Dipole Design

The journey to a 160/80/60m dipole

Keith Witney; VE7KW

A Dipole is simple. Correct!? 
Dipole Design

• Theory
  • Basic dipole
  • Half wave dipole
    • Effect of Height
  • Flat tops
  • Off Centre Fed
  • Multi-band
    • Resonant
    • Non-resonant
  • SWR / Matching Circuits / Common Mode
  • Efficiency
Dipole Design: Theory

• A dipole is simply an antenna (or anything else) with two elements
  • In an ideal world, the feed line is not part of the dipole
• It can be horizontal, vertical or anything in between
• The elements need not be equal and are unlikely to be balanced in reality.
• The pattern is affected by height above “ground”, balance, other conductors in the near field and the dipole dimensions
Dipole Design: Bandwidth

- On 80m in particular it is difficult to get an antenna that covers the full band.
- There are several techniques for improving bandwidth
  - Bandwidth improves with increasing element diameter (caging)
  - Linear loading (most often used for beams)
  - Capacitive stubs
It looks as if a 300mm cage is required. This is quite acceptable. The impedance varies with height the plot shown is at 15m. Further investigation indicates that only 50% of the leg (highest current) needs to be caged.
Dipole Theory: Half Wave Dipole

- The Half Wave Dipole is a special case
  - Has a low driving impedance
  - Produces, ideally the classic dipole pattern, in free space
  - Also works on odd multiples; 3/2, 5/2

- For a horizontal half-wave dipole the pattern and impedance is dependant upon height above real ground.

- For a vertical half-wave dipole the pattern is relatively height independent but is influenced by ground conductivity.
Dipole Design: Flat Tops

- AKA Doublet (88 ft) Antennas
- One of the first antennas
- Normally not resonant
- Normally balanced and fed with balanced line via a Balanced Matching Circuit (Very hard to find now)
- Highly sensitive to other conductors
- Pattern is height and dimension sensitive.
Non resonant 86 foot doublet

- Premise is that a doublet requires no ground but must be fed through a tuner (except for the half wave point).
- 2x 43 ft is chosen as 43' verticals seem to be an optimal non resonant length to include 80m.
- 88 foot doublets are the classic dimension.
- It is apparent why a 600 ohm feeder and matching network is required!
- Note that with a tuner(at 600 ohms) this antenna is usable except at its resonance points.

50 ohm SWR
This is the λ/2 point

600 ohm SWR
Needs tuner to remove reactance.
Dipole Design: Off-Centre Fed

• A dipole with unequal poles
  • Resonant Dipole
    • The feed point is moved from the centre to obtain a different feed point impedance. Typically 300/450/600 ohms to enable low loss feeders to be used.
    • The feed point will again repeat for odd harmonics
    • Requires a transformer/balun to match the higher balanced impedance to the 50 ohm unbalanced transmitter
  • Non-resonant dipole
    • By examining the standing wave patterns on the antenna a compromise feed-point, typically 33% and length, typically 70% of a half wave-length at the lowest frequency, can be found which when fed via a transformer balun will enable satisfactory operation on several bands via an additional matching unit
    • Sometimes the feed-line is included to enable additional bands (G5RV and variants)
    • An excellent Balun is required.
The concept of an OFCD is that you can pick a point, offset from the centre where the impedance will be similar at several amateur bands. This impedance varies with effective height above ground but for the purposes of this discussion will be taken as 200 ohms. The expected result is that an antenna can be developed for 80 through 10m less 30 and 17m.
The curves given in the article (August 1990 QST) looked very promising but the description seemed to be very installation specific which raised flags.

I decided to model this dual OCF at the 22 ft reported. It allowed the antenna to be non-resonant and if you take the 2:1 SWR around 65 ohms we get 150 kHz but this is not the results as described.
CQ-DL double OCF curves

I was unable to recreate these results with an EZNEC model.

Double OCF.EZ 50 ft high, long and short at 90 degrees. Note to get 7 Mhz etc. on frequency 80m is too low. In addition it is only 100 kHz wide. It seems as if the Germans are relying on being low and the legs being close together to broaden the response. Unfortunately this occurs because of the resistance loss into ground!
Don VE7DS has had great success with a “G5RV” variant by ZS6BKW and lent me his version for tests. I did not have the vertical height available for the twin lead (50 ft) so ran it horizontally and tested the antenna at 25 ft.

It indeed can be used on all bands. It did not evidence any significant improvement on WSPR vrs my R9 but the bandwidth was wider.
Dipole Design: Off Centre Fed

Based upon the modelling and my tests, I concluded that while these antennas can be a useful multi-band antenna, they had some uncertainties which I would like to avoid.

• Dependence upon location, height and effect of conductors within 1λ

• Ground losses affecting efficiency at the lower frequencies.

• Difficulty in routing and securing the down leads

• Effect of vertical conductor radiation – G5RV variants (acts like an upside down ground plane vertical!)
Dipole Design: Traps

- **In band**
  - This is the simplest conceptually as effectively the extra length is cut off at the higher frequency.

- **Out of Band**
  - When the operating frequency is above the trap resonance it behaves as a capacitor shortening the antenna. When the operating frequency is below the trap resonance it acts as an inductor lengthening the antenna. Thus with the proper chose of wire length either side of the trap, two frequencies can be made resonant.
  - Out-of band traps have less loss because less current flows through them at the operating frequencies.

- **Traps shorten the antenna**

- **High trap Q values are required to minimise losses**

- **A good example are the traps used in Cushcraft products where a high Q inductor is placed in a high Q coaxial capacitor and out of band traps are used to cover 2 or 3 bands.**
Dipole Design: SWR/Matching Circuits

• A half wave dipole, at resonance has a feed point impedance of 25-73 ohms depending on height and antenna construction. Typically this is close enough. However, in order to feed it with Coax you need a BALUN. Also a typical wire dipole has a 3:1 bandwidth of about 5% so you may need additional matching for full band coverage on 80 and 160m.

• The matching circuit can be at the antenna, at a point in the feed-line, or in the shack
  • Efficiency versus convenience and practicality
Dipole Design: Efficiency

• Never quantified in a manufacturer’s ads

• What we want to do is take the maximum undistorted power out of our amplifier and transform it into EM waves travelling in free space
  • The receive problem is almost the reverse except for signal to noise considerations

• We will assume that the transmitter manufacturer has done what ever is required to maximize the efficiency of the transmitter into a 50 ohm coax so our problem is to minimise the losses between the Transmitter Antenna Port and EM waves in free space.
  • Assuming a modern transmitter/coax feed configuration, match coax to 50 ohms, match antenna to 50 ohms unbalanced, minimise component losses, MAXIMISE the conversion of RF at the antenna feed point to EM waves travelling in free space
Dipole Design: Efficiency

Let’s take some representative loss values (all are design dependant)

- ATU when tuned ~ 1dB.
- Loss of 100 ft of RG58X with a 3:1 SWR ~0.7 dB, 10:1 ~1.8 dB
  - Is it worth remoting an ATU? Only decreases the loss by ~1.4 dB at 10:1
- Loss of 1/2\( \lambda \) 80m dipole #28 vrs #10 Cu wire ~0.1 dB
  - Probably not a big issue as skin effect and mechanical issues predominate
- In band trap loss ~ 1dB
- Out of band trap loss ~0.5dB
- 4:1 balun loss ~0.1dB (Current Balun assumed)
Objectives

• VE7KW has an R9 (a OCF vertical dipole on most bands) which covers 80 through 6m but not 160 or 60m. It would also be desirable to be able to have an antenna for diversity reception (V to H).
• Frequencies: 1.8-2.0 MHz, 3.5-4 MHz, 5.25-5.45 MHz
• SWR: less than 10:1 (KAT 500 matching limit)
• Power capability: 500 W (KPA 500)
• Single 50 ohm coax feed line 75-100 ft.
• Maximize “efficiency”
• Available length 200 ft
• Available height approx. 70 ft
First Approach; Fan Dipole 80 and 60m only

Advantages:
- Resonant
- Simple in concept but difficult to achieve
  - The issue is that the second dipole “loads” the first dipole
  - This could be an advantage if it produces linear loading and increases bandwidth

Disadvantage
- Mechanically somewhat complex to build and raise
- Not easy to obtain predictable results and adjustments
The hope was that the coupled elements would result in broader bandwidth. This did not happen and this approach was abandoned due to its mechanical complexity.
Second approach: Off-center Fed 160/80/60m

- Considerable modelling was undertaken to come-up with a suitable compromise combination of lengths and feed-point. The concept of capacitive stubs to extend bandwidth was also investigated. The modelling was very sensitive and this did not bode well for actually making an antenna that would work reliably.

- It was decided to “simplify” matters a bit by using a fan arrangement of OCF 80m and 60m dipoles. This was constructed and worked but needed a lot of tuning and was not considered “stable”
Note that with the proper Balun transformer, the SWR for each band is reasonable.

The Balun is essential to remove the feed line from the response and prevent issues such as RFI and “RF in the shack”

Suitable baluns for frequencies below 80m are non-trivial.
This is a 33% offset 80m with parallel parasitic 60m OCF to Infill for 15m. Element spacing had to be >1 foot. It was determined that the elements would ideally be twice as long as the lowest desired frequency but this is impractical.
This is the non-resonant 80m and 60m OCF dipole developed from the parasitic design above fed at the same 33% point.

43 ft and 86 ft with 30 ft and 60 ft gives us decent results on 80 through 40.

If we make it with the long element cut for 160m. We get 160 and decent results up to 40m so this is worth considering if you have the room.
The parallel 80m and 60m 33% OCF was built and tested at 25 ft. This was optimized through several iterations.
WSPR tests were conducted using the K3 main and sub receivers with two instances of WSPR. This was done on both installations (25 and 70 ft) with similar results. The average OCFD-R9 was 1 dB. Note that the negative values are for a single KA 5 station. It was noted that the OCFD had more receptions than the R9.
It is evident that the transmission line radiates from the current plots. It actually operates more like an off centre fed inverted L.

3.7 MHz     7.1 MHz
10.1 MHz     21.1 MHz

The previous models had the Balun transformer at the feed point. The effect of moving it down to the end of a typical length of open transmission line (46’) was investigated.

It is evident that the transmission line radiates from the current plots. The antenna actually operates more like an off centre fed inverted L.

Note that this means that anything near the transmission line and the transmission line above ground will affect the antenna pattern and operation.

Alternative feed point offsets were investigated but nothing could be resolved.
K5GP OCFD with capacitive loading and trap
This was a presentation to CTDXCC Sept 22, 2008. No technical validation was given but it appears that this is an OCFD conformed to available space with coax capacitors to provide a stub to broadband 80m and a trap to get the 160m but the topography is not modelled as a trap but rather series and parallel elements. An example is given for 40/30/20 so maybe a 160/80/60 is possible along with the extended 80m bandwidth? Unfortunately it will be a bit too long.
Trap and Capacitor practicalities

• High Voltage / High Current capacitors are expensive and difficult to obtain

• Coax capacitors are really transmission lines and are not practical beyond a frequency dependant length. For example, Glen provided me with 11.5 ft of RG400 which should be 11.5\*29.5\,\text{pF} = 453\,\text{pF}. This measured 327\,\text{pF} with an LC meter (1 MHz) and 354\,\text{pF} with the VNWA (4.4 MHz)

• We want Hi Q inductors which implies a “square design”. A 4in PVC form is the most practical

• A Type 2 (Red), T200 ferrite core could also be used.
Third Approach: Trap Dipole

A wound L and fixed C trap would have been preferred but suitable capacitors are hard to find (the best solution would be a combination L and C trap like those used in the R8/R9 antennas but these use custom forms). Coax traps seem to be the solution if a suitably low loss design could be achieved. It is noted that out of band traps are preferred as they have lower losses.

Considerable modelling effort was spent to try and come up with a single out of band trap that would take care of both 60m and 80m (This is also a R8/R9 trick). This was complicated by difficulties in modelling traps in EZNEC6 (It turns out that you have to place the traps at a node which means you are constantly juggling element segments).

Eventually a 80/60 meter trap dipole was built and tested successfully. It was realised that adding an 80m trap and lengthening the antenna for 160m would just enable it to fit in the available space. This was done and is in operation.
The trap designs are from the “Trap” program. While unclear, it was determined that this produces values for a series configured Coax Trap. Again, the resistance is not accurate but also not critical for our purposes.
A test trap was made with 11T of RG58 on a 2” form. This was tested with the VNWA and a 2 turn loop with 50 ohms in series placed at one extreme end of the trap form, Trap1 5.226 MHz, Trap2 5.242 MHz and using the 20 dB pad method.
The trap losses can be determined by frequency from the load data. As only 80m is critical, I looked at these across the band. So placing the trap about 100 kHz lower would have been better.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total loss</td>
<td>2.068</td>
<td>1.779</td>
<td>1.535</td>
<td>1.181</td>
<td>0.944</td>
<td>0.781</td>
<td>0.666</td>
<td>0.584</td>
<td>0.525</td>
<td>0.484</td>
<td>0.455</td>
</tr>
</tbody>
</table>
Final? 160m/80m/60m Dipole

- 40 ft wire, 3.5 MHz trap, 9 ft of wire, 5.35 MHz trap, 40 ft wire; on each side of centre.
- So total length ~90*2 = 180 ft
- Bandwidths can be handled by the KAT500
- I have yet to try the capacitive stubs to increase Band width
WSPR tests: 160m/80m/60m Trap Dipole

- These preliminary results seem to indicate that the antenna has a lower angle of radiation than expected.
- Keep in mind that these values cover a five hour period and not all stations were on for that time period. Lots of readings are required for reliable conclusions.
- The Antenna does seem to cover NA quite well and down into the South Pacific and SA.
Dipole: Final Thoughts

- OCF, Doublets and other open wire feed antennas require considerable clear space to install and normally require heights in excess of 60 ft.
- OCF and doublets require good Baluns and tuners or they will act more like a random inverted L.
- Linear loaded antennas such as fan dipoles are not easily designed but for one or two elements can be trimmed.
- Trap antennas make the length of the lowest frequency shorter. Losses are reasonable but can be reduced if an out of band trap solution is obtained.
- Bandwidth is a difficult problem. A promising solution may be capacitive stubs.

- Any antenna is better than no antenna!
Dipole: Additional design Information

Some interesting items came up in this journey

  • The practicalities of building traps with available materials
  • The design of out-of-band traps, in particular to enable tri-banders.

Modelling issues

  • An antenna as a transmission line
  • NEC trap placement
  • The use of Ltspice to model antennas
A quick look with the Coax trap program showed that a coax trap was not practical so a wound L would be required with RG 400 Coax stubs used for the C.

Capacitors

One concern is that coaxial capacitors are really transmission lines and the C will be higher past a couple of degrees in length. $\lambda_p = 69.5\%$ so

$$\lambda (f) = \left(\frac{983.6}{f}\right) \times 12 \times 0.695 = 360 \text{ Deg}$$

$\lambda (3.7) = 2217 \text{ in}$

$\lambda (5.35) = 1533 \text{ in}$

<table>
<thead>
<tr>
<th>RG400</th>
<th>29.4 pF/ft</th>
<th>El degrees at (freq MHz)</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 pF</td>
<td>12.24 in</td>
<td>1.99 (3.7)</td>
<td></td>
</tr>
<tr>
<td>40 pF</td>
<td>16.33 in</td>
<td>3.84 (5.35)</td>
<td></td>
</tr>
<tr>
<td>55 pF</td>
<td>22.45 in</td>
<td>5.27 (5.35)</td>
<td></td>
</tr>
<tr>
<td>300 pF</td>
<td>122.45 in</td>
<td>19.48 (3.7)</td>
<td></td>
</tr>
</tbody>
</table>

11.5 ft of RG400 (including BNC connectors) resulted in 327 pF (LC meter), 354 pF (VNWA LC meter). Calculated is $11.5 \times 29.4 = 453$ pF so assuming that he LC meter is at approx 1 MHz and VNWA was at 4.4 MHz the effect of the coax length is observed.

Inductors

We want maximum Q so; square ($L/D = 1$), large dia wire, low loss form

We want to avoid ABS but any of the hard plastics should be OK. Air, of course, would be best! The largest PVC pipe available from home depot is 4 in.

I looked at using copper tubing but this was impracticle. Using #14 insulated wire the optimal (shortest wire length square coil); 38 uH 36.5T on a 3” Dia form wound 3” L, 68 uH 31.5 T on a 4” Dia form wound 4” L. On the 3” form, the 68 uH is 43.5 T 4.9” long.

There is also the possibility of using 3” pipejoiners which are close to 3.5”Dia and about 6” in length.

68uH = 32T (352”) 38uH = 24T (264”) #14 enameled.

Another option is using type 2 ferrite. A larger core size should give higher Q and better power handling. The T200A (1” high versus 0.55” for T200) material requires fewer turns which would be beneficial. Note that 23-27 pF of capacitance is added which presumably will reduce the C values of the 300 and 55 pf capacitors.

<table>
<thead>
<tr>
<th>Type 2 material (Red) on T200 size core</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductance</td>
</tr>
<tr>
<td>68 uH</td>
</tr>
<tr>
<td>38 uH</td>
</tr>
</tbody>
</table>

As I have a T300A and T200 core and 20 ft #14 wire, I could get the T200A by stacking two cores.

According to the micrometals power handling table either core should be suitable for 500W out.
Out of band traps should have less loss at the frequencies of interest. However their design is not straightforward and poorly documented. A rule of thumb was given by Hayward?. Antenna length is that of a dipole at the Geometric mean frequency and the traps are placed in the centre of each leg. This gave a starting point.

This is the method used:

1. Select trap frequency (start with Geometric mean (sqrt(f1^2+F2^2))
2. Assume a convenient C as this is harder to change and calculate L (L= 1/(4pi^2*C*fo^2))
3. Start with an overall length = λ/2 at fo
4. Start with trap at 25 and 75% of λ/2 (centre of legs)
5. Iteratively move trap to get F2 (5.3)
6. Increase overall length to get F1 (3.73)

This was redone using coax traps as designed by the Coax Trap software. This changed the C and L and required modification of the trap placement.

A quick look at the effect of asymmetrical dipole legs with the hope of having a double resonance to broadband the 80m dipole did not result in any significant bandwidth changes.
A word about Modelling Theory

NEC is a hybrid code which uses an electric field integral model for small wire-like objects and a magnetic field integral equation to model closed surfaces with time harmonic excitation.

SPICE takes a text netlist describing the circuit elements and their connections, and translates this description into equations to be solved. The general equations produced are nonlinear differential algebraic equations which are solved using implicit integration methods, Newton’s method and sparse matrix techniques.

A wire antenna can be considered to be a transmission line between the wire and “ground” consisting of Capacitance to the earth, inductance and resistance (including radiation resistance). An exact model is not possible but an engineering approximation can be made (”Mathematical Model of an Antenna”). While the resistance term varies with frequency and is the most difficult to model, this is not significant for our resonance purposes.
For EZNEC the trap was placed at the end of the inner legs resonant on 60m and outer leg wire added to get resonance at 80m. As this did not work as expected, the 10m-20m trap dipole example was modified for 80m-60m by changing the wire lengths and trap values to the as built case (80m 60m trap dipole R7.EZ). Again EZNEC Wanted longer outer wire legs.

To try and resolve this the LT Spice model below was developed. It turns out that for NEC to work with coupled resonators, the segments must be aligned and the same length. This is a bit inconvenient as the number of nodes needs to be constantly adjusted.
The EZNEC model, before knowing about the trap at nodes issue, (left) resulted in 80m legs too long (blue on right) but when Adjusted, good results were obtained.
For LTSpice the antenna wire parameters were calculated according to “Mathematical Model of Wire antennas” using a spread sheet “Antenna modelling parameters.XLS”

These values were first tried as a lump sum model which proved the concept but as what we really have is a transmission line between the traps, a transmission line model was developed as shown above. This agrees reasonably well with the as built measurements.
References

VE7KW development documents
  • VE7DS OCFD (ZS6BKW)
  • 80m Antenna evolution
  • Parasitic OCF design
  • Antenna modelling
  • 160/80/60 OCF Horizontal
  • VECTOR 80/60 in-band Trap Dipole
  • VECTOR 80/60 out-of-band trap dipole
  • VECTOR 80/60 as built

The off-centre Dipole Revisited ---, QST August 1990
RadCom Oct 2015 Antennas p 30-31