NanoVNA
Good for Tuning Antennas

An ”Electric Smith Chart”

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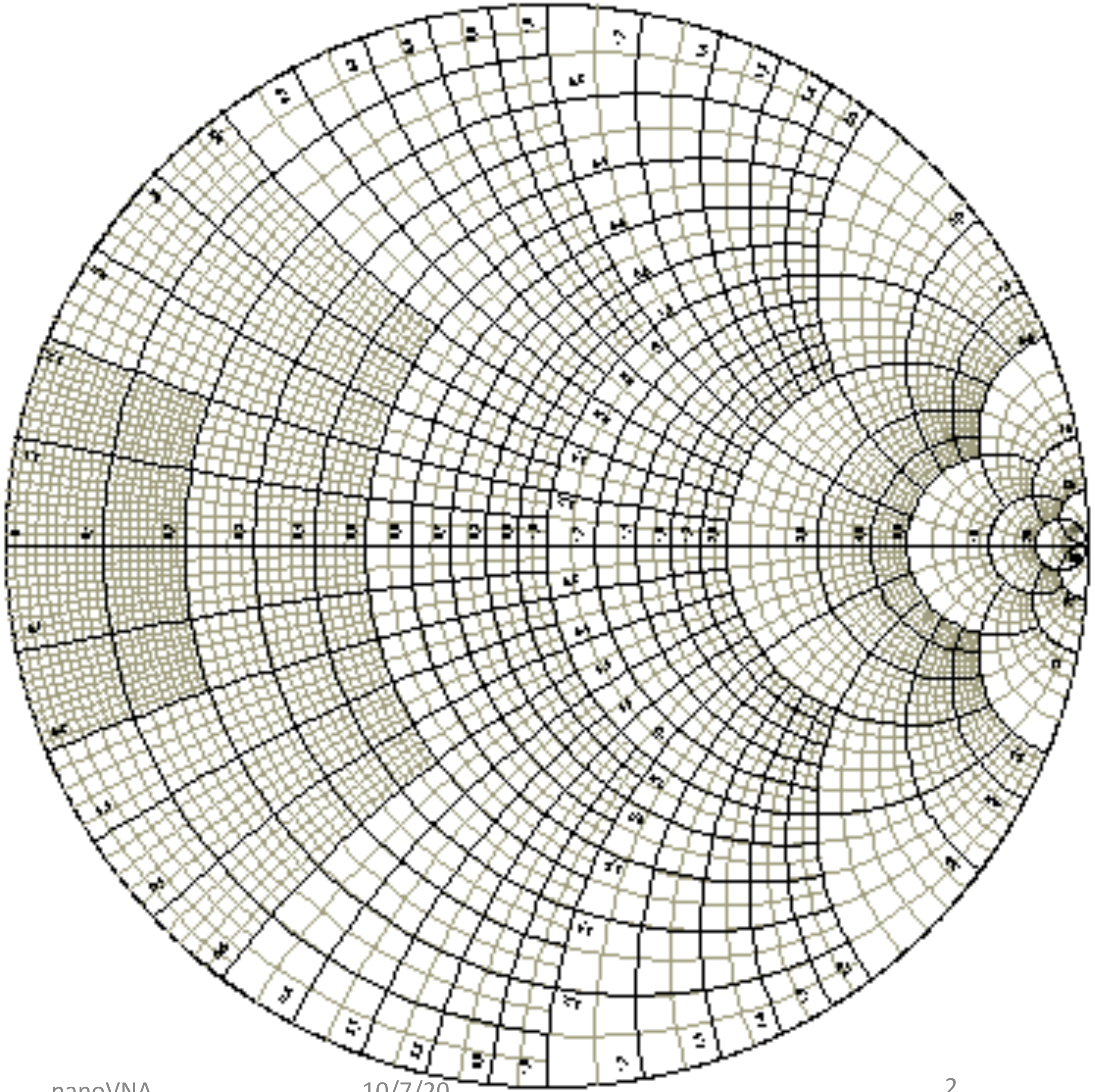
Ahhhh!!!

It’s October. I’m not sure which round thing is scarier.
Some would say it is the Smith Chart!



Antennas

- Frequency Domain – an antenna presents an impedance at the feed point that depends on frequency
  - At resonance, the impedance looks like a resistor (radiation resistance)
  - Off resonance, the feed point impedance looks more reactive
- Ideal situation:
  - The antenna is tuned to resonance at the desired operating frequency
  - The radiation resistance of the antenna is the same (usually 50 Ω) as the transmission line back to the rig and the rig's output impedance – matched!
  - Matched means that the VSWR (voltage standing wave ratio is 1:1 – all transmitter power goes from the rig into the radiation resistance of the antenna).

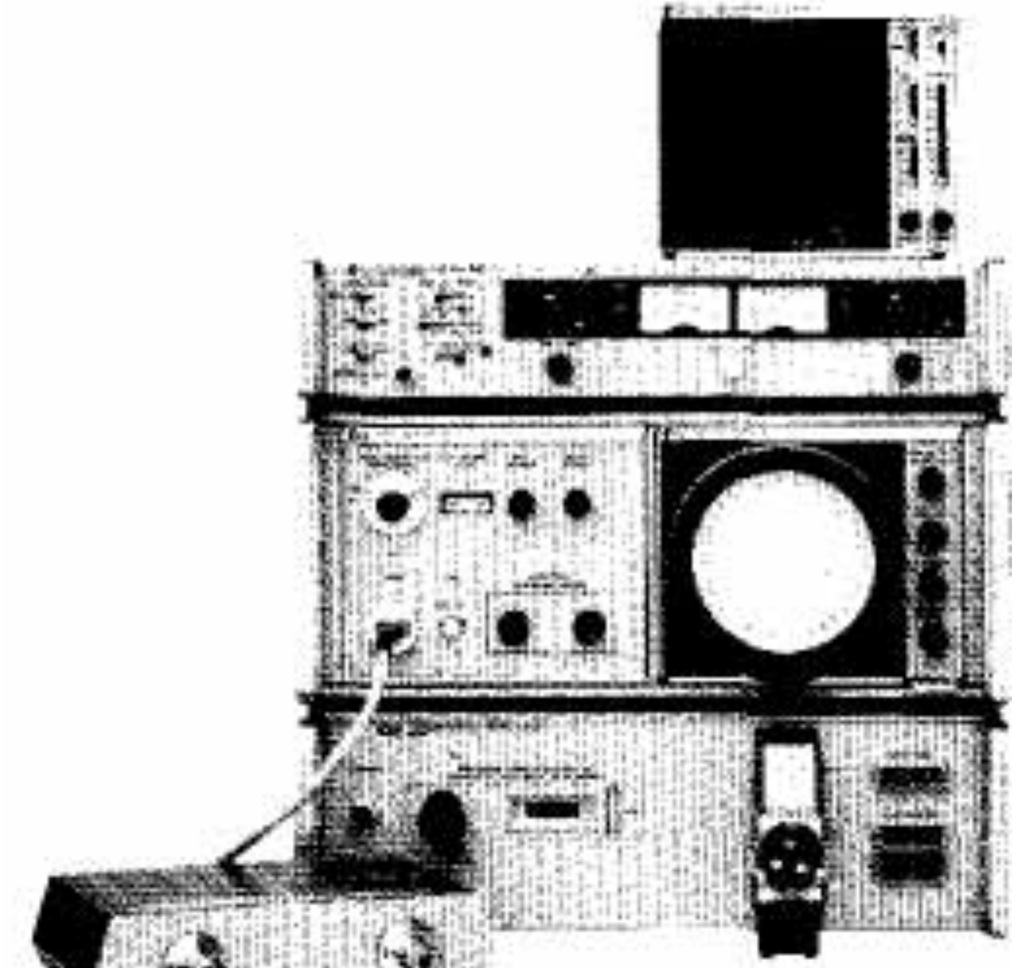
Some Available Background Info

- Smith Charts and Transmission Lines
  - Jim Stiles, University of Kansas, 2010: http://www.ittc.ku.edu/~jstiles/723/handouts/2_4_The_Smith_Chart_package.pdf
  - For a deeper dive on S-parameters – HP Application Note 95 http://www.hparchive.com/Application_Notes/HP-AN-95-1.pdf
  - Transmission Lines – "**Transmission Lines (Schaum's Outline Series)" Paperback –** June 1, 1968 by Robert A. Chipman (Author)
    - Alas, I can't find my copy – at least it seems to be available on Amazon.com
  - Microwaves 101: https://www.microwaves101.com/encyclopedias/smith-chart-basics
  - If you want to drown in network theory, "**Network Theory:** An Introduction to Reciprocal and Non-reciprocal Circuits" by Herbert J. Carlin and Anthony B. Giordano, Prentiss-Hall, 1964. (Yep, I took a course with Carlin back in the day).
  - Lots on the web.
- NanoVNA
  - A tutorial in three parts by Gunthard Krause, DG8GB
  - http://www.gunthard-kraus.de/
  - Daniel Marks's (KW4TI) presentation http://www.kb5tx.org/Presentations/RARS-Club-NanoVNA-presentation.pdf

What is a VNA (Vector Network Analyzer)?

- Measures impedance as a “vector”.
- Because of how reactance works, reactive impedance varies with frequency.
- How to think about impedance
    - Pure inductors are reactive with the magnitude of $Z = X_L = 2\pi FL = \omega L$ (ω is frequency in radians per second)
    - Pure capacitors are reactive too with the magnitude of $Z = X_C = 1/(2\pi FC) = 1/\ \omega C$
    - What is interesting is that reactive impedance is thought of in terms of “imaginary” numbers. $Z_L = j\ \omega L$ and $Z_C = 1/j\ \omega C$ where $j = \sqrt{(-1)}$.
    - The vector “thing” is considering impedances that are sums of real (resistive) and imaginary (reactive) parts – a “complex” quantity or R + jX.
- The VNA measures complex impedances as a function of frequency and plots them on a Smith Chart on the LCD display.

Vector Network Analyzer back in the day (1971)



I used something like this in "G-school" in 1974-75
There was an "electric Smith Chart" (polar) display connected to a separate S-parameter test set with APC-7 connectors. Calibration was by hand (using a crank to move the reference plane to null out fixture and cable electrical lengths). The unit I used worked up to about 12 GHz (my measurements focused on 4-8 GHz). Cost? Probably $5000+ nearly 50 years ago.

Hewlett-Packard Network Analyzer

8411A Harmonic Frequency Converter
84128 Phase Magnitude Display
8414A Polar Display
8717A Transistor Bias Supply
8745A S-Parameter Test Set
11599A Quick Connect Adapter
116008 or 116028 Transistor Fixture
11609A Cable Kit
The 8410s Option 400 or 401 System

The future N1GNB in the Cornell microwave lab using the HP S-parameter test set, ca 1974

Nerds R Us

- Note the holstered calculator
- No more slide rules here!
- Nice Tektronix scope too.

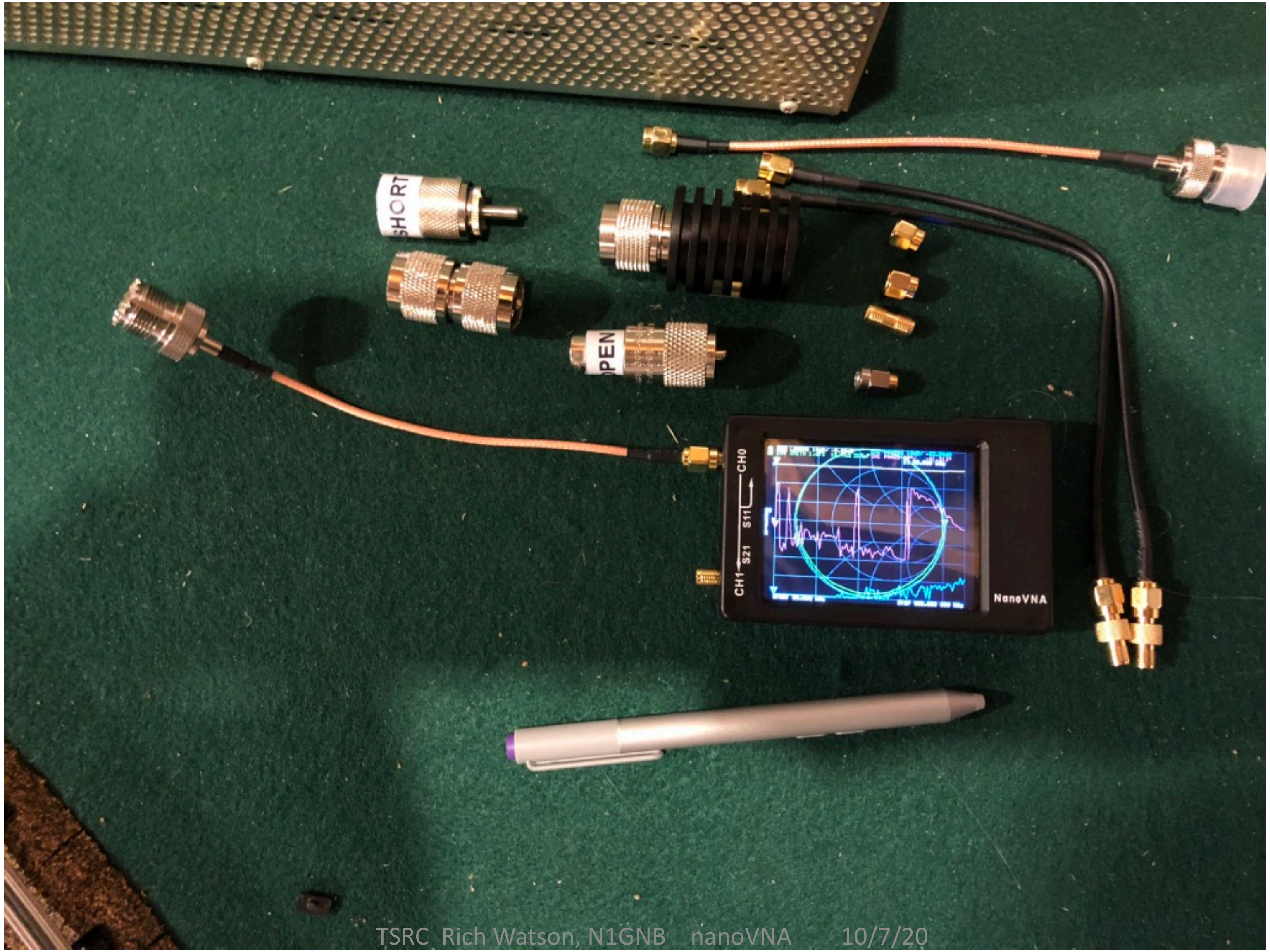
- My professor, Walter Ku, didn’t like the fact that characterizing SMA-to-microstrip launchers wasn’t very repeatable.
- He “sentenced” me to 3 weeks of investigating this problem.
- He finally took me to Griffiss Air Force Base in Rome, NY where there was an HP system that allowed very quick automated calibration. Same results!
- The nanoVNA has that sort of automation! A little cheaper…

NanoVNA with included and additional accessories

Now we can use this NanoVNA for 50 kHz to 900 MHz
Priced at $70 to $100 in 2020 (Amazon)

Comes with:

SMA to SMA cables
SMA short
SMA open
SMA 50 Ω load
SMA barrel
USB charging and host control cable



Desirable additions:

SMA to UHF cables
UHF short (made)
UHF open (made)
UHF barrel
UHF 50 Ω load
Longer USB charging and host control cable (USB-C to USB-A)
Stylus for on-screen menus

Some Smith Chart ideas – picture from HP App Note 95

- Interesting places on a Smith Chart
  - Center – 50 Ω (typically) resistive (all impedances are "normalized" to 50 Ω) – 1 +j0 at the center means 50 Ω
  - Left side – 0 Ω resistive
  - Right side – infinity Ω resistive
  - The circles are constant resistance (regardless of reactance)
  - The lines splaying out from infinity at the right are curves of constant reactance.
- The Smith Chart can depict the reciprocal of impedance – admittance. It looks the same, but with the infinity point left and the 0 point right.
- The nanoVNA normalized to 50 ohms (not helpful for 450 Ω ladder line).
- The nanoVNA is good not just for antenna analysis, but also linear RF low-level receiving amplifier or filter measurements as seen in the chart (no, it won't handle legal limit RF).

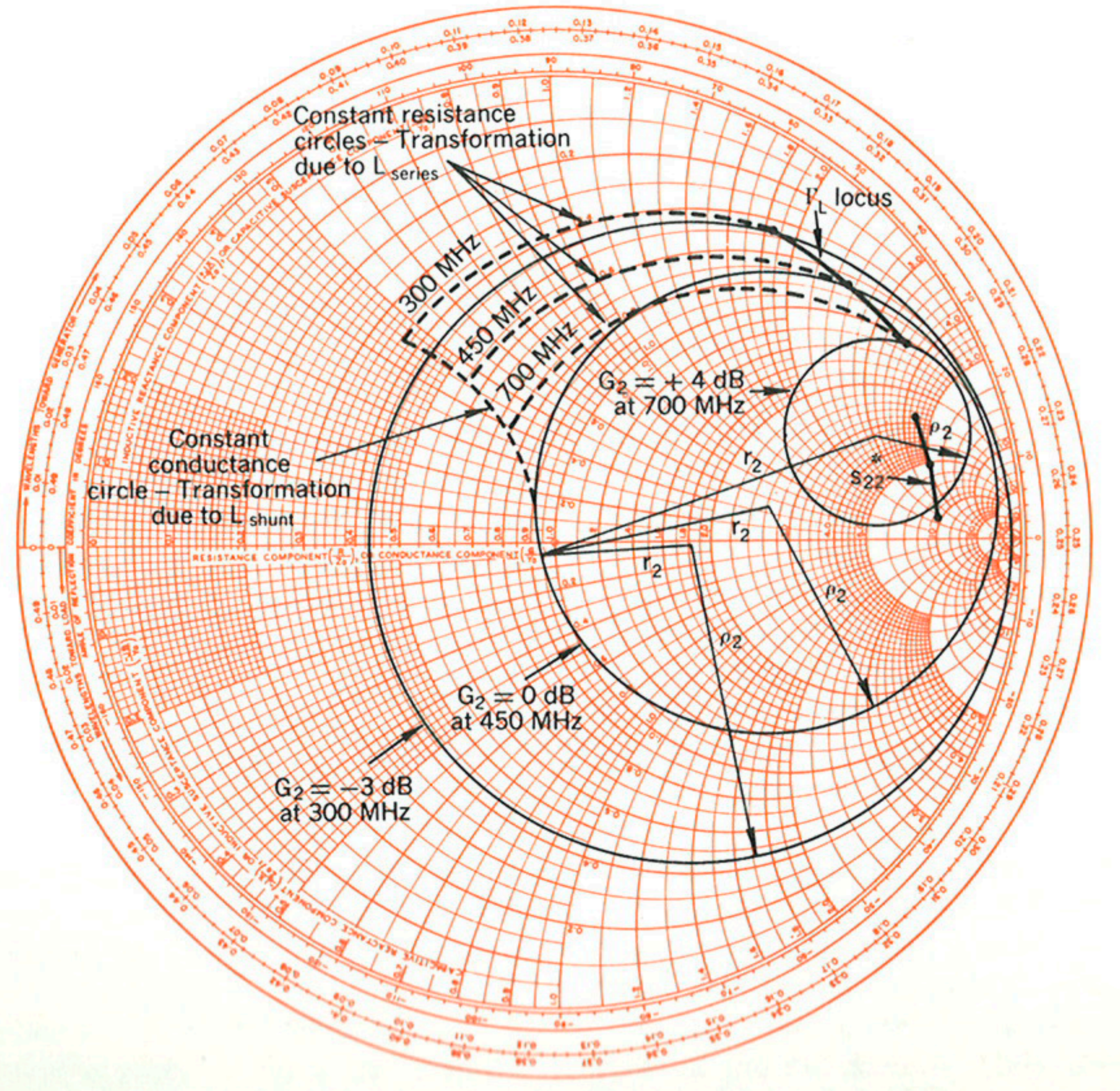


Fig. 8 Smith Chart for broadband amplifier design example.

Transmission Lines and the nanoVNA

- Measurements right at the antenna feed point are indeed practical with the nanoVNA. It is small, battery powered and can be operated from the admittedly awkward touch screen user interface.
  - The user interface is a royal pain for me.
  - Using the nanovna-saver program on my Surface Pro 3 running Windows 10 worked very well. The NanoVNA is attached using a USB-C to USB-A adapter cable.
- More practically (for me, anyway), the nanoVNA can be attached to the 50 Ω transmission line heading up to the antenna (RG-8x in my case).
- I confess that I have not mastered using the nanoVNA ”barefoot” without an attached PC running nanovna-saver. But ”barefoot” use could be handy up on a tower.

What do T-lines do to antenna feed impedance?

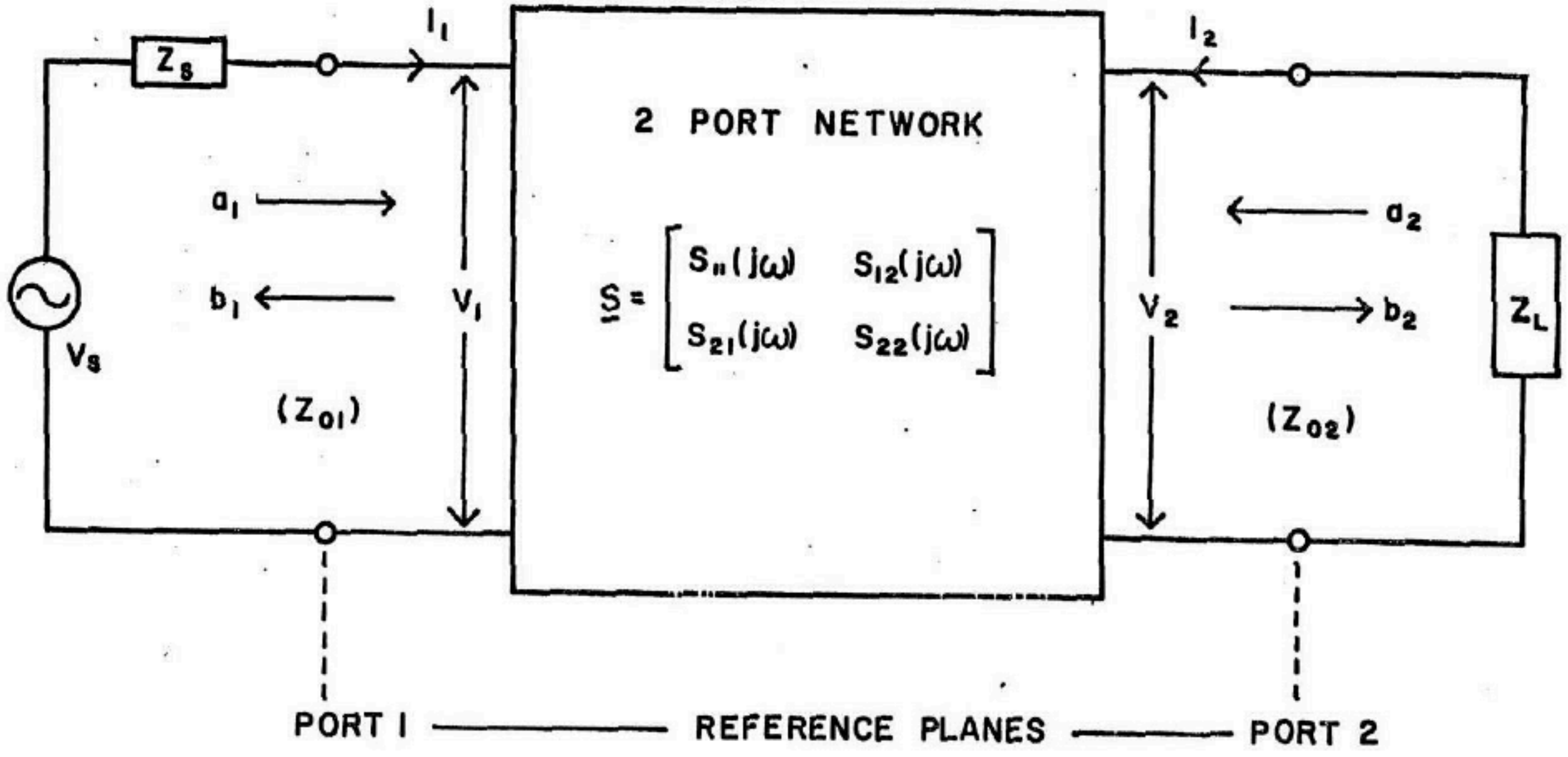
- The Smith Chart shows normalized impedance (Z/Z_0) at a "reference plane" where Z_0 is the characteristic impedance of the transmission line (50 Ω for most ham applications).
- A T-line has "electrical length", backing the measurement off in distance from the antenna feed point. The reference plane is not right at the antenna, but some distance away. A quick note – electrical length is not necessarily equal to physical length due to the dielectric constant of coax insulation.
- Yes, impedance changes with distance from the feed point.
- On the Smith Chart, that means moving around a circle centered at the 50 Ω center point (coordinates 1+j0 normalized). One trip around the whole Smith Chart is ½ of a wavelength at the measurement frequency.
- As a side note, if you short out the transmission line at the feed point and "back off" by ¼ wavelength, the 0 + j0 Ω impedance become infinity! (only at that one frequency).

The Smith Chart is good for depicting complex numbers - impedance or reflection coefficient

- We hams are interested in matching an antenna to a transceiver – reflection is the name of the game.
- Smith Chart distances from the center represent reflection coefficient (the middle is 50 Ω with a reflection coefficient of 0. The outside of the Chart is where the reflection coefficient magnitude is 1 (all energy is reflected).
- A VNA measures S-parameters (as we will see in the next slide). S11 is the complex reflection coefficient.
- The Smith Chart circles tangent to the right side are impedances with constant resistance.
- A T-line can be thought of as a 2-port network, one port faces the antenna, the other port faces the transceiver.
- The 2-port is “terminated” by the antenna impedance at one end and the transceiver at the other. The transmission line (RG-8x or whatever) has a characteristic impedance Z_0 of 50 Ω which matches the output impedance of the transceiver by design.
- All we must worry about is the antenna.

FIGURE 3-1.1 Two Port Network

Z_L is the antenna impedance, Z_S is the transceiver impedance
S11 at the input is what we are interested in, the reflection coefficient

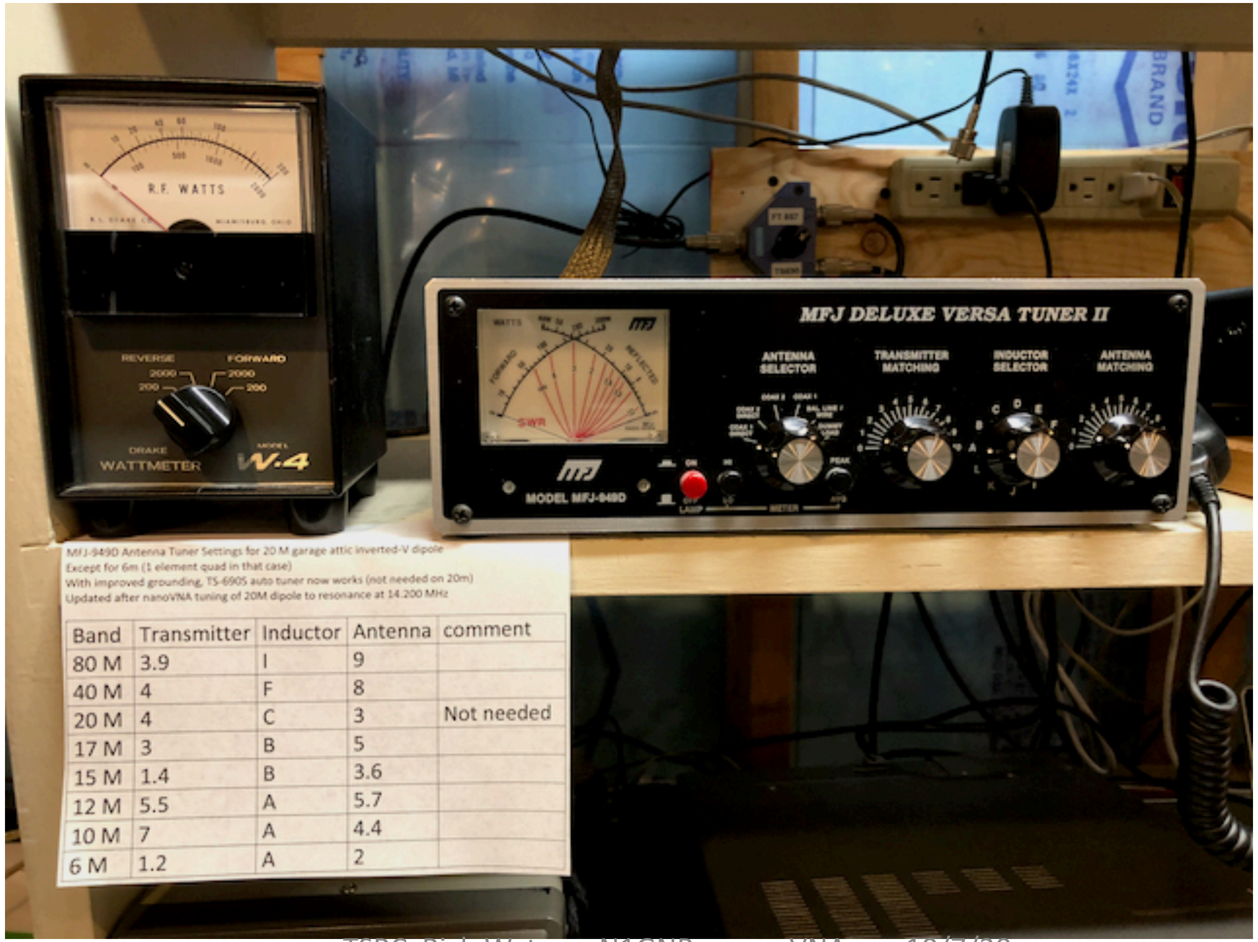


Reflection Coefficient S11

- The complex reflection coefficient is S11 looking into the T-line towards the antenna.
- If the reflection coefficient is 0, all transmitted power heads up the antenna and out. The VSWR would be 1:1 in that case.
- VSWR = (1+|S11|)/(1-|S11|). |S11| means "magnitude" of the complex S11.
- Return Loss in dB RL = $20\log_{10}|S11|$. A low VSWR means very high return loss (not much energy bounces back).
- On the Smith Chart, VSWR is 1:1 at the middle. With a short or an open at the far end, VSWR is ∞:1 (everything comes back – no return loss). The entire outside circle of the Smith Chart corresponds to no return loss and very high VSWR.
- Low return loss (high VSWR) is a bad thing – little energy leaves the transceiver.
- Impedance: $Z = Z_0(1 + S11)/(1 - S11)$

NanoVNA in action

- 20M dipole in my garage attic – I always needed to use an antenna tuner. At first, I needed my MFJ-949D. The rig's antenna tuner had problems.

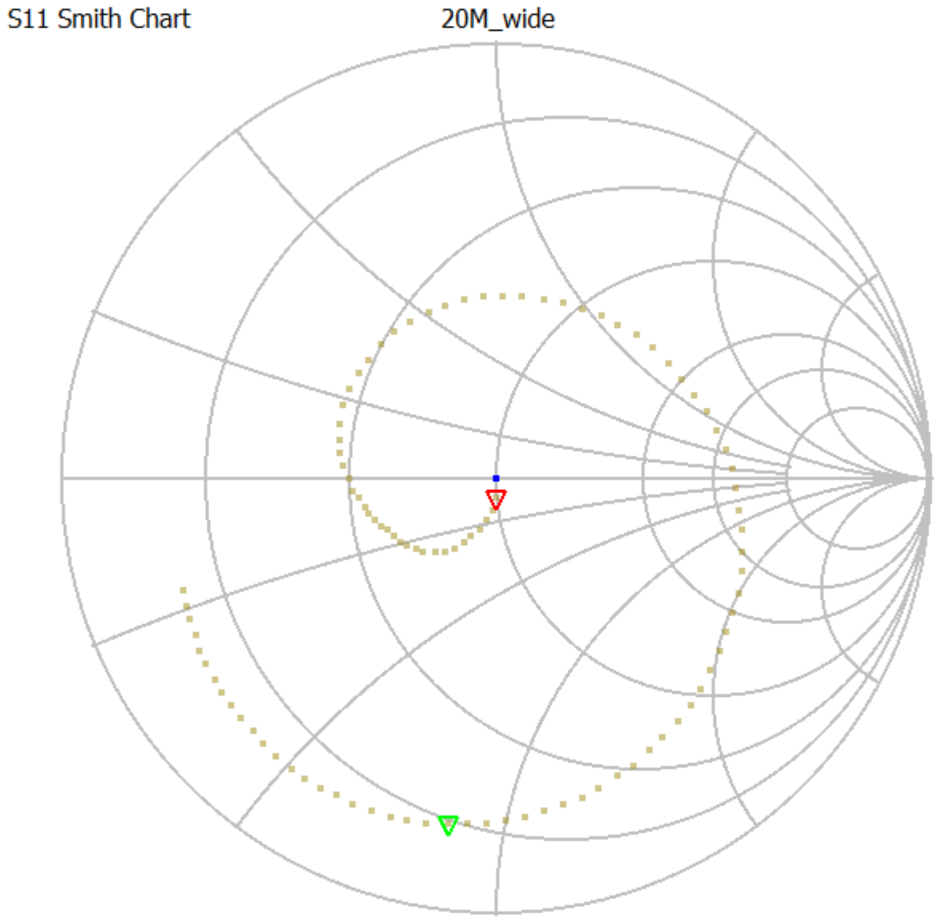


NanoVNA in action

- I took some time, effort and heavy braid to do a better job of grounding the station down in the cellar.
- Now the rig's antenna tuner could handle most bands.

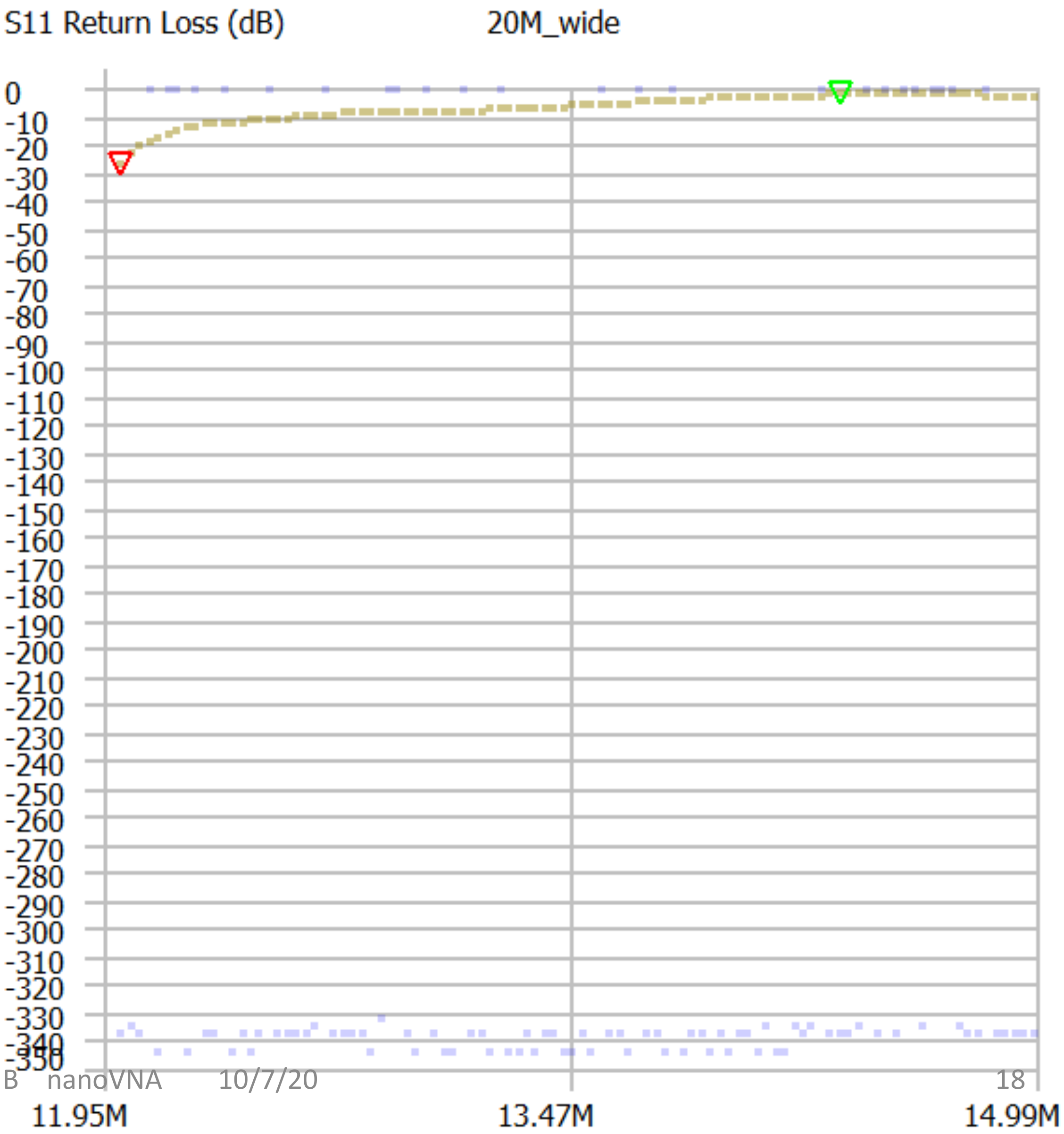
So, Better grounding helped – resonance in 20M band? Well, no.

- Here is the Smith Chart view from nanovna-saver
- Green is at 15 MHz and Red is at 12 MHz.
- Ouch – the antenna gets near the middle (good match) just below 12 MHz.
- Needs some tuning.



20M dipole – before tuning: return loss view

- Return loss is near 0 except below 12 MHz.
- The “dip” with higher (30 db) return loss near 12 MHz shows that energy there actually goes into the antenna.

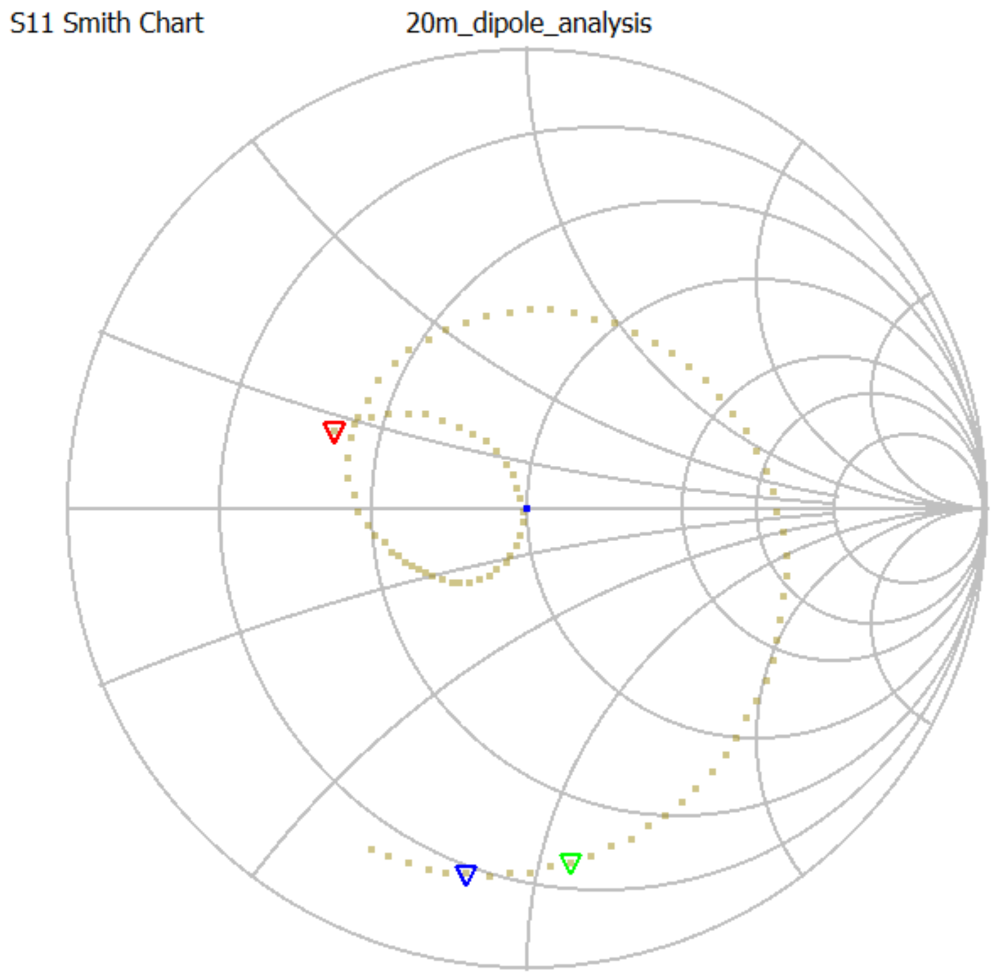


If I were really good at the nanoVNA user interface…

- I could have brought the nanaVNA to the garage attic and done my measuring and element length adjustments *in situ*.
- I did do this and had problems. My finger is too ham-handed (not to make a pun or anything). Also the menus are complicated and deep.
- So, back to the shack in the cellar to do the tuning from the rig end of the transmission line.
- I calibrated the nanoVNA (more detail on this later) and hooked it where the T-line leaves the shack and heads to the garage attic.
- Since the antenna resonated at 11.95 MHz, I had to shorten the dipole halves. After a bunch of trips between the shack and the garage attic to tune, things got better…

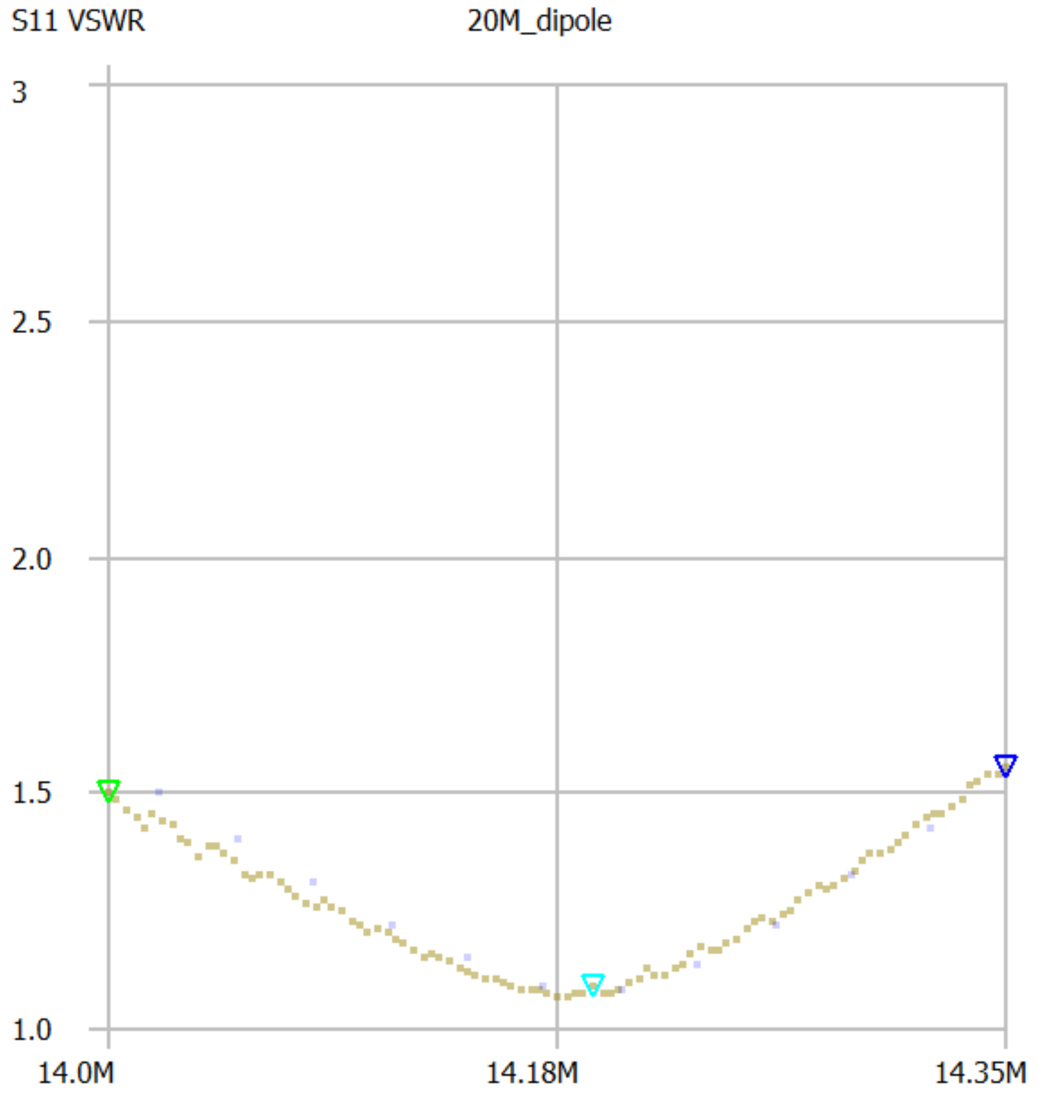
After tuning the 20M dipole – Smith Chart view

- Resonance (hitting the middle of the Smith Chart (1+j0)*50 Ω moved to 14.200 MHz (ha!)
- As one moves off-resonance, it is interesting to see the “tour” of impedances (and reflection coefficients) on the Smith Chart.
- Red is low freq – 11.5 MHz; Green is high freq. at 14.5 MHz.



Looking at VSWR of tuned 20M dipole

- I learned how to look at VSWR directly in nanovna-saver.
- The light blue triangle is 14.200 MHz.

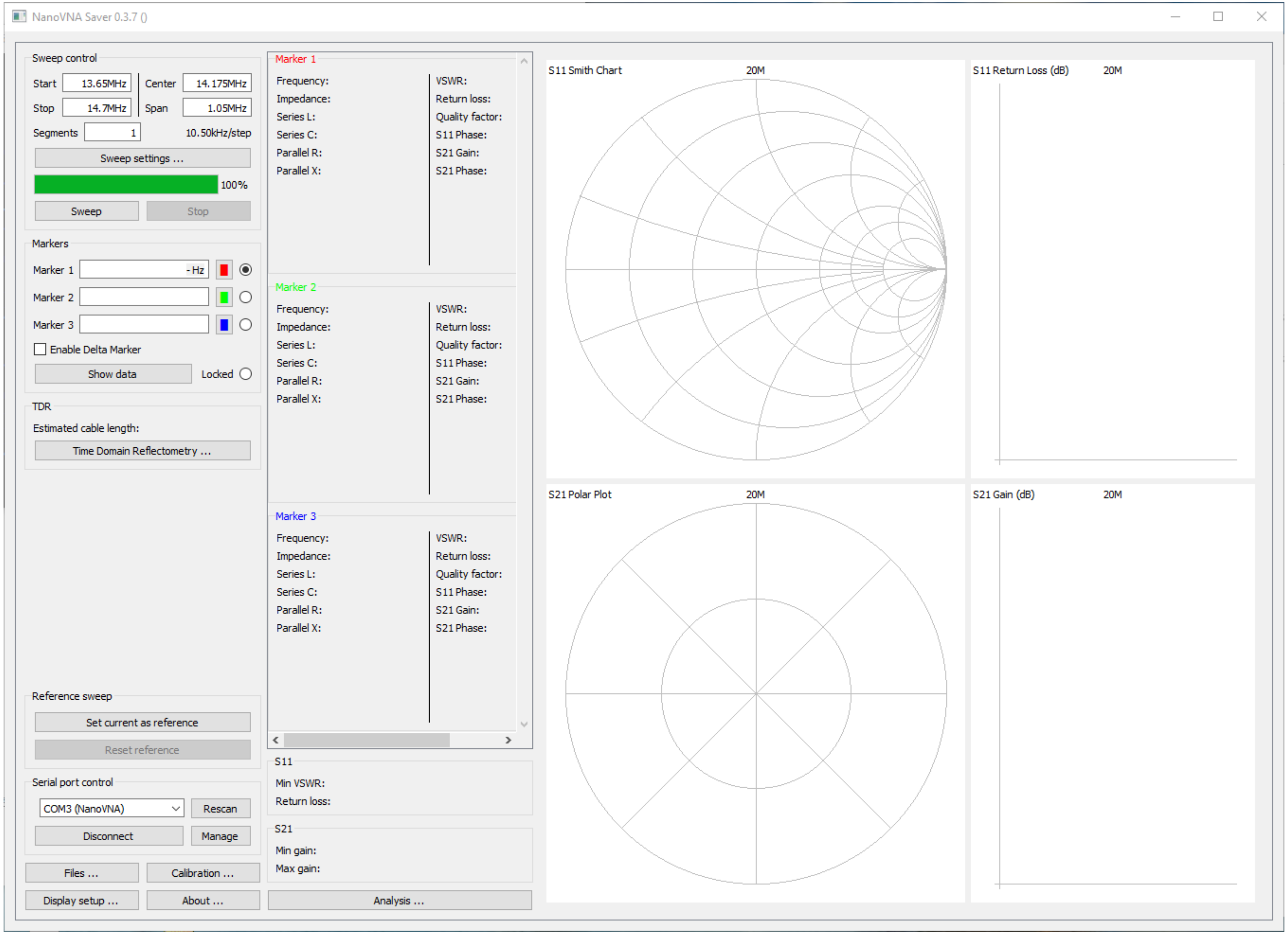


Starting up the nanoVNA

- Daniel Marks' presentation is shows how to navigate the menus to do the calibration.
- But the nanovna-saver PC program allows this too (easier for me).
- Download and install nanovna-saver (on-line for PC, Mac, Linux)
- Nanovna-saver set-up steps
  - Connect the nanoVNA to the PC (or Mac) via supplied USB-C to USB-A cable
  - Launch nanovna-saver, make sure the USB port appears in lower-left
  - Connect nanoVNA in nanovna-saver
  - Set up the sweep range of interest (101 points available – default at startup is 50 kHz to 900 MHz); I set up the sweep to average 3 measurements per point. Doing "DC to daylight" measurements might miss some fine details with 101 points (can be logarithmically spaced). Setting up for a narrow band is the name of the game.

Nanovna-saver 0.37 screenshot

- Newer version than I used in April and May
- Serial port control LL
- Calibration also LL
- Sweep controls UL
- Ability to place markers



Calibrating the nanoVNA

- Calibration procedure once frequency range of interest is selected
  - This discussion assumes set up of just nanoVNA port 0 for reflection measurements only
  - Hit Calibration… in lower left of nanovna-saver
  - In the calibration pop-up window, hit Calibration Assistant
    - Connect Short (I just used a PL-259 plug with center pin shorted to sleeve, follow directions to allow the nanoVNA to take short data across the frequency range
    - Connect Open (just a PL-259 with no connections, follow open directions to capture cal data
    - Connect 50 Ω load and collect cal data
    - Cal data gets stored in nanovna and can be output as a file for future use
    - Calibration is done
  - You can do 2-port measurements (S21 or gain of a passive filter, for example)
    - The calibration process uses a through cable (barrel) connector in that case as well.
    - S22 measurements
    - One thing I learned was that a passive filter may provide a good match in the passband, but a terrible one outside the passband (self-evident, I imagine, given some thought).

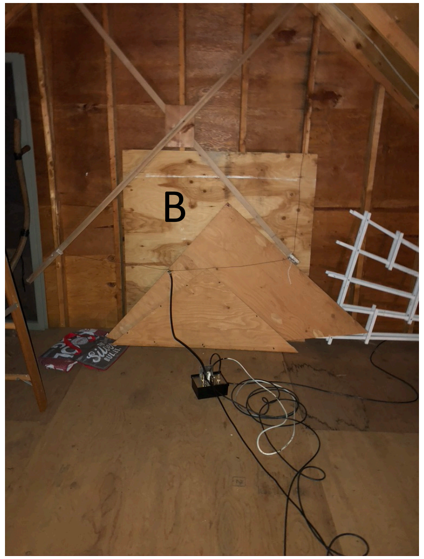
Measure the antenna characteristics

- Measurement is simply the reflection characteristics as seen at the measurement reference plane (end of the transmission line just before connection to equipment such as tuners, rigs, etc. in the shack)
- When calibrating for PL-259 connectors, the reference plane is not "at" the nanoVNA SMA connector, but where the short, open and load calibrations are done – about 6-7" out from the nanoVNA. Think of the cable kludge as a measurement "fixture".
- Connect port 0 of the nanoVNA to the transmission line end
- Select the graphs desired: Smith Chart, VSWR, return loss, etc.
- Hit sweep to collect the data
- Data shows up in the graphs on the right side of the nanovna-saver window

Results

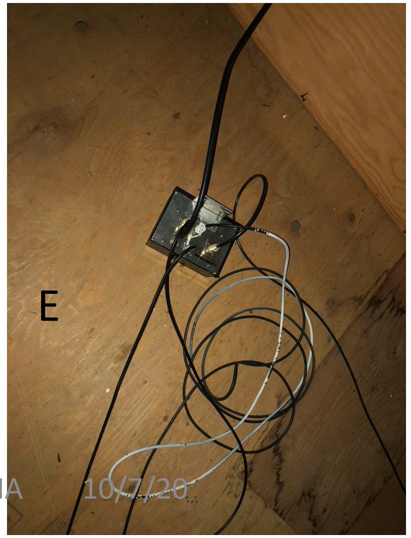
- You have seen the results of tuning the 20M dipole (an inverted Vee in the garage attic with the ends - 2 feet worth - bent to horizontal)
- The 20M dipole results allow the antenna to be used with no antenna tuner engaged near 14.200 MHz. Up around 14.300 MHz and down near there is a 1.5:1 VSWR and can be touched up with a tuner if desired (or not)
- How about other antennas in the garage attic?
- First a comment on antenna connections in the attic
  - Ameritron remote 4:1 antenna switch specified for HF (but pressed into service for 6M and 2M – seems to work)
  - Four antennas connected: 20M dipole, 6M 1-element quad, 2M Yagi, 2M J-pole
  - 100 ft of RG-8x from antenna switch to shack in cellar

Antennas in garage attic

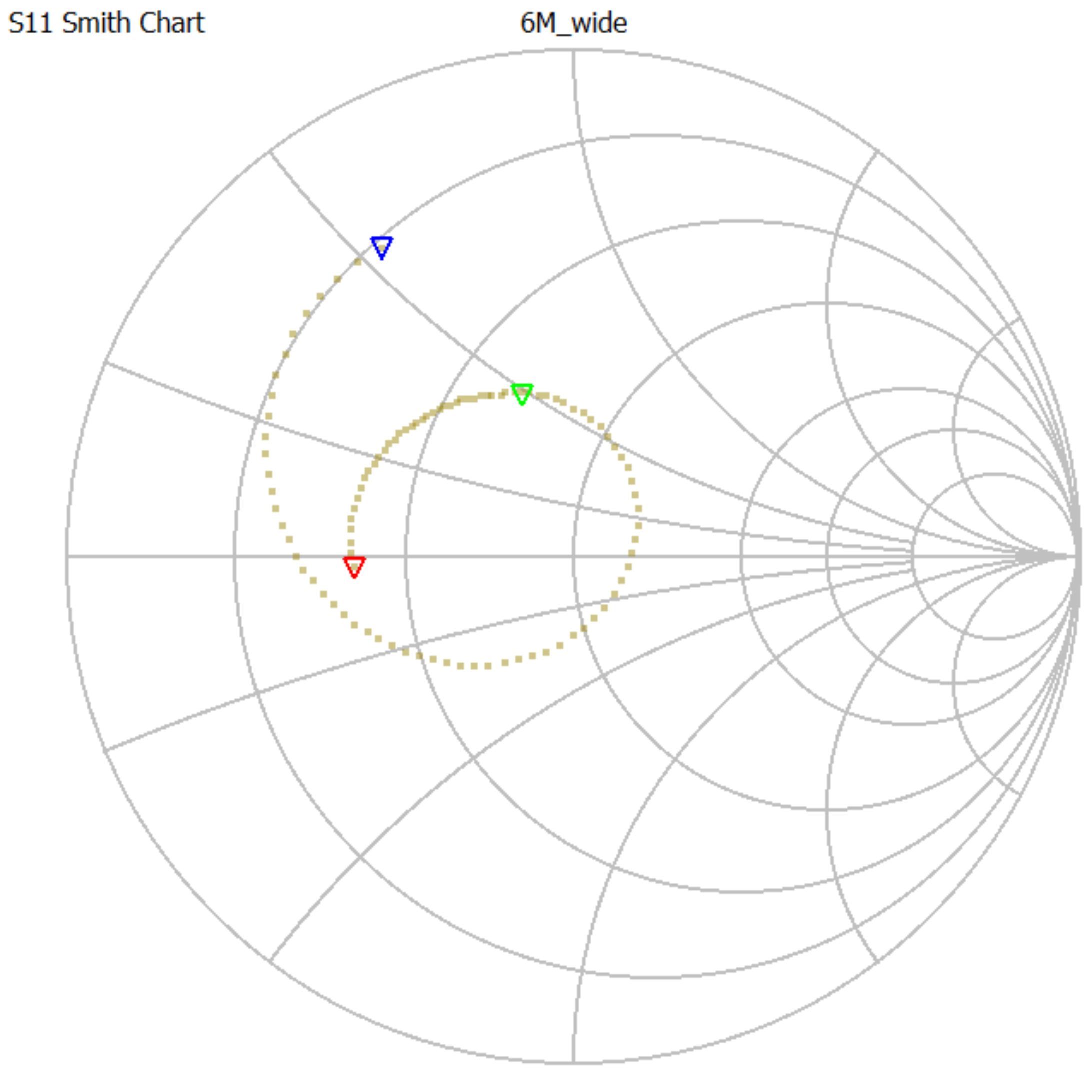


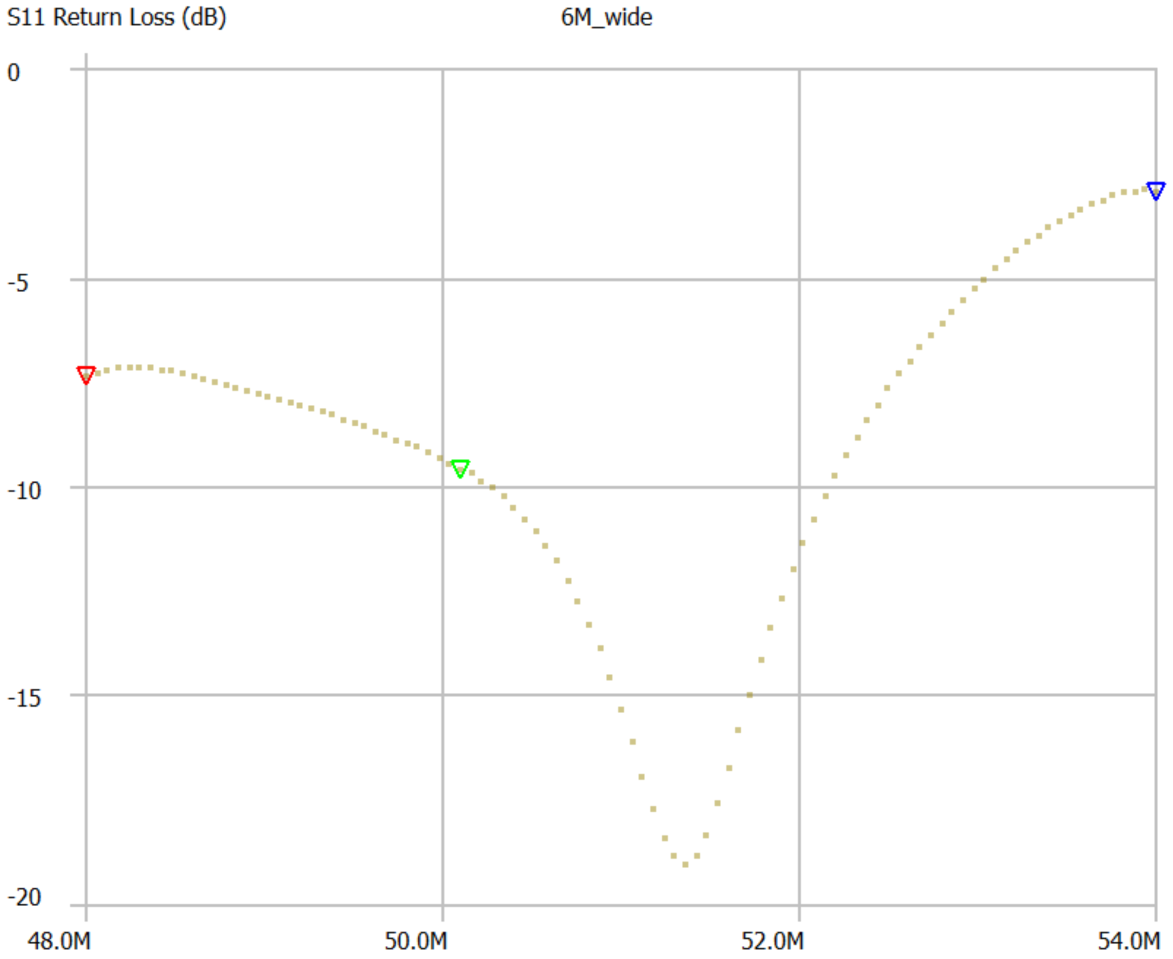
Antennas left to right plus antenna switch

A) Center feed point of 20M inverted V dipole
B) 6M 1-element quad against wall
C) 7-element 2M Yagi
D) 2M J-pole
E) Ameritron remote antenna switch



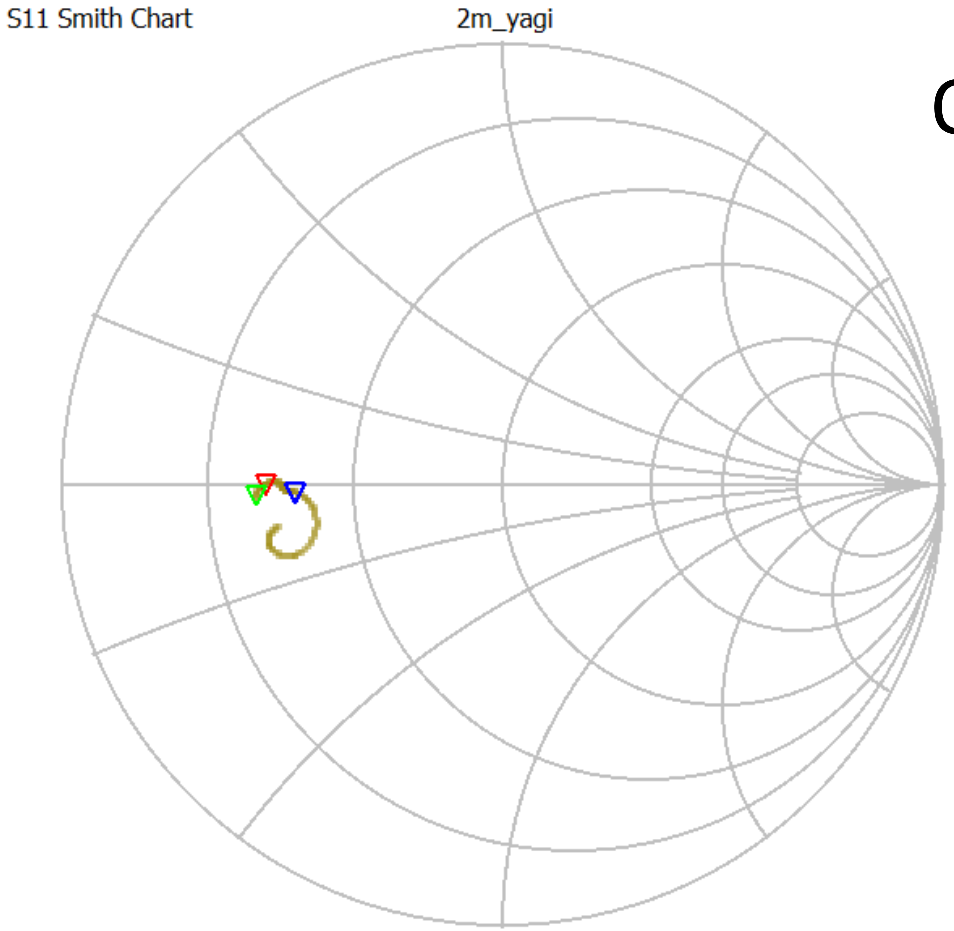
6M 1-element quad



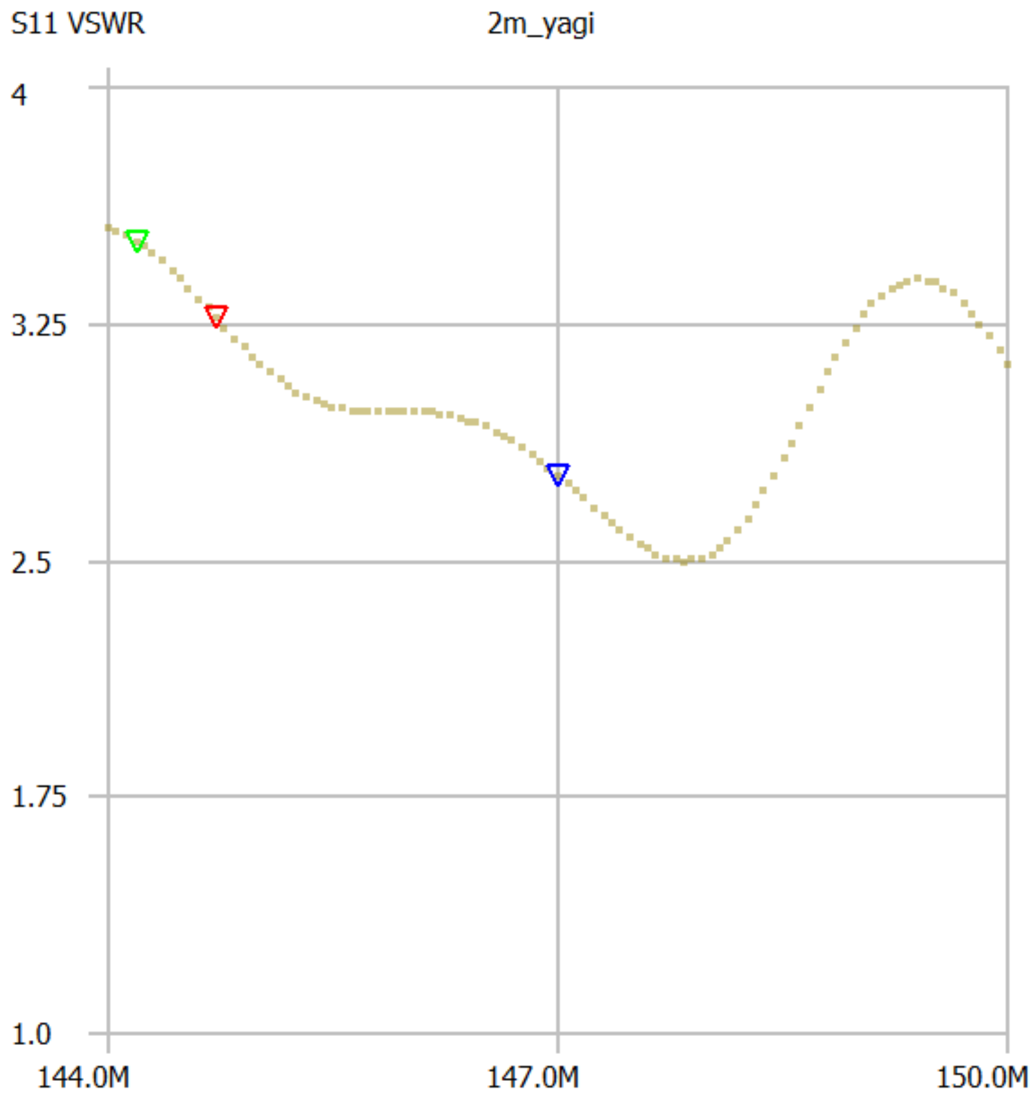


Resonant at 51.5 MHz – quad needs enlargement

2M Yagi

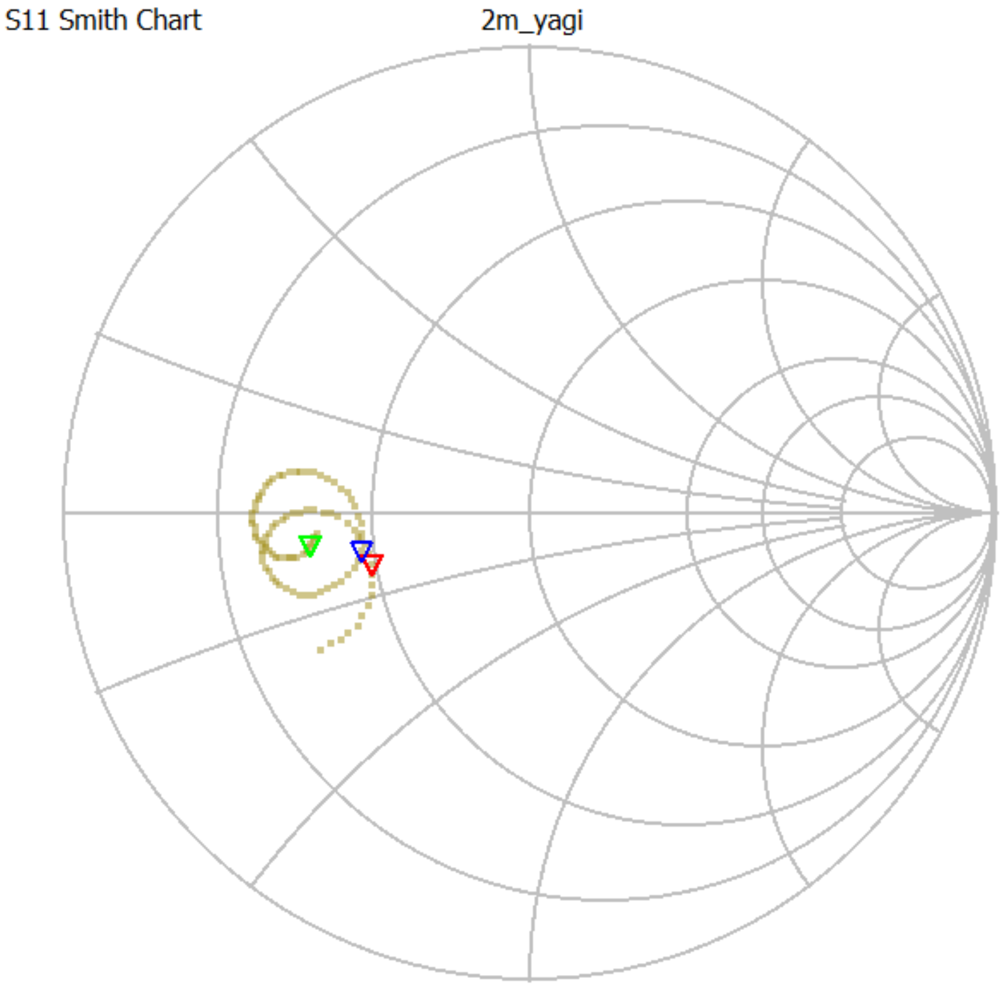


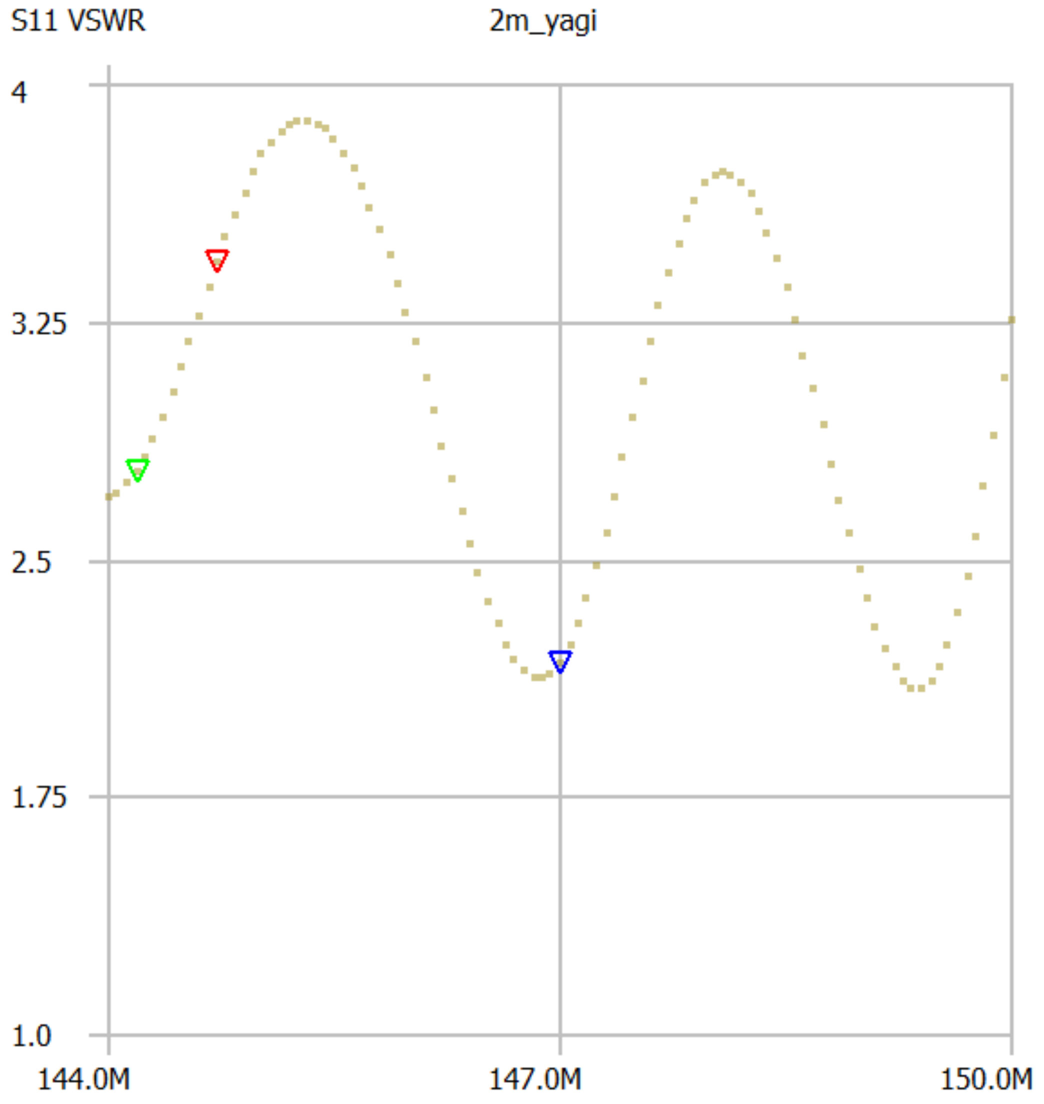
Ouch!



2M Yagi really needs work: best VSWR is at ~148.5 MHz
3.25:1 at ~145 MHz with in-line Ameritron switch not spec'ed above 30 MHz, though. Resistive impedance is 20-ish ohms.

2M J-Pole





Not so great.

Not terrible at 147 MHz, pretty bad at ~145 MHz (but the darn thing works, getting into the 145.33 MHz repeater)

Conclusions

- Thoughts on nanoVNA
  - When operational, worked well with nanovna-saver PC program last spring – I was able to tune my 20M dipole
  - I had hopes for adding 17M dipole elements off the center insulator
  - But it wasn’t quite working right when I fired it up early this month (Oct. 2020)
- What went wrong with my nanoVNA? My current peeve.
  - I couldn’t calibrate or read in existing saved calibration files
  - I tried two different USB-C to USB-A cables
  - I successfully connected it to new and old nanovna-saver program versions on the PC
  - I successfully installed the current Mac OS X version and successfully connected to the device
  - In all cases I had the same problem
  - A new one from Amazon (with the SMA calibration HW, USB cable, etc. is $70).
  - Maybe I will try to re-install or update the firmware before buying another one.

What didn’t I get to try?

- The TDM (time domain reflectometry) feature sounds interesting. Good for spotting T-line problems (kinks, poor connections, etc.), measuring electrical length
- Resolving my antenna issues
  - 2M Yagi uses a folded dipole (~300 ohms) with a quarter wave RG-8x coax balun I built back in the 1980s – is the balun length correct? Anything else messed up?
  - Analyze use of ferrite beads – choke balun at 20M dipole feed point – I put one one - did it help?
  - I have a Comet 3-band mobile antenna (6M, 2M, 70cm). How well does it work (with the grounding scheme I have in place)? Can it be improved though better grounding?
- Fixing my nanoVNA by reflashing will be a great “exercise for the student” using ST-Link2

Other references

- RF parameters
  - **S-, h-, T-, Y-, Z-, ABCD- Parameter Conversion**
    - **https://www.rfcafe.com/references/electrical/s-h-y-z.htm**
    - **I used T (scattering transmission) parameters in grad school to model cascaded T-line elements including microwave transistors to simulate wide-band amplifiers; all my measurements were S-parameters**
    - **Many of you may be familiar with H-parameters (for transistors H21 = Hfe, for example) or Z-parameters**
- Nanovna-saver software for various platforms – github
    - **https://github.com/NanoVNA-Saver/nanovna-saver/releases/**
    - The newest version as of this writing seems to be V 0.37
    - I've installed and tried the Windows and Mac OS X versions
- NanoVNA software and firmware
    - https://oristopo.github.io/nVhelp/html/software.htm
- Google IO groups
    - nanoVNA https://groups.io/g/nanovna-users – for "regular" (smaller) nanoVNA
    - nanovna-f@groups.io - there is a more "jumbo" nanovna with different HW and SW bases that costs more (metal case, though), with perhaps less active online support