Using Sim Smith to Improve Antenna Matching

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The Objectives

• Eliminate antenna tuners
• Improve match to our rigs
• Minimize losses
• Improve operating efficiency
• Prepare for automatic switching
I wanted to replace these tuners that I also had to tune.
With this switching that I can automate with band decoders.
The Tools

• NEC Design Software
• Vector Network Analyzer
  or
• Vector Impedance Analyzer
• Sim Smith Design Software
The Process

- Measure an existing antenna
  or:
- Export antenna design from NEC
- Import data into Sim Smith, use it to design matching networks
  - Stubs
  - Matching sections
  - Capacitors, inductors, transformers
About Analyzers

• **Vector Analyzer** – includes phase
  – Needed for any design work

• **Vector Impedance Analyzer (VIA)**
  – Single Port
  – Measures impedance \((R + jX)\)
  – Time Delay Reflectrometry (TDR)
    • Line length, cable quality, splices
    • Works even w/antenna connected
About Analyzers

• Vector Network Analyzer (VNA)
  – Two port analysis
  – Measures impedance, TDR, and
  – Measures response through a network or system
  • Coax loss, velocity factor
  • Bandpass filter response
  • Coupling between antennas
  • Gain (loss) of networks and systems
Single Port Vector Analyzers

- AIM 4170 $545, 180 MHz
- AIM UHF $900 1 GHz
- Power AIM (Broadcasters) ($3K)
Two-Port Vector Network Analyzers

• TenTec TAPR – 100 MHz discontinued, works up to 120 MHz
• AIM VNA-2180 – 180 MHz $1,500
• N2PK – 60 MHz
  M0WWA builds to order w/options
• DG8SAQ VNWA 3E – 1.3GHz $750
  – Sold by SDR kits in the UK
  – Cost includes shipping to US
Low Cost Vector Analyzers

- All use a Windows computer to process and display data
- All couple data via USB port
- All come with free software
- All come with calibration set
- DG8SAQ powers from USB port
- All others need DC power
- All export data in standard formats
My Choice – DG8SAQ VNWA 3E

• Self powered from USB port, easiest to set up in the field
• Full specs to 500 MHz, reduced dynamic range to 1.3 GHz
• Active Yahoo user group support
• Ongoing development of software, firmware, hardware by DG8SAQ
About the Smith Chart

• Developed by Phillip Smith in 1939
• A method of plotting $R + jX$ data that allows graphical computations involving transmission lines
• Allows a “way of looking” at a problem that, with experience, suggests solutions
• A great learning tool
About the Smith Chart

• Impedances plotted on the chart are “normalized” to Zo

• *Normalized* means every data point is divided by the same value, in this case, Zo
The Smith Chart

Zo
Constant SWR Circles
1.5:1, 2:1, 3:1, 4:1
Transmission Line Rotates Impedances Clockwise toward the Transmitter
Impedances Rotate Counterclockwise toward the Antenna
Once around the chart = 180°
Halfway around the chart = 90°
We know that a 90° ($\lambda/4$) line “inverts” the load impedance.

Examples:
- A short becomes an open.
- An open becomes a short.
- Inductive becomes capacitive.
The Smith Chart

$\lambda/4$ Transformer

Open

Short

\textbf{$\lambda/4$ Transformer}
The Smith Chart

$\lambda/4$

$20 \Omega$

$125 \Omega$
$\lambda/4$ Transformer
The Smith Chart

\[ \frac{\lambda}{4} \]
This Talk is About Sim Smith

• Software that graphs transmission line problems and solves them
• We plug in our circuit, Sim Smith does all the math, graphs the result
• Sim Smith makes it easy
• It’s like NEC for transmission lines
• Runs in Java
• Let’s look at Sim Smith
Zooming in on lower left corner
50Ω Plots at the Center
80M Dipole Imported From NEC,

$Z_0 = 50\,\Omega$
SWR View $Z_0 = 50\Omega$
Zo = 75Ω
Zo = 75Ω

R = 76.439
X = ~0
Pin = 1

76.439 Ohms
-36.9m Ohms

3.675 MHz

xMtch type
75 Zo
1 SWR
0 QEye

steps from to name
LeesonDipole.dat 1 2 3 4
50 lin 3.50 GHz

SWR ~ 1.545
R = 79.43
X = 33.58
Mag = 0.214
Deg = 70.22
Series Resonant Circuit, $Z_o = 75\Omega$
Impedance Transformed Along Line
Impedance Transformed Along Line
Impedance Transformed Along Line
Impedance Transformed Along Line
At Antenna

Impedance at 180° at 3740 kHz

3500 kHz

4000 kHz

180° at 3740 kHz

3500 kHz

SWR=1.459
R=54.66
X=-13.3
Mag=0.187
G:MHz 3.740MHz Deg=-140.9

Zo:75.0
SWR Reduced By Line Loss

At Antenna

104 Ft Line Loss

3500 kHz

3.5018MHz SWR~2.634

4000 kHz
"Leeson" 80M Dipole Matching

180° 50Ω Line
+90° 75Ω Line
Tuned to 3675kHz

R = 76.439 Ohms
X = ~0
Pin = 0.858
76.439 Ohms
36.9m
180 deg

R = 73.992
X = ~0
Pin = 0.933
-36.9m
90 deg

R = 75.999
X = -0.882
Pin = 0.957
3.675 MHz

Mag = 0.2065
Angle = -1.542

3.675 MHz

50 Zo
1 SWR
0 QEye

steps from to name
LeesonDipole.txt 33
50 lin 3.53 3.8

Zo: 50.0
"Leeson" 80M Dipole Matching

At Transmitter

At Antenna

Line Loss

At Transmitter

At Antenna

SWR: L A B G
P Gain: L A B
Line Loss

SWR At Antenna

SWR At Transmitter

<table>
<thead>
<tr>
<th>MHz</th>
<th>SWR@MHz</th>
<th>xMtch type</th>
<th>Zo</th>
<th>QEYe</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.675</td>
<td></td>
<td></td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>swr</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.108</td>
<td>dB</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Line Loss

180° 50Ω Line
+90° 75Ω Line

SWR At Antenna

SWR At Transmitter

SWR: LABG
PGain: LABC

Angle = -1.978
lin = 1
deg

<table>
<thead>
<tr>
<th>MHz</th>
<th>xMtch</th>
<th>type</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.675</td>
<td>50 Zo</td>
<td>1 swr</td>
</tr>
<tr>
<td>0.108</td>
<td>100f</td>
<td>0 QEye</td>
</tr>
</tbody>
</table>

Mag = 0.20
R = 72.79
X = -9.18
Deg = -17.7
One More Time Around (360°)
Designing Matching Networks

• We need to learn a bit more about the Smith Chart to design networks

• There are two versions of the Smith Chart

• The standard version works with impedance \( Z = R + jX \) Ohms
  – Good for adding series reactance to a circuit
  – Centers of circles are on the right
The Impedance Smith Chart

Center of Circles
Two Versions of Smith Chart

• The inverted version works with admittance \( Y = G + jB \)
  – Good for adding components in parallel in a circuit

• Centers of circles are on the left
Inverted Smith Chart for Admittance

Center of Circles
Inverted Smith Chart for Admittance

0.02 mho (50Ω)
SimSmith Has Circles For Both
And Always Uses the Right Ones
When matching, we want to end up at the center of the chart.
Designing Simple Networks

• Adding reactance moves the impedance along the circles

• Series reactance moves $Z$ along circles centered to the right

• Parallel reactance moves $Z$ along circles centered to the left
  – Capacitance moves $Z$ downward
  – Inductance moves $Z$ upward
A Simple Problem, at Only One Frequency

• We have a $50 + j40 \, \Omega$ load (it’s inductive)

• We add a series capacitor

• $Z$ moves along a right-centered circle, because it’s a series cap
Series Reactance Moves Z
Along Circles Centered Right

$1 + j0.8 \ \Omega$

w/cap
A Parallel Example

• Same 50+j40 Ω load (.0122 +j.0097 siemens)

• On a paper Smith Chart, we would turn the chart upside down and plot it as 0.61 + j .485

• We’re used to thinking impedance, and there’s a lot of trig in making that conversion
SimSmith to the Rescue

• We draw the circuit with R, L, C, stubs, transmission lines, etc.

• Sim Smith does all the math, plots everything in the right place, computes the right way, always displays the result in Ohms (the Impedance Smith Chart)
Parallel Reactance Moves Z
Along Circles Centered Left

1 + j.8 Ω
w/cap
Our Simple Example

• Obviously, series C was the best solution for this network, but most matching stubs are connected in parallel

• We’ll nearly always be following the left-centered circles
Back to Antennas

• We design antennas to cover an entire band, not just one frequency
• NEC designs and antenna measurements produce not just one point on the Smith Chart, but many points
• SimSmith plots those points as a curve for the frequency range we are interested in
Back to Antennas

• Each point on the curve follows its own circle

• This can be tricky to visualize, so let’s look at our 80M dipole
80M Dipole Imported From NEC

50Ω System

4000 kHz

3500 kHz
Back to Antennas

• Adding 110° of coax, we get the Red curve

• Adding the parallel capacitor we get the Blue curve
110 Degrees Along Line, Add Cap

50Ω System

No cap

w/cap

4000 kHz

3500 kHz
Stub Matching

- A stub is a short length of transmission line connected in parallel with the main transmission line.

- An *open* stub <90° looks capacitive.

- Find a point on the line where the impedance is inductive (the top half of the Smith Chart) and add an open stub.

- Or add a shorted stub <90° at a point where impedance is capacitive (in the bottom half of the Smith Chart).
Simple Stub Matching

• Find a point on the transmission line where we can move along a left circle to bring the curve closer to the center
• Usually easiest to add a small length of line, but we can also move along the line toward the antenna
• Add a stub that moves the impedance
  – Open stub to move down
  – Shorted stub to move up
• Tweak position and stub for best SWR
Example – My 15M Yagi

• Home brew 4-element, I didn’t get the match quite right, and it’s up there

• A stub near the antenna will reduce SWR on the long run to the shack, also reducing cable loss

• There’s a coax splice below the rotator, a good place for a stub

• I made a VNA measurement there
SWR of 15M Yagi

Graph showing SWR vs frequency for a 15M Yagi antenna, with a SWR of approximately 1.712 at 21.225 MHz.
Smith Chart View of 15M Yagi, measured at junction below rotator
Let's Design a Stub
Add Coax To Rotate Impedance
Add Coax To Rotate Impedance
Add Open Stub
Add Open Stub
SWR View

At Antenna

With Stub

21MHz 21.225MHz 21.450MHz

SWR≈=1.022
Add 120’ Coax To Reach Shack
At Antenna

In Shack

SWR View

21.225MHz SWR~=-1.015 PGain~=-0.91dB
SWR and Feedline Loss

Feedline Loss

SWR At Antenna

SWR In Shack
Circuit For Stub

R = 29.644 Ohms
X = -4.946 jOhms
Pin = 0.812

R = 38.304 Ohms
X = 20.308 jOhms
Pin = 0.820

R = 49.027 Ohms
X = 0.4088 jOhms
Pin = 0.820

R = 49.812 Ohms
X = 0.7273 jOhms
Pin = 1

Mag = 7.527 m
Angle = 104.10 deg

29.644 Ohms
-4.946 jOhms

45 deg @MHz
21.225 ft
3.8613 vf
0.6666 Zo
50 /100f
0.50 @freq
10

28 deg @MHz
21.225 ft
2.4026 vf
0.6666 Zo
50 /100f
0.50 @freq
10

1.103K @MHz
21.225 ft
1 120 vf
.845 Zo
50 /100f
.22 @freq
2

21.225 MHz xMtrch
50 type
1 Zo
swr
0 QEeye
W6GJB’s 80M Dipole In Shack

DG8SAQ Vector Network Analyzer Software
9/4/2012 5:16:45 PM W6GJB 80M Dipole

Cursor Trace4: 3.500MHz 11.74

1: 3.501MHz 0.13+0.30 1.97
2: 3.598MHz 0.06+0.02 1.18
3: 3.699MHz 0.44+0.02 2.57
4: 3.900MHz 0.59+0.27 4.61
5: 3.999MHz 0.56+0.49 6.79
6: 3.999MHz 0.47+0.64 8.78

SWR 6:1 4:1 2:1

3500 4000
TDR of W6GJB’s Dipole Feedline

Antenna

21.5m (70.52 ft)
2:1 @ 3665 kHz
A Stub to Match for 75M SSB

- SWR too high for power amp to load above 3650 kHz
- Set Sim Smith display limits to 3650 – 3900 kHz (makes it easier to see what you’re doing)
- Add length to make Z inductive
- Add open stub
Smith Chart View of the Stub

Before Stub

With stub

10 ft coax added
Sim Smith Circuit for the Stub

R = 23.004 Ohms
X = -0.992 Ohms
Pin = 0.979

R = 67.741 Ohms
X = 45.078 Ohms
Pin = 0.924

R = 23.004 Ohms
X = -0.992 Ohms
Pin = 0.979

R = 24.597 Ohms
X = 10.358 Ohms
Pin = 0.993

R = 27.583 Ohms
X = -5.708 Ohms
Pin = 1

Mag = 0.2974
Angle = -161.5°

23.004 MHz
3.675 Mhz

-112.9 deg
112.89 deg
16.441 deg
47.387 deg
3.675 MHz xMtch

3.675 ft
10.267 ft
29.593 ft
50 Zo

0.50 /100f
0.50 /100f
0.50 /100f
0.50 /100f

10 @frq
10 @frq
10 @frq
10 @frq

50 Zo
50 Zo
50 Zo
50 Zo

50 swr
1 swr

0 QEye
0 QEye

-0.5 PG(dB)
-0.5 PG(dB)
SWR and Loss View of the Stub

Line loss

SWR Before Stub

3650 kHz

SWR in shack

With stub

3875 kHz

3.7625MHz SWr 3.50 dB PGain=-0.58dB
Two Methods to Compute Loss

• Include impedance mis-match between transmitter and line (called “mismatch loss”)
  – Not really loss, simply less power transferred to line

• Ignore mis-match, assume some sort of antenna tuner is used, or that Zs is significantly less than Zo
Without Mis-Match Loss

Line loss

SWR Before Stub

SWR in shack

With stub

3650 Hz

3.7625 MHz kHz

103 P Gain~=-0.58 dB

3875
When To Include Mis-Match Loss

• Most VHF/UHF systems
  – The path between the output devices and the output terminals is quite likely to be matched
  – The source is likely to be 50Ω

• When you know the source Z is really the same as Zo
When To Ignore Mis-Match Loss

• Any time an antenna tuner or matching network not part of the model is used to drive the line
• Any “tuned” power amp
• The source impedance, Zs, of most HF power amps, including transceiver output stages, is likely to be closer 25Ω than 50Ω
Maximum Power Transfer

• The classic theorem requiring $Z_L = \text{the conjugate of } Z_{\text{SOURCE}}$ applies to a variable LOAD impedance

• If $Z_{\text{SOURCE}}$ is variable, maximum power transfer occurs when $Z_{\text{SOURCE}} \ll Z_L$
Maximum Power Transfer

• The maximum power transfer theorem was derived for linear circuits

• Impedance matching at power amp outputs is really a matter of providing an impedance that the output devices want to see

• That may or may not be

\[ Z_L = Z_{\text{SOURCE}} \]
Matching my 80/40 JA Fan Dipole

67 FT 8213
80 CW JA

4 FT 8213
40 CW JA

10 FT 8213
40 SSB JA

2 FT 3227
23' 8213 OPEN STUB
75 SSB JA
My 80/40 EU/VK Fan Dipole

1. NE/SW DIPOLE 80/40

2. VERY SHORT
   - 45° 3.7 MHz
   - 50 Ohms
   - Shorted STUB
   - 75 SSB

3. VERY SHORT
   - 45° 7.05 MHz
   - 50 Ohms
   - Shorted STUB
   - 40 CW

4. 16 FT 3227

5. 40 CW

6. 22.5 FT 3227

7. 60° 7.15 MHz
   - 50 Ohms
   - Shorted STUB
   - 40 SSB
User Controls

Stubs
Stubs for my JA Fan Dipole
Stubs for my EU/VK Fan Dipole
Tuners I Replaced
(one more was added after photo)
Cost/Benefit Analysis – Benefits

- Antenna tuners are gone
- SWR <1.5:1 all bands
- Switching is simple, instantaneous
- Exactly resettable
- Much less clutter on operating desk, space above desk for P3 VGA
- Ready for YCCC “Mother of All Antenna Switches” to control it
Cost/Benefit Analysis – Benefits

• I had a lot of fun designing and building it (and learning things)
• I’ll use the VNA to tune bandpass filter boxes
• The VNA is a big help in finding issues in the antenna system, and in evaluating products like relay boxes
Cost/Benefit Analysis – Costs

- Some good coax, ~ 200 ft
- Top Ten 1x6 switches ($110 each)
- Connectors
  - PL259s ~ $3 each
  - Tees, a few at ~ $11 each
  - Elbows, a few, ~ $9 each
- Vector analyzer $500 - $1,500
  - Lower cost units plenty good enough for HF work
  - Or borrow one
Cost/Benefit Analysis – Savings

- Antenna tuners, manual switching
  - I’ve already sold five for a total of about $1,100
  - I had ordered three of the new Elecraft tuners and am beta-testing one with my Titans, but I could live without them
  - I’ll keep the beta unit for CQP
Rules of Thumb for Matching

- Locate matching elements as close to the antenna as practical
  - Generally yields a better match
  - Reduces line loss by minimizing the length of line with high SWR
  - Practical for monoband antennas
- Matching in the shack works fine too, and is easier to switch
Ideas for Matching

• Try a 75Ω matching section in 50Ω line for an antenna near resonance
  –90°, 180° and multiples of 180°
  –Add coax if needed to adjust length between 75Ω section and antenna so curve crosses the center horizontal (zero reactance line)
  –Tweak lengths watching SWR at TX
1\lambda \text{ of } 75\Omega \text{ CATV Hard Line}

Line Loss 0.76\text{dB}

No Matching

w/ 58 ft CATV Hard Line

w/ Stub
3\lambda/2 of 75\Omega CATV Hard Line

Line Loss 0.85 dB

No Matching

w/ 88 ft CATV Hard Line

w/ Stub
2\(\lambda\) of 75\(\Omega\) CATV Hard Line

No Matching

Line Loss 0.9 dB

w/ 117 ft CATV Hard Line

w/Stub
$5\lambda/2$ of 75Ω CATV Hard Line

- Line Loss 1.02 dB
- No Matching
- w/Stub
- w/146 ft CATV Hard Line
Rules of Thumb for Matching

• Don’t rule out a 75 ohm matching section with a tri-bander

• $2\lambda$ on 20M (117 ft of CATV hard line) is $3\lambda$ on 15M and $4\lambda$ on 10M

• I’m using 117 ft lengths of CATV hard line on my 20M and 15M monobanders, and may put one half that length on my 10M Yagi (because it’s much closer)
Rules of Thumb for Stubs

• Try for an open stub first
  – It’s usually shorter for moderate mismatches

• Higher $V_F$ coax requires more coax, but cutting errors will be lower

• Use good coax, but don’t worry about small loss differences
Other Smith Chart Uses

• Smith charts can work for design of L – C networks too

• Many networks can be built with L and C or stubs, or even a mix

• BUT – although stubs are “sort-of like” L and C, they are fundamentally different
How Stubs Are Different

• An open stub $< 90^\circ$ is capacitive, but it’s capacitance varies with frequency.

• Likewise, the inductance of an shorted stub $< 90^\circ$ also varies with frequency.

• A stub or matching section that is $90^\circ$ or $180^\circ$ at some frequency $F$ is $85.5^\circ$ or $171^\circ$ at $0.95x F$. 
How Stubs Are Different

- These subtle differences often make one or the other kind of component a better choice for any given circuit
Thinking About Stubs and Antennas

• Near resonance, a half wave dipole (or quarter wave vertical) acts much like a series resonant circuit

• Near resonance, an open $\lambda/4$ stub or shorted $\lambda/2$ stub acts much like much series resonant circuit

• Near resonance, a shorted $\lambda/4$ stub or open $\lambda/2$ stub acts much like a parallel resonant circuit
Thinking About Stubs and Antennas

• An open stub shorter than $\lambda/4$ looks capacitive, and can tune out inductance

• A shorted stub shorter than $\lambda/4$ looks inductive, and can tune out capacitance

• Stubs move impedance along left-centered curves to, or away from, center of Smith chart
The Ultimate Matching Section

• Loss in any line causes the impedance to move closer to the center of the chart (lower SWR)
• High losses >>> low SWR
• 1,000 ft of RG58 makes almost any antenna look perfectly matched
  – Approaches 1:1 for almost any load
  – Burns 99% of the TX power at HF
References

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Using Sim Smith to Improve Antenna Matching

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