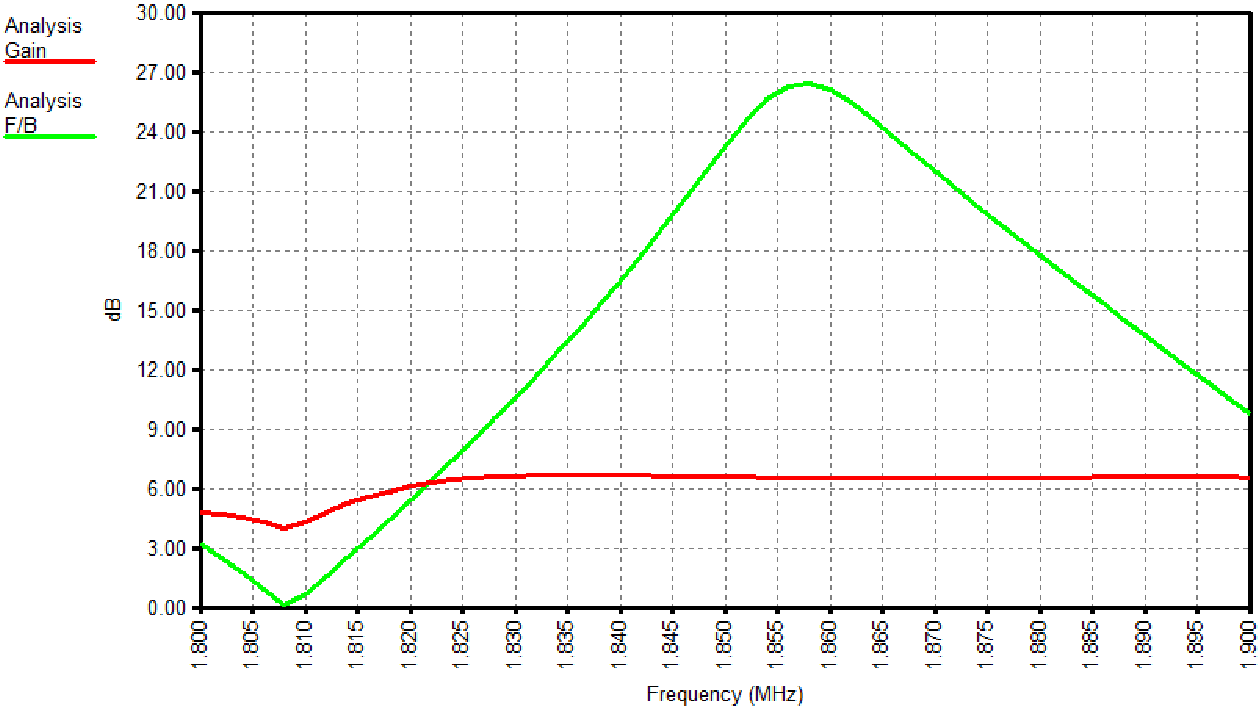


Figure 8 - 1.845 MHz Gain and F/B

The F/B peak is at 1.858 MHz. Note that at the low end of the band the array reverses direction as the high frequency director becomes ineffective and the low frequency reflector becomes a director.

1.850 MHz Target

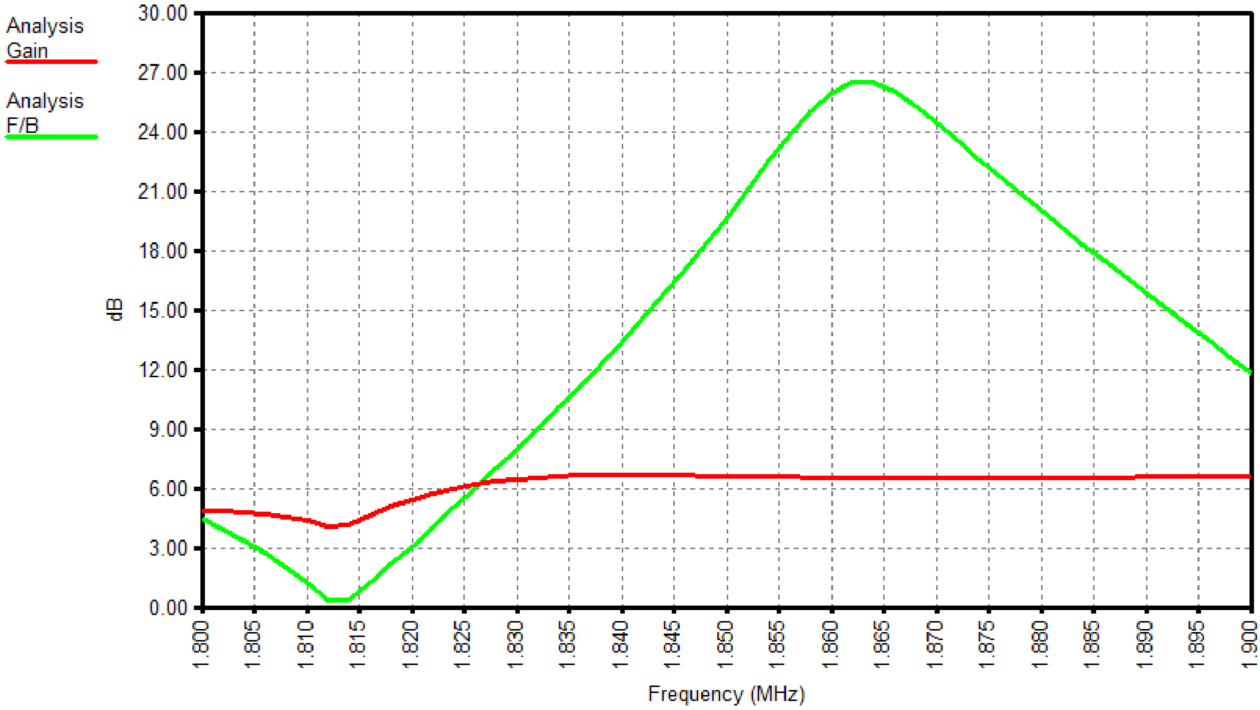


Figure 9 – 1.850 MHz Gain and F/B

Operating the 1.850 MHz setting below about 1.825 MHz becomes problematic.

Comparing the Targets

All four gain and F/B traces are plotted on a single graph:

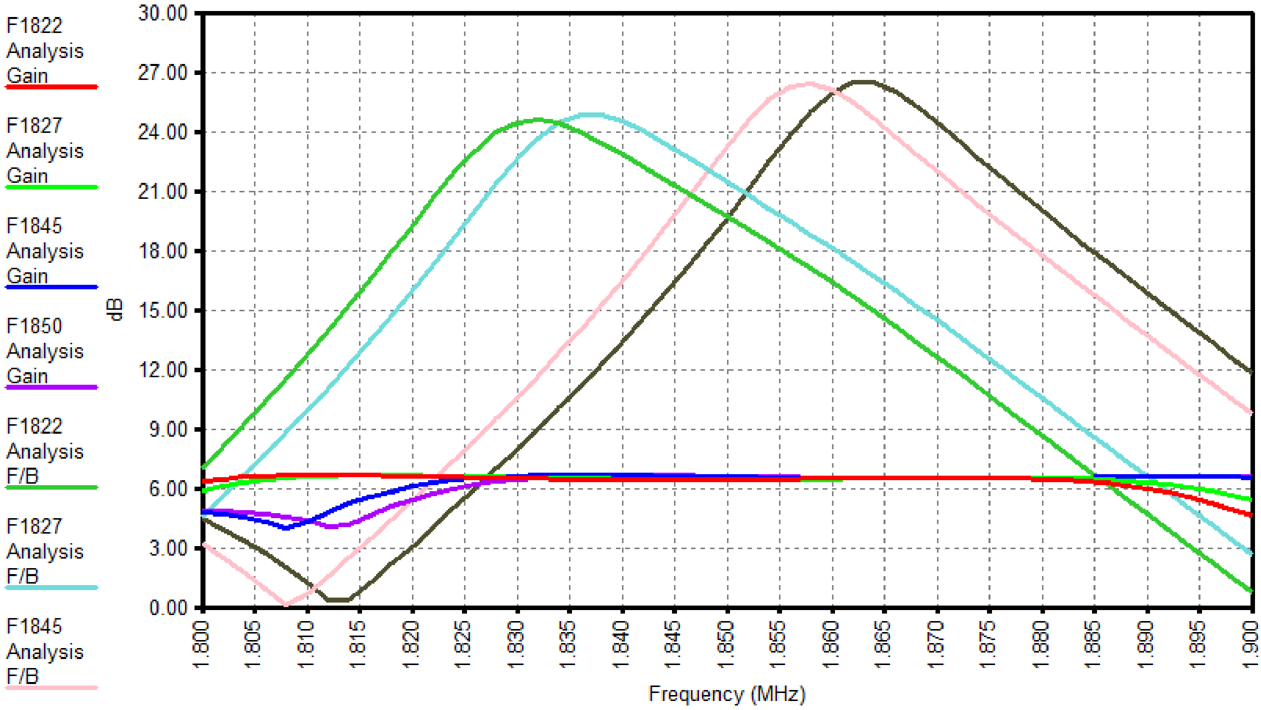


Figure 10 - All Four Targets

I need not add the 4 frequency targets to the graph. The F/B peaks tell the story. They move from 1.822 MHz on the left to 1.850 MHz on the right. The gain values are all very flat and consistent, although using an SSB setting at the bottom of the band is a problem. The gain drops as the pattern reverses direction. The SSB settings start to become a problem under 1.825 MHz.

The CW settings start to be a problem above 1.885 MHz.

The listed target frequencies, according to these models, are a little under the frequency of the F/B peak. The gap is around 10 KHz.

Impedance Matching

Several different forms of impedance matching have been used over the years. This includes L networks and ¼ wavelength transmission line transformers. The most recent matching solution is *single stub matching*.

The single stub match can be targeted at any frequency in the span. I'm going to pick 1.822 MHz and 1.845 MHz as examples. The stubs will be added to the model so that SWR sweeps can be added to the F/B and gain graphs. This will provide a look at the SWR bandwidth.

I will be using the model generated impedance values at 1.822 MHz and 1.845 MHz to drive the calculations. In practice, it would be better to use the measured values from the array to compute the stub values for actual stubs.

Single stub matching is described in a number of places. I'll be using the **TLCalc1.xls** Excel spreadsheet to calculate the cable lengths and then the SimSmith program to verify the results and use lossy cables.

The TLCalc1.xls spreadsheet was created by Mike, AA3RL. It contains a number of useful calculators. Additional documentation on determining the single stub matching solutions can be found on this page:

https://www.qsl.net/aa3rl/tlcalc1.html

SimSmith, by Ward, AE6TY, is available on the Internet as a free download. Using SimSmith provides a double check on the calculations and also includes a lossy transmission line model. RG-213 50 Ohm coaxial cable is used.

1.822 Matching

At 1.822 MHz the feed point impedance of the middle vertical is 21.72 + j 0.8319 Ohms. The SimSmith results are:

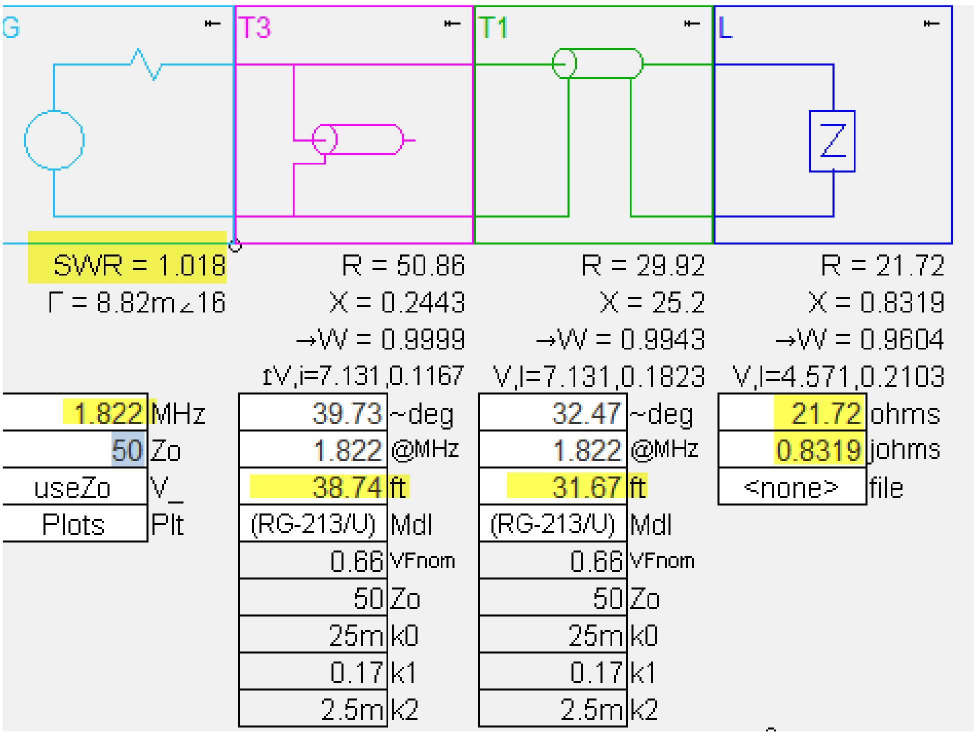


Figure 11 - 1.822 MHz Single Stub Matching

The solution is 31.67’ of RG-213 cable connected to the feed point. At the other end of that cable a 38.74’ RG-213 open stub is connected in shunt. The result at that point is a 50 Ohm SWR of 1.018. The loss in the matching network is a little less than 4%. For cable cutting purposes the degrees value can be used.

I added those cables to the model and added the SWR sweep data.

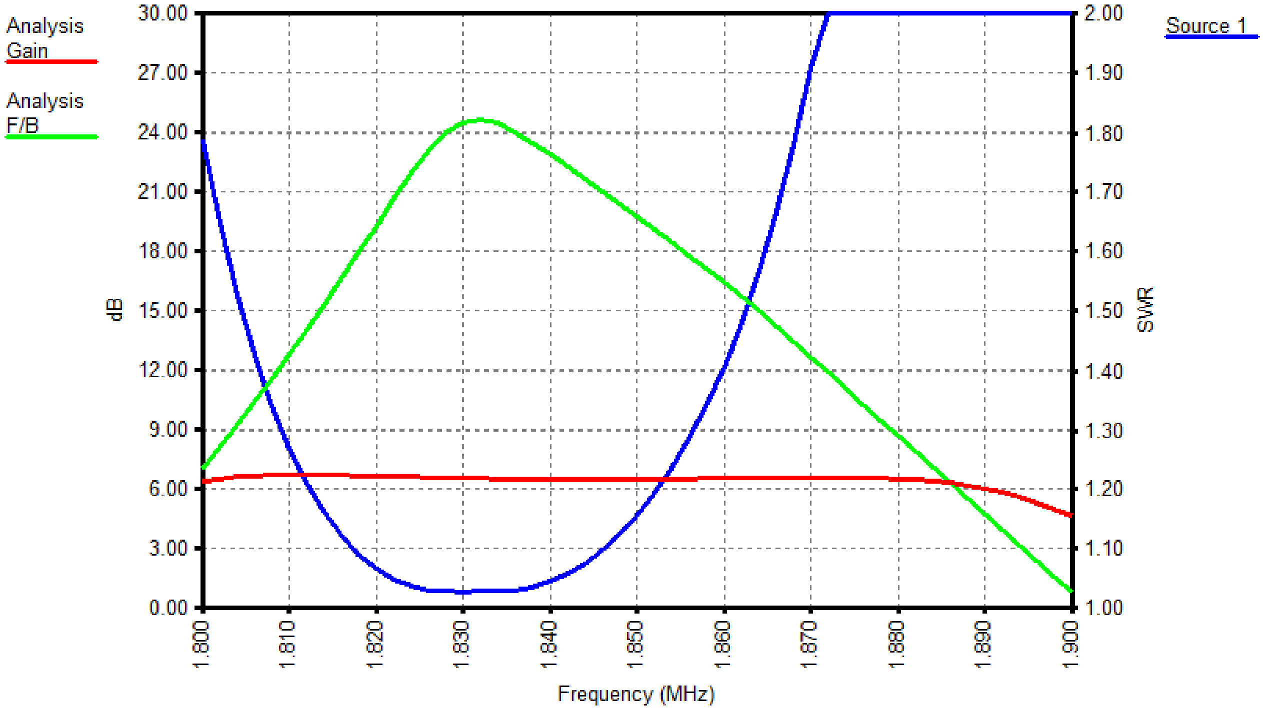


Figure 12 - 1.822 MHz Gain and F/B with SWR

The SWR is drawn in blue with the Y axis values on the right-hand side of the graph.

1.845 MHz Matching

At 1.845 MHz, the feed point impedance of the middle vertical is 21.81+ j 6.335 Ohms. The SimSmith results are:

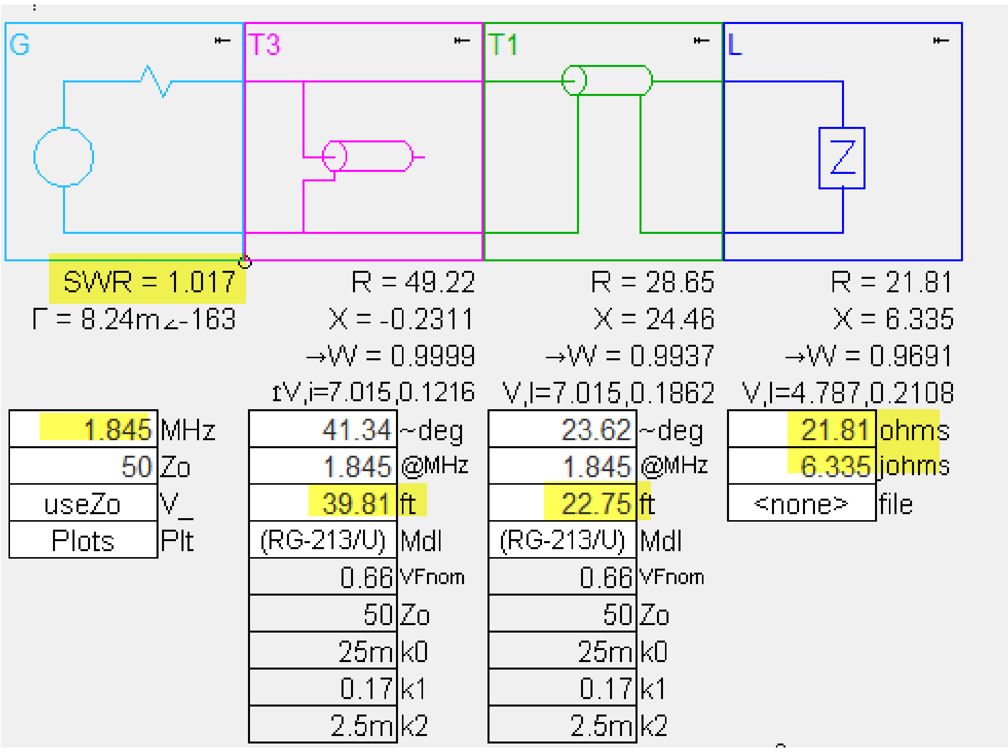
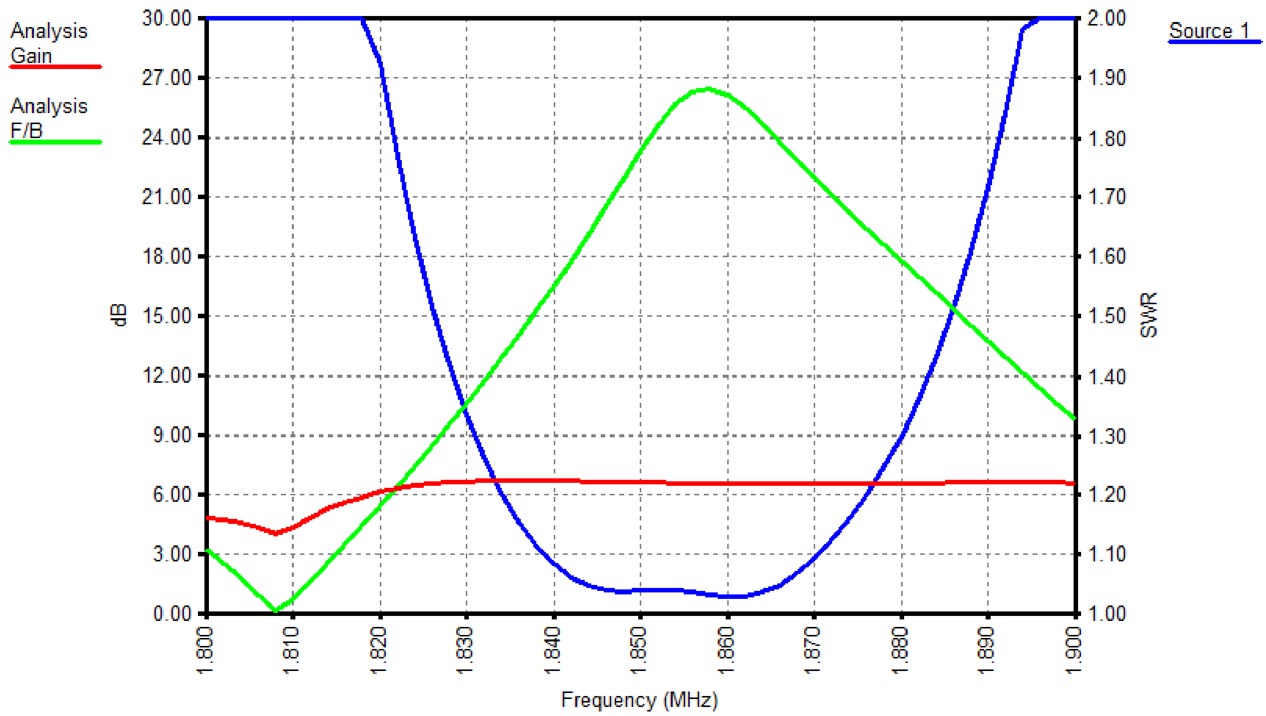


Figure 13 - 1.845 MHz Single Stub Matching

The solution is 22.75' of RG-213 cable connected to the feed point. At the other end of that cable a 39.81' RG-213 open stub is connected in shunt. The result at that point is a 50 Ohm SWR of 1.017. The loss in the matching network is a little more than 3%.

I added those cables to the model and added the SWR sweep data.



The SWR is drawn in blue with the Y axis values on the right-hand side of the graph.

The SWR graph suggests a little bit of the *double dip* that was seen with other matching solutions when the array is adjusted to higher frequencies.

NOTE: when I added the RG-213 transmission lines to the model I forgot to add in the expected loss. Loss was part of the SimSmith model. This difference probably explains why the SWR does not drop to 1.0 at the target frequency in the sweep.

Direction Reversal

I've mentioned before in this note that the array reverses direction as you get too far away from the target frequency. Here is a bit more information on that topic. This is based upon my observation of models over the last few decades. It is probably included in some book, articles, and web sites, but I don't remember ever seeing it.

Parasitic elements need to be reasonably close in their resonant frequency to nearby radiators to pick up enough current to reradiate it and actively participate in the total array. If the parasitic element resonant frequency is too far away from the target frequency the coupled current flow will be low enough that the parasitic is effectively *invisible* at the target frequency.

Without going into all of the details of why parasitic antennas work, we all know that elements a little electrically longer than the driven element function as reflectors and elements a little electrically shorter than the driven element function as directors.

Being electrically longer is the same as having a lower resonant frequency. Being electrically shorter is the same as having a higher resonant frequency.

In the next sweep of the 1.822 MHz target frequency array, I increased the frequency sweep limits to 1.7 MHz up to 2.0 MHz – way beyond the intended operating frequencies. As before the red trace is the gain and the green trace is the F/B ratio.

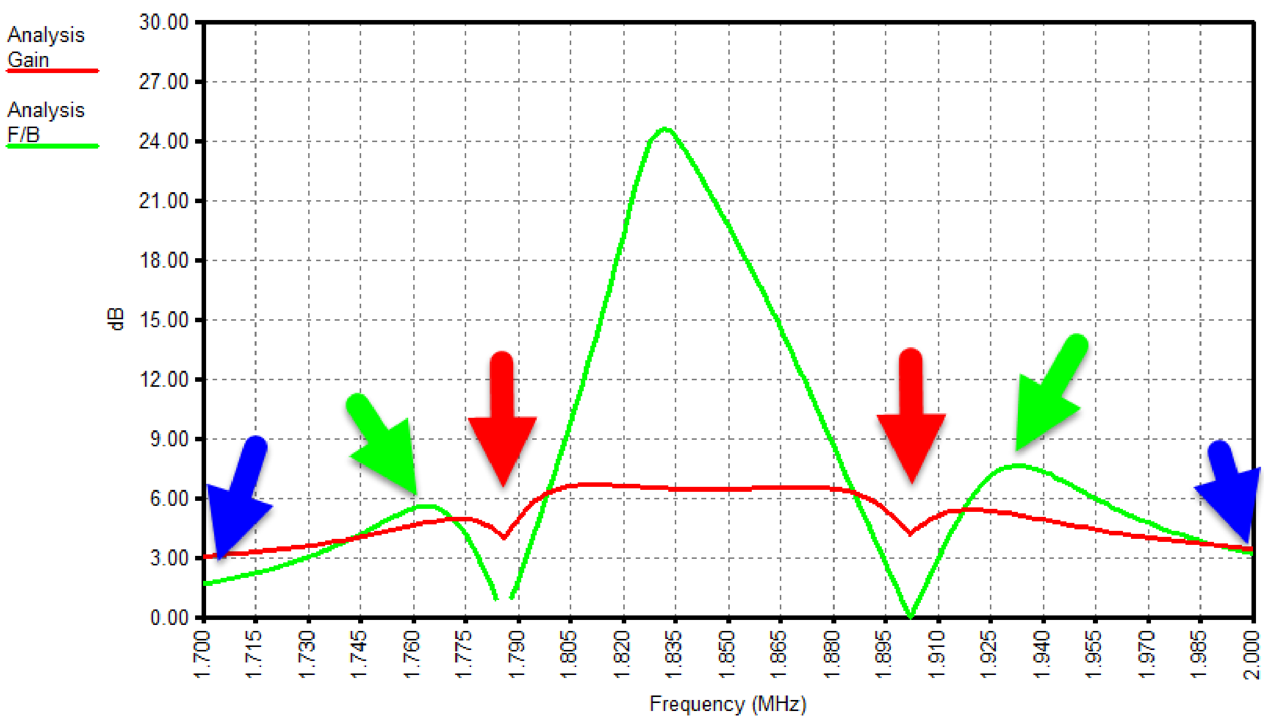


Figure 14 - 1.7 to 2.0 MHz Sweep of the 1.822 MHz Tuning

The blue arrows at the limits of the sweep point out a F/B ratio that is moving towards zero dB. This is because both the front (1.904 MHz) and rear (1.800 MHz) parasitic are far enough away from the test frequency that they are both becoming invisible. When invisible all that’s left is the single center driven vertical which has an omnidirectional pattern when by itself.

The green arrows, both above and below the target frequency, show the maximum reverse direction F/B ratio.

Consider the low side peak around 1.762 MHz. At this low frequency the 1.904 MHz director is effectively invisible and has little influence on the array due to the low current flow in it. The 1.800 MHz reflector is now at a higher frequency than the target (1.762 MHz), so it is now acting as a director, which is in the opposite direction of functioning as a reflector.

Consider the high side peak around 1.934 MHz. At this high frequency the 1.800 MHz reflector is effectively invisible and has little influence on the array due to the low current flow in it. The 1.904 MHz director is now at a lower frequency than the target (1.934 MHz), so it is now acting as a reflector, which is in the opposite direction of functioning as a director.

The red arrows highlight the frequencies where the F/B is zero, and the array pattern is bidirectional as it reverses direction.

The next set of azimuth pattern plots were taken at the important frequencies just discussed.

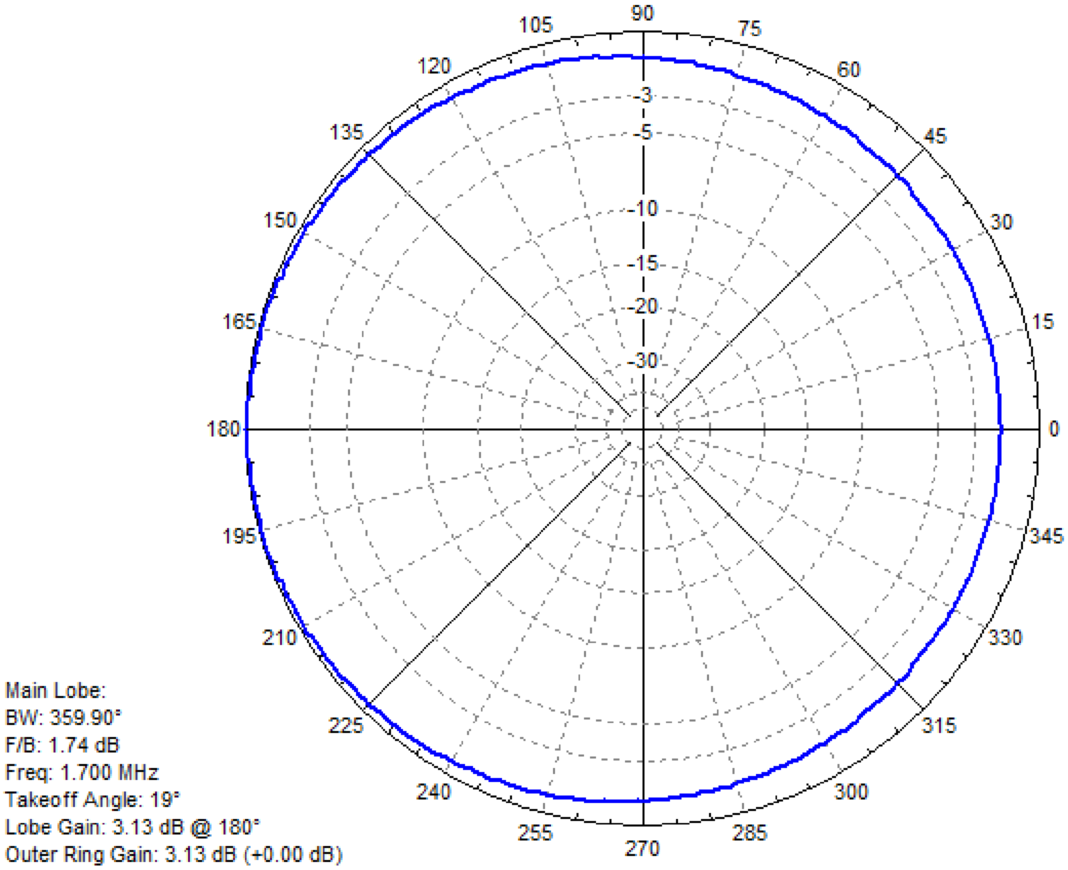


Figure 15 - 1.700 MHz

At 1.700 MHz the array pattern approaches omnidirectional since both parasitic elements have a low coupled current and are moving towards being invisible. If there is any direction at all it is to the left, which is the opposite of the intended array direction.

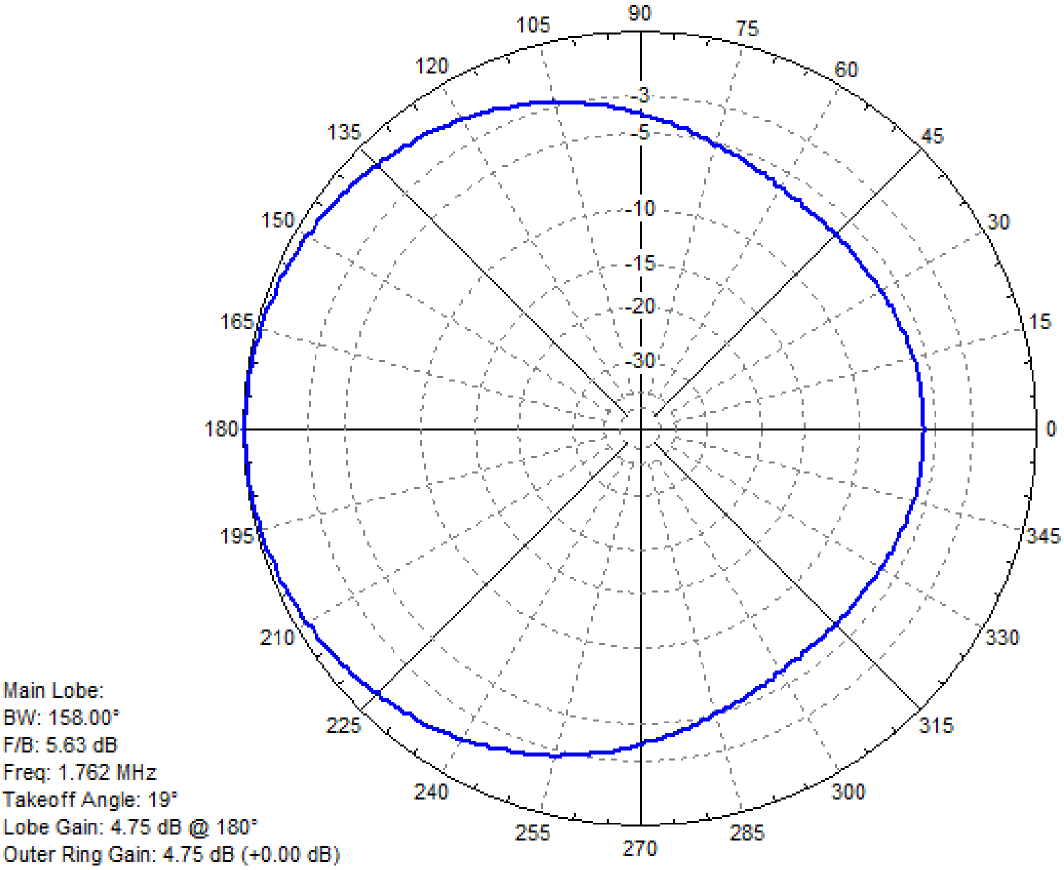


Figure 16 - 1.762 MHz

The pattern at 1.762 MHz shows the maximum F/B in the opposite direction. It is 5.63 dB. The reflector tuned to 1.800 MHz is higher in frequency than the test frequency, so it is electrically shorter and acting as a director. The director at 1.904 MHz is too far away in frequency to have a substantial influence.

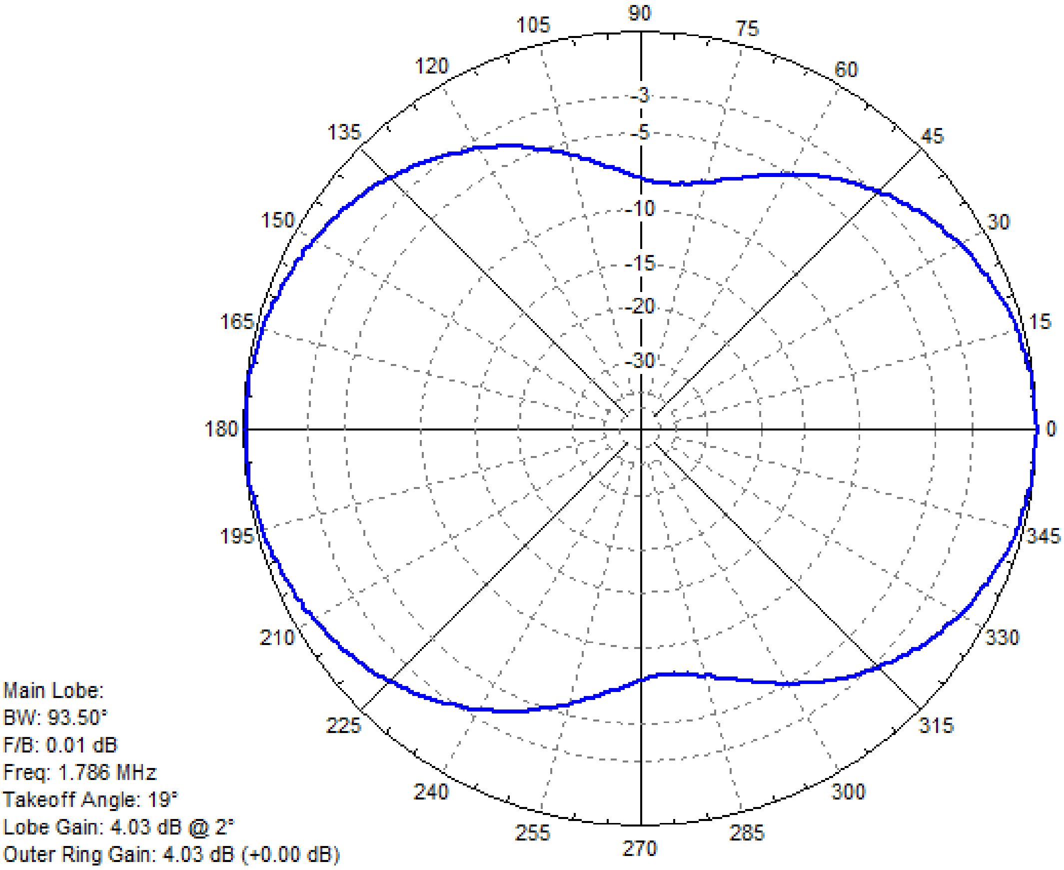


Figure 17 - 1.786 MHz

At 1.786 MHz the array is bidirectional, not unidirectional, and not omnidirectional. The F/B is 0.01 dB, which is close enough to 0 dB.

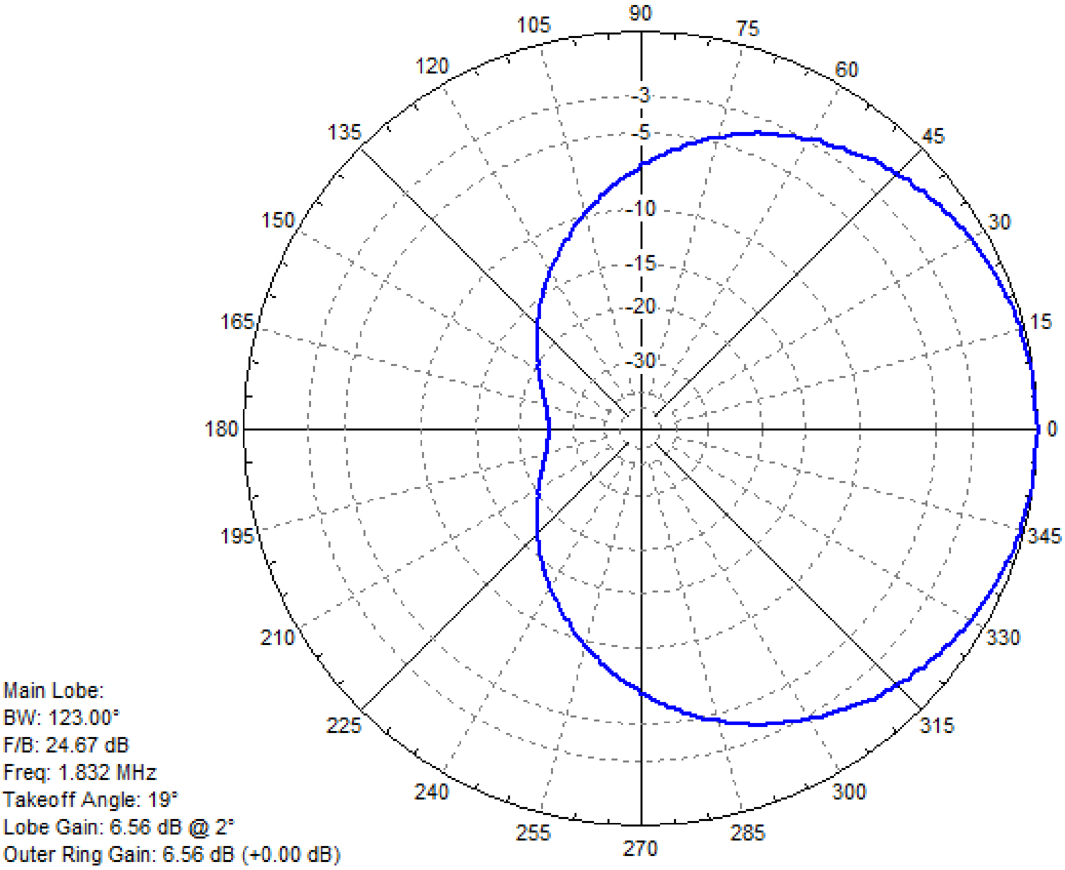


Figure 18 - 1.832 MHz

At 1.832 MHz is found the highest F/B ratio for the 1.822 MHz target. The F/B is 24.67 dB. The pattern points to the right – the intended direction!

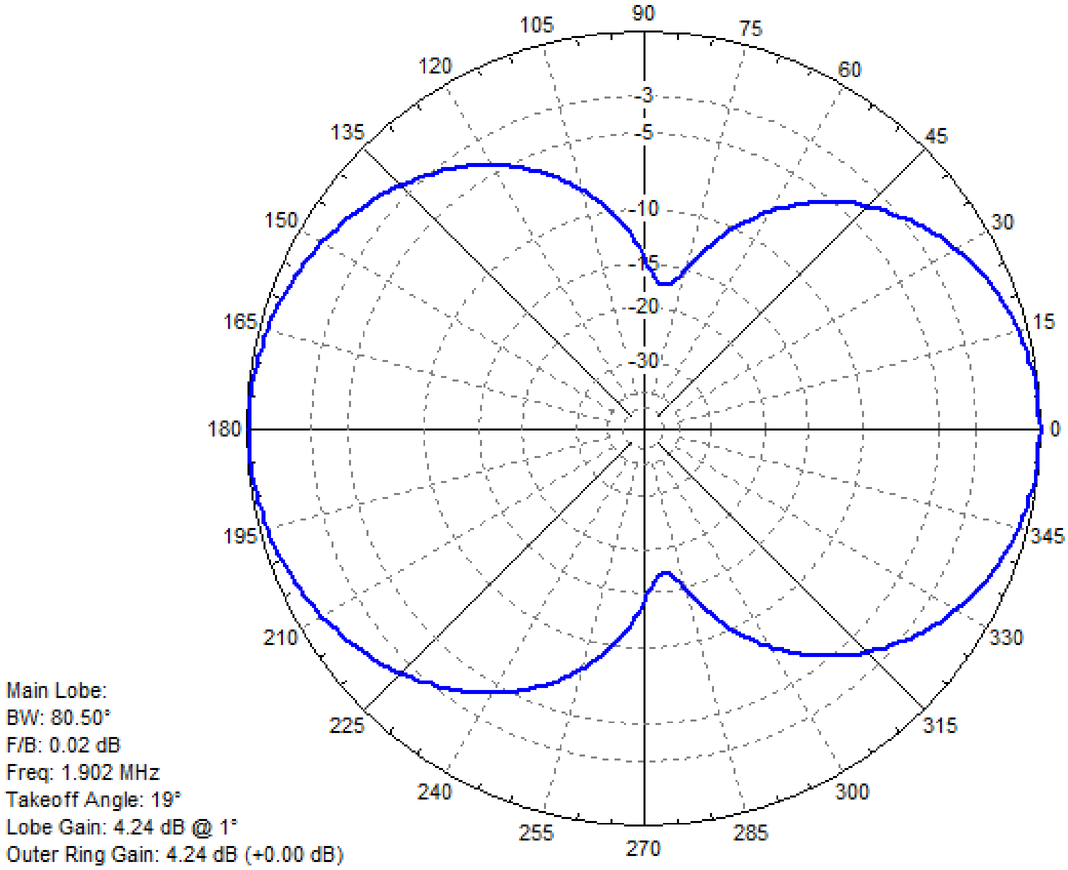


Figure 19- 1.902 MHz

Up at 1.902 MHz the pattern is again bidirectional with a 0.02 dB F/B ratio.

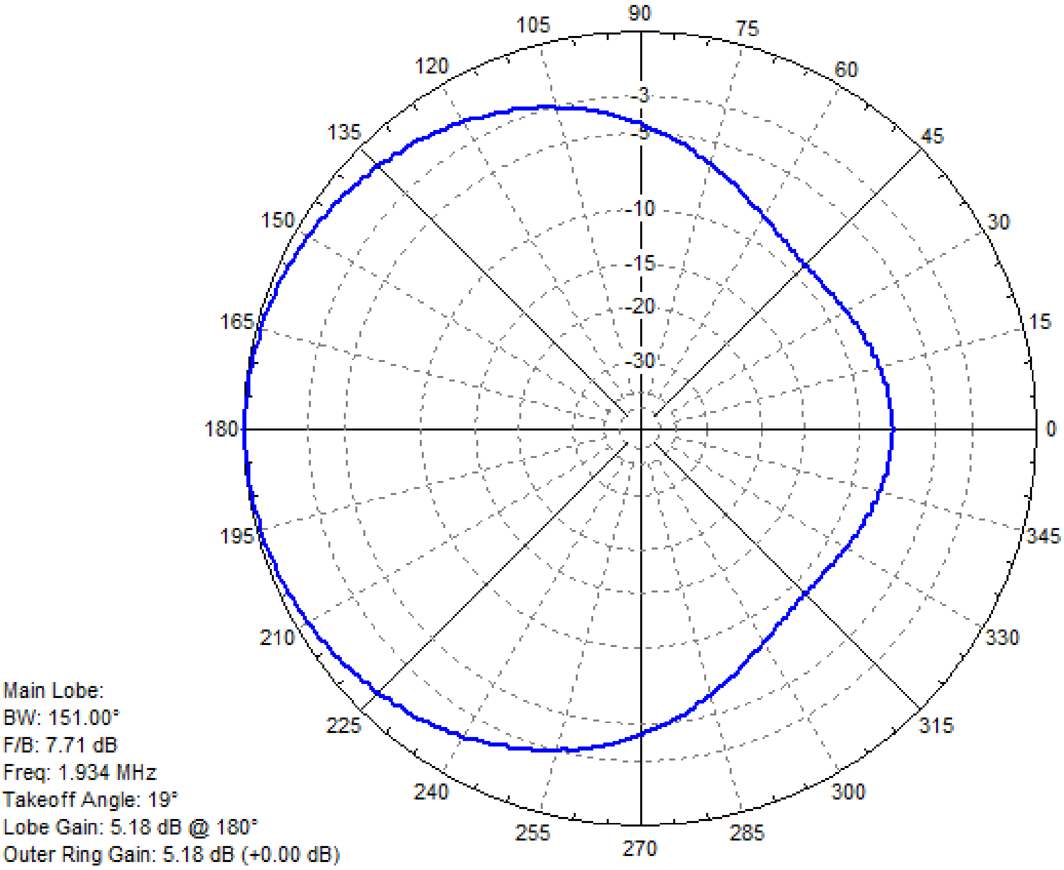


Figure 20 - 1.934 MHz

Finally, at 1.934 MHz the maximum F/B is achieved in the opposite direction. The original reflector down at 1.800 MHz carries a small amount of current so it is effectively invisible. What was once a director at 1.904 MHz is now a reflector.

Parasitic arrays that include both a reflector and at least one director should show the same behavior. This includes the popular Yagi. While the OWA Yagi increases the SWR bandwidth, it too will show direction reversals.

Optimizing the Design

Back when the array was designed and built tools like AutoEZ did not exist. AutoEZ has both a true optimizer as well as the ability to automate running a set of models as opposed to one by one manually, changing parameters between each run and quickly exploring a design space.

I thought I would spend some time using AutoEZ to see what improvements I could make to the array performance. Improvements come in several categories such as maximum gain, F/B ratio, and SWR bandwidth. This becomes subjective.

The one thing that can't be changed is the location of the parasitic elements. They are located over extensive radial systems with miles of wire that can't be moved.

What I can change is the tuning of the parasitic reflector and director.

The obvious approach is to allow the optimizer to change the reflector and director inductance (or frequency) and look for more gain or a higher F/B or whatever should be improved. Before doing that, I took another look at the original parasitic targets. I've repeated the table here from earlier in the note:

160m Array Tuning			
Mode	**Target Freq.**	**DIR Freq.**	**REF Freq.**
CW	1.822 MHz	1.904 MHz	1.800 MHz
CW	1.827 MHz	1.909 MHz	1.805 MHz
SSB	1.845 MHz	1.927 MHz	1.823 MHz
SSB	1.850 MHz	1.932 MHz	1.828 MHz

What caught my eye was that on the 1.822 MHz target the frequency span down to the reflector is 22 KHz, whereas the span up to the director is 82 KHz. Not very symmetric spans, although there is no design approach I am aware of which suggests they should be.

Still, I decided as a first step to focus on the 1.822 MHz target and fix the reflector to 1.800 MHz. The director loading inductance would be varied from 3 uH down to 0 uH in steps of 0.1 uH.

In reviewing the results, I found the director loading inductance of 2.4 uH to stand out. The normal inductance is 1.05 uH, for a 1.904 MHz resonance. I modified the 1.822 MHz model to have a director inductance of 2.4 uH and then added a single stub match. The feed point impedance to match is 15.44 - j 3.792 Ohms.

The comparison of the gain and F/B curves is:

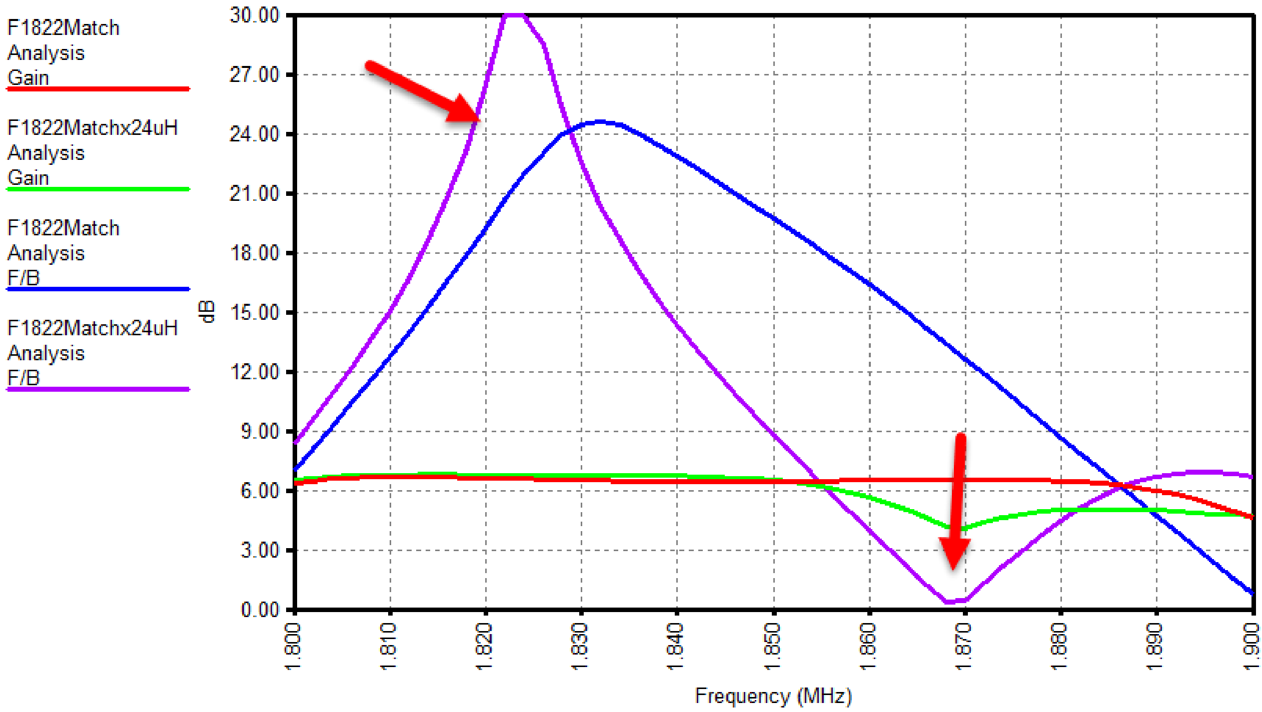


Figure 21 - 1.822 MHz with 2.4 uH Director Gain and F/B Comparison

The 2.4 uH director has a higher and sharper F/B peak (purple) of a little over 30 dB. The F/B peak is shifted down in frequency, close to the 1.822 MHz target.

The 2.4 uH director gain, in green, is a fraction of a dB higher than the 1.05 uH director.

Unfortunately, the F/B peak is narrower and the array reverses direction and drops in gain around 1.870 MHz, much lower in frequency than the 1.05 uH director.

The SWR bandwidth is also reduced with the 2.4 uH director loading inductor.

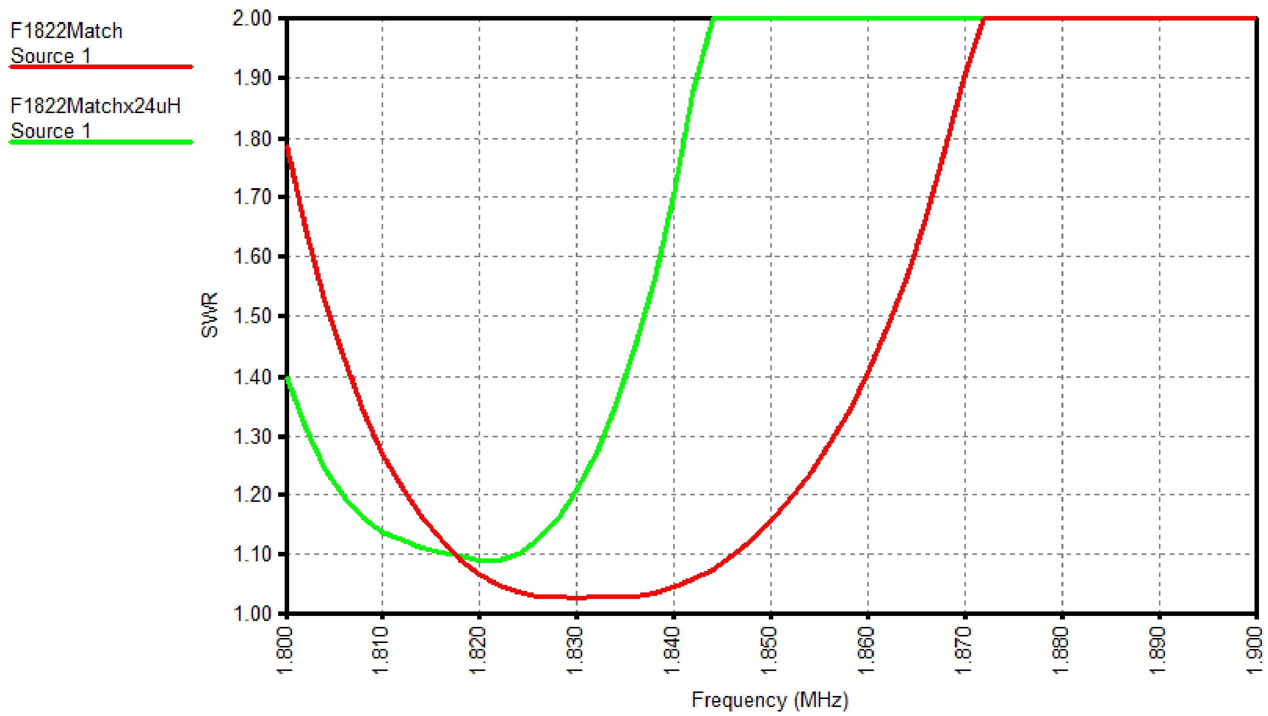


Figure 22 - 2.4 uH Director SWR Comparison

The 1.05 uH director is shown in red and the 2.4 uH director is drawn in green. The 2.4 uH director has an SWR of 1.5 or better bandwidth of 40 KHz, whereas the original 1.05 uH bandwidth is close to 60 KHz.

While there was a small F/B and gain improvement, the narrower bandwidth, for the gain, F/B, and SWR curves more than negates any improvement. The original inductor loading value of 1.05 uH is better in my opinion.

The next approach I took was to allow the optimizer to change both the reflector and director loading inductor values. This changes their resonant frequencies.

When running the AutoEZ optimizer there is a set of weighted targets/objecives that are set to drive the optimizer in a particular direction, towards a particular goal.

For what I found interesting I used the following targets:

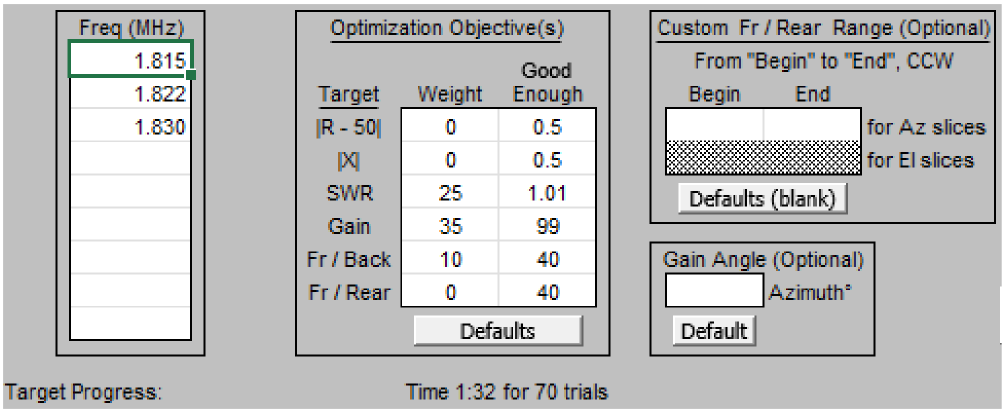


Figure 23 - Optimization Targets

With the 1.822 MHz target the reflector inductance is 5.525 uH. The director inductance is 2.16 uH. In practice these would need to be converted to measurable frequencies. Both are lower in frequency than the current 1.822 MHz parasitic frequencies.

The gain and F/B comparison is:

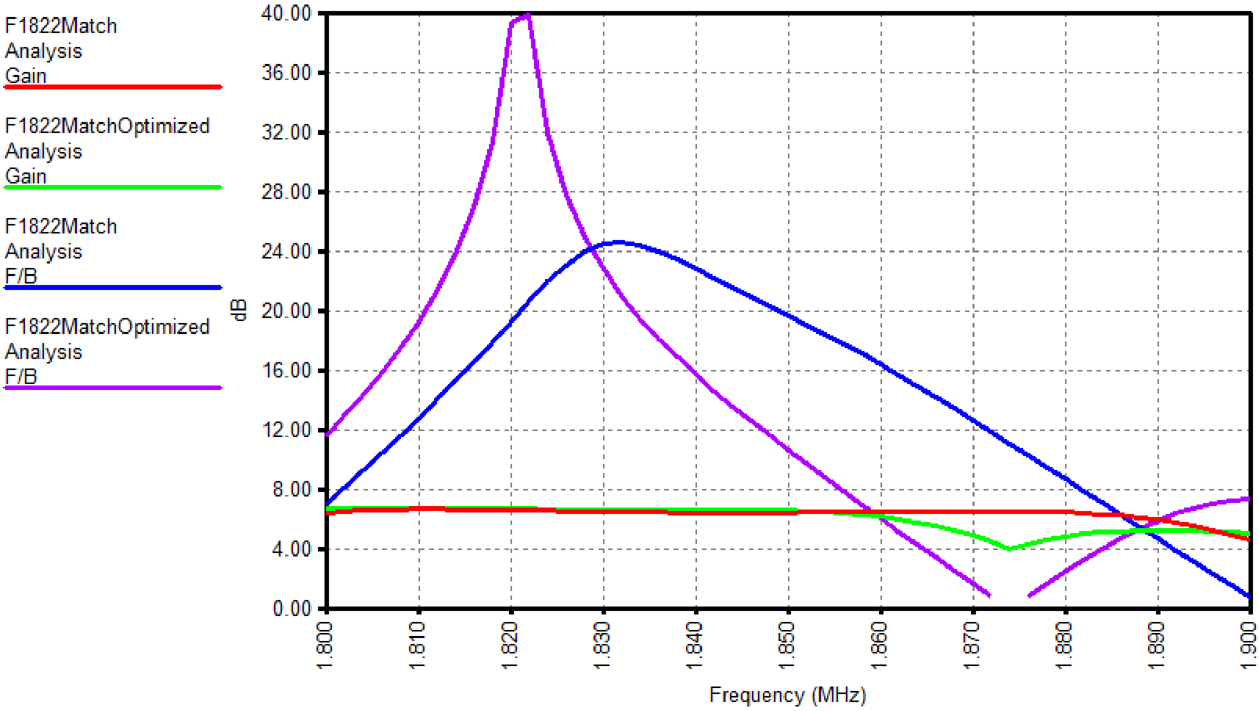


Figure 24 - Optimized Gain and F/B

The purple trace is the optimized F/B and blue is the original 1.822 MHz design.

As with the previous design, the F/B peak is much higher, but also a narrower shape. The gain is a fraction of a dB higher. The direction reversal is lower in frequency around 1.875 MHz.

The SWR comparison is:

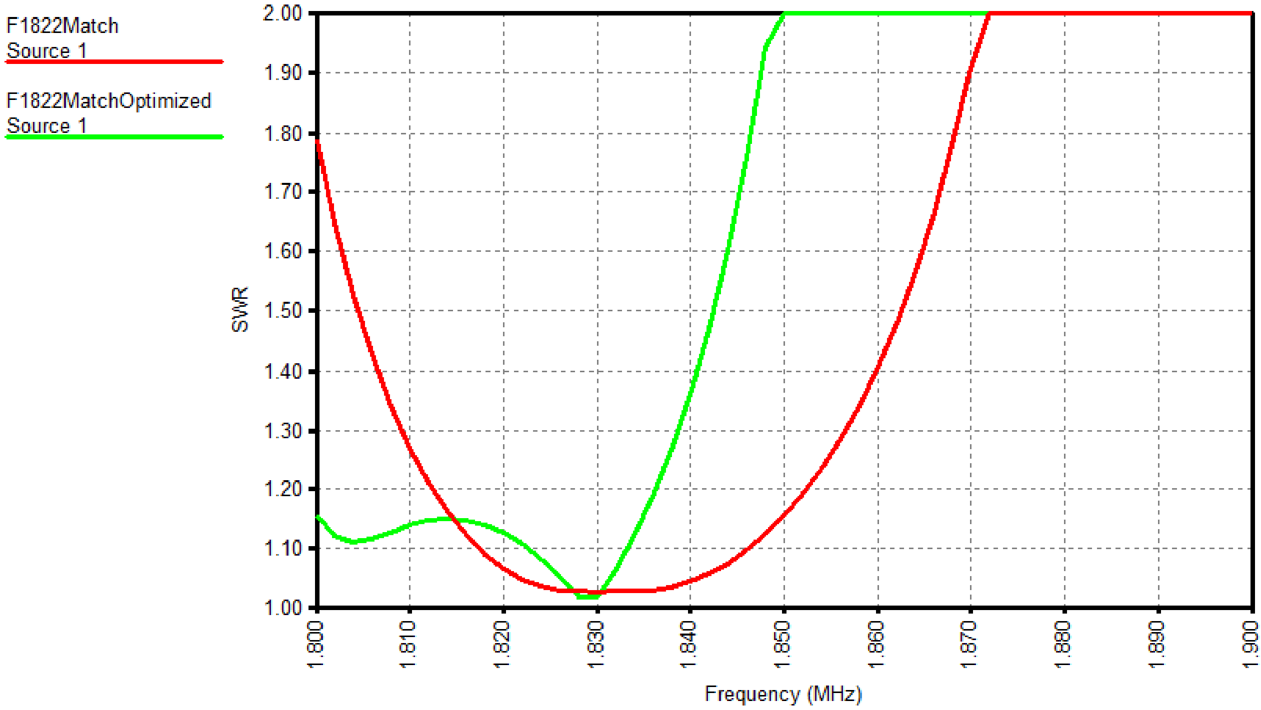


Figure 25 - SWR Comparison

This optimized SWR curve has an interesting wiggle which I suspect is due to an interaction between the single stub matching and the array.

None of these optimized designs strike me as interesting enough to pursue.

I am reminded of the phase *there are no free lunches*, or as Thomas Sowell says, *there are no solutions, only trade-offs.*