# AFFORDABLE TEST EQUIPMENT FOR HAMS

HRU 2024

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# IN MEMORIAM

- This presentation is dedicated to the memory of **Andrew Kirschenbaum WA2CDL SK**
- Andy did so much for the local radio amateur community, including delivering his take on this subject. His loss was simply devastating.

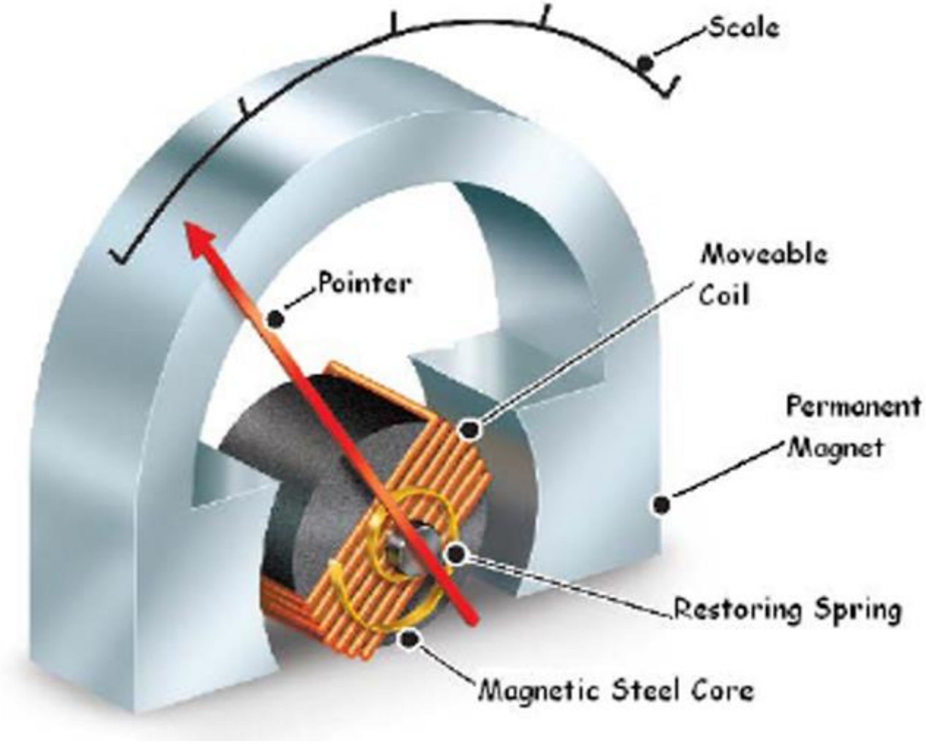
- If I can see further, it is only because I am standing on the shoulders of giants

  -Isaac Newton

# A QUICK NOTE

- This is not an academic lecture. Feel free to comment
- If you have a question, just ask ….. although we cannot go off on lengthy tangents
- If you have an illuminating personal note or suggestion, feel free to say it
- You have a say on the pace. How quickly we progress through the presentation depends on your inputs.
- I intend to try to finish the presentation and will stay until they throw us out of the room

# D’Arsonval Galvanometer



# D’Arsonval Galvanometer

- Imagine a disc of magnetic core that can rotate within a donut of magnetic core
- Both cores are wired in series with many turns of very thin wire. Since the inner core will only be allowed to rotate inside the outer core over 90 degrees or so, very flexible wires can connect them
- As a DC current passes through the wires, making two electromagnets, the cores attract (or repel) each other, such that the inner core, with an attached pointer, rotates inside the outer donut core
- The magnetic force depends directly on the current
- The unit is set up with a small spring to return to a stable no-current position, and the higher the current, the more the two cores rotate relative to each other
- When properly built, the deflection can be fairly linear with current

# D’Arsonval Galvanometer - 2

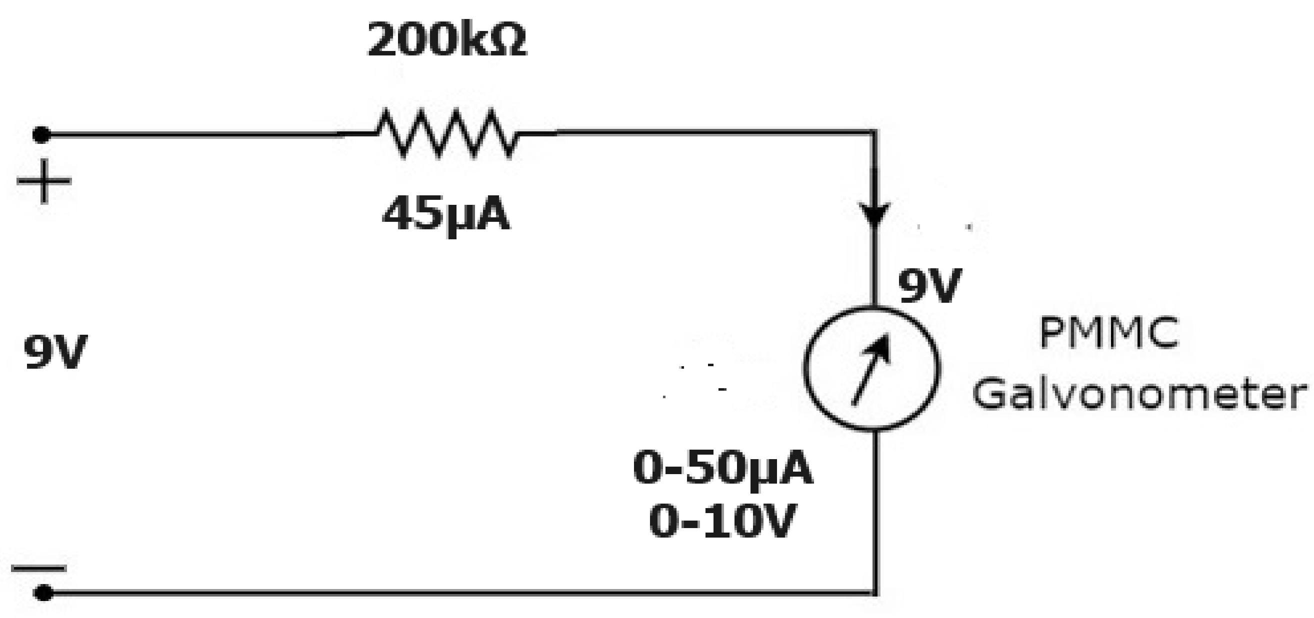
- Question: How much current does it take to move the cores (and the pin attached to the center movable core) to rotate over the full range of motion (typically 90 degrees)?
- Answer: How much do you want to spend?
- Typically the least expensive units are 1 milliamp full scale. A little more effort and cost will yield a movement that is 50 microamperes (uA) full scale. More sensitive and significantly more expensive meters are used in quality test equipment, but the classic hobbyist test equipment usually has the 50 microamp movement.

A classic voltmeter

# A basic voltmeter

- Imagine a 0-50 microamp meter movement with a 200Kohm resistor in series. (the meter has about 1K internal resistance which we ignore here).
- Connecting the leads across 9.0 volts will cause a current of 9/200,000 = 45 millionths of an amp (45uA) microamps.
- It is obvious that 50uA will be reached at 10 volts.
- We now have a voltmeter with a scale of 0 to 10 volts DC
- A fresh 9V battery has almost 10 volts, so this is a good meter to test such batteries

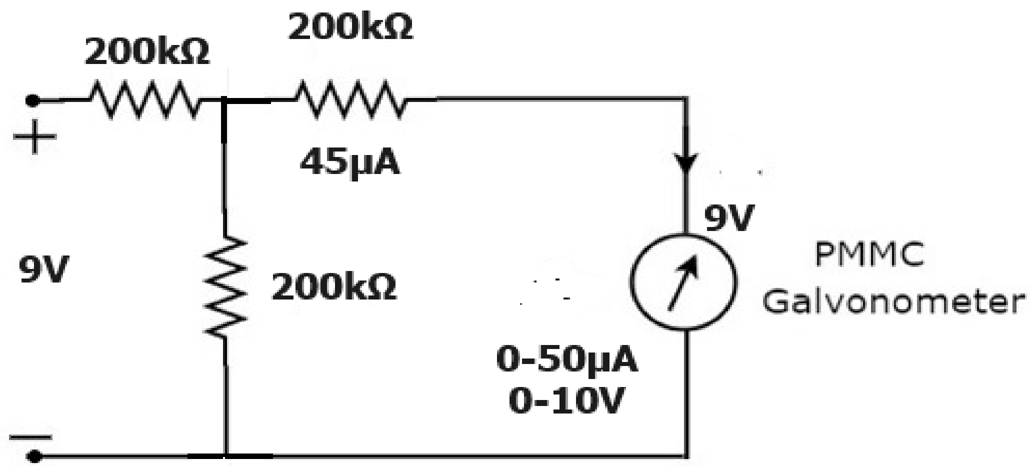
# Basic Voltmeter



# Does a voltmeter affect the circuit it is testing?

- The 0-10 VDC meter we are discussing draws 50 microamps. A 9Volt battery will not change the voltage for such a small current
- However, some circuits use high value resistors and 50 microamps will cause a noticeable error
- For example, placing two more 200K resistors in series across the battery will have half of the battery voltage at the junction.
- Applying the voltmeter in parallel will change the effective ground-side resistance to 100K.
- The meter will read 100K/100+200K or one third of the battery voltage, 0r 3.0 Volts
- So, be vary aware that such meters can load down high impedance circuits

# High Impedance Circuits




It should read 4.5V
But it reads 3.0V

# So what do we do about that?

- Really nice Digital Multimeters are available for under ten bucks (much more on them coming up). I have several Harbor Freight units that work fantastic and sell for seven bucks
- TEMU has them for even less
- These units have a 1 Megohm input impedance regardless of voltage range, which is noticeably better. More expensive units typically have a 10 Megohm input impedance. (We'll get into how they do that later).
- In the test on the previous slide, a 1Megohm input results in a reading of 4.1V, and 10 Megohms produces 4.45V.
- Digital meters are more accurate too.
- Their only downside is if you are watching a varying voltage, you can see how much the meter pointer wobbles, while a wildly flashing display on a digital meter can be worthless

# Multimeter

- Usually people buy a multimeter with a big rotary switch that changes the voltage range.  A typical unit allows you to switch between, say,  0-10, 0-50 and 0-250 VDC by switching in 200K, 1Meg or 5 Meg resistors respectively to provide 0-50uA
- You have to be careful to set the appropriate range.  If you have no idea of the voltage, start with the highest voltage scale and work your way down
- Today there are automatic ranging meters, but I find them slow to respond as they mull things over.
- Multimeters also have AC voltage, DC current, and resistance testing scales.  Let us introduce them one at a time.

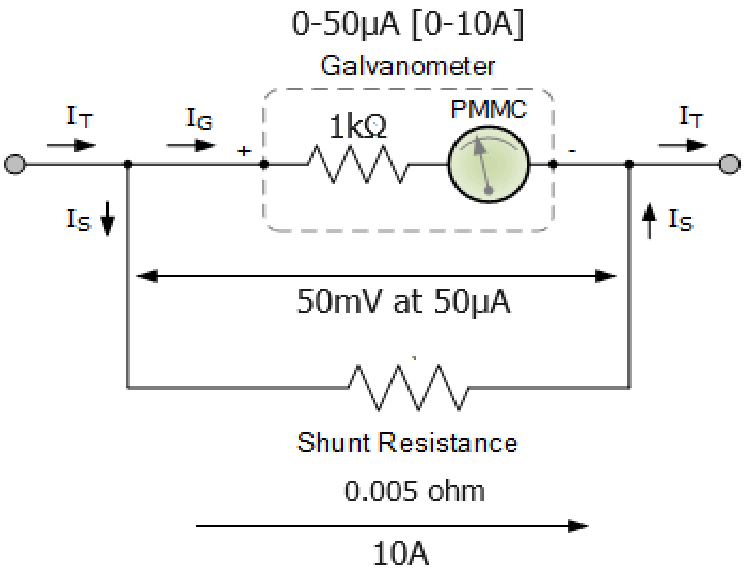
# AC voltmeter

- An inexpensive voltmeter just puts a 4-diode bridge circuit in series with the input to rectify the AC to a DC voltage
- Such a circuit leaves AC ripple on the rectified DC, but usually the meter movement is mechanically sluggish enough to average it out
- Diodes add a small error and the meter scales usually have some compensation to account for it
- Also the readings need to be adjusted to correctly indicate the voltage, and usually show the average of the rectified voltage
- For true readings, especially for non-sinusoidal waveforms, you need a “true-RMS” meter which adds complexity and is significantly more expensive. For simple testing it is not needed
- Inexpensive AC voltmeters are most often used for AC power, and tend to only have 0-250 VAC and 0-500 VAC scales. If you want precision readings at low voltages or unusual frequencies, wait for the oscilloscope section of this presentation.

# Ammeter

- Our meter reads 0-50 microamps and has a typical 1Kohm internal resistance due to all those turns of really fine wire.
- We often need to check a larger DC current, say 0-10 Amperes; How do we do it?
- Putting 50 uA through a meter with a 1K resistance means that it has E=IR of 50 microamps X 1000 ohms = 50 millivolts (1/20 of a volt)
- Again using E=IR to get 50mV across a resistor with 10 amps going through it we calculate .05V / 10 = 0.005 ohm
- We can buy “ammeter shunts” that are high power, low resistance.  Since P=EI, 0.05V X 10 means a 0.005 ohm shunt will dissipate half a watt as heat

# Ammeter shunt



# Multimeter notes

- A multimeter typically has several DC current scales that use different resistance shunts.  0-2 milliamps, 0-20 milliamps and 0-200 milliamps are typical selections.
- Some units have a 0-5 amp scale with a higher power shunt and a separate jack that the probe plugs into.
- The shunt component values are calculated with same process as the last slide, just using the relevant numbers
- Note that it is very easy to make a mistake and blow out the shunt, or even the meter movement; be careful….
- If you want to measure the AC line voltage and forget that your last measurement was on a current scale, it will be jarring (gepoppencorken mit spitzensparken)

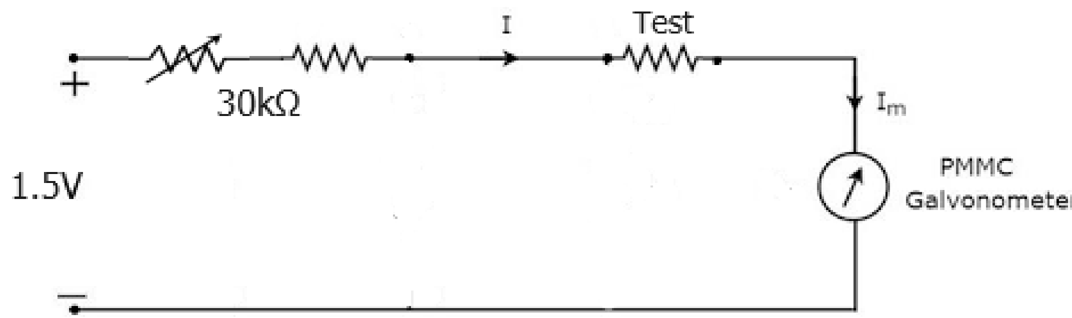
# Ohmmeter

- To measure a resistance value takes an ohmmeter
- Such a meter has a small (usually 1.5V) replaceable battery.
- Lets stay with our old friend – the 50uA meter.
- If we have a series circuit with the battery, a 30K resistor, the resistor under test, and the 0-50uA meter, if the resistor under test is 0 ohms, we put 50uA through the meter for a full scale reading
- If the test resistor is an open circuit, obviously the meter will not budge
- If the test resistor is also 30K, we get 25uA and the meter reads half scale
- Let us assume that the highest reading we can interpret is at 2 percent meter deflection, or 1 uA. That occurs at 1.5 Megohms
- Notice that the scale is not only backwards but non-linear

# Ohmmeter - 2

- The meter scale of an ohmmeter has to be designed and built at the factory to handle the highly non-linear response
- Note that the internal 30K resistor in this example has to include a variable resistor to adjust for battery aging.
- To use an ohmmeter, first short the test leads and adjust the variable resistor to read 0 ohms (50uA)
- Then measure the resistor under test and get the best reading off of the scale. Here 30k provides half-scale
- Usually multimeters have several different ranges, and if the meter is near either full scale or zero, try a different range until the reading is somewhere in the middle.

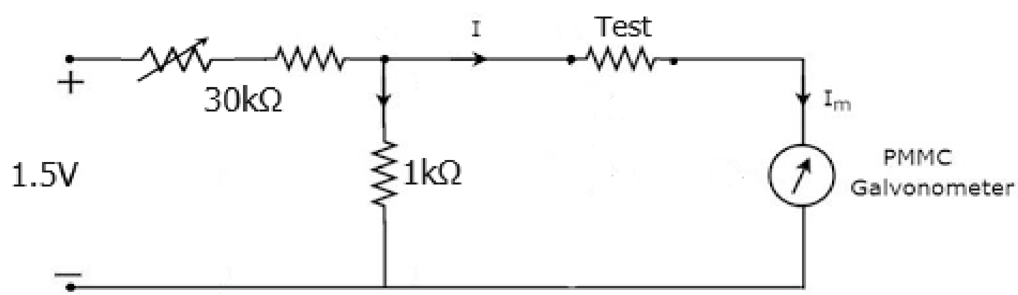
# Ohmmeter - 3



# Ohmmeter -4

If we add a 1K resistor from the junction of the 30K and test resistor to the negative lead, we have a voltage divider producing 0.05 volts through 1K (actually 0.048V and 968 ohms, but lets not sweat it)

- Now half scale occurs at 1K and the high end is 60K



# Digital Multimeter

- Today, low cost digital multimeters are the standard.
- The key to a digital meter is a tiny computer IC that includes some processing and an analog-to-digital converter
- Such meters require a battery for both power and the ohmmeter function
- All of the previous functions are redesigned. Instead of producing 0-50uA, a voltage of 0-5VDC is brought to the very high input impedance A/D converter
- A digital number from 0 to (typically) 4096 (12 bit resolution) results and is processed and sent to a typically 4- digit display
- For voltage ranges above 5 Volts, precision resistor networks step down the voltage
- For voltage ranges under 5 Volts, an integrated circuit (op amp) using precision resistors provides a precise gain to amplify the signal

# Digital Multimeter

# Digital Multimeter – 2

- The analog to digital converters usually have a very high input impedance, and the input networks maintain that impedance
- Inexpensive digital meters have a 1 Megohm input impedance on all ranges; more expensive ones have 10 Megohm inputs
- This causes significantly less error getting voltages from high impedance  circuits under test.
- Digital meters use input resistances to tailor voltage, current and resistance monitoring circuits much like we discussed earlier for analog meters

# Digital meter sampling

- The small microcontroller in a digital meter updates the digital display roughly twice per second, which is the most pleasing way to show changing numbers.  Not too fast, not too slow …. Just like baby bear's porridge
- The system calculates the readings many times per second, Typically something like 128 (2 to the $7^{th}$ power) readings are added and then divided by 128 (simply by shifting the data 7 places – avoids long division)

# Digital meters - AC voltage

- For AC readings, the A/D input is typically from 0 to 5V, with zero at 2.5V. As with DC readings, a large number of readings are added. Since AC average value will be about 2.5V, a feedback loop keeps the input centered at 2.5V
- Meanwhile, in a separate process, negative input readings (under 2.5V) have the minus sign removed (absolute value) and are averaged as above.
- At 60Hz, the timing is set such that each cycle is sampled 32 times and the timing is synchronized to 60Hz, so each average is a number of complete cycles. For a 16.666 mS cycle, 32 samples occur every 521 uS and 32 complete cycles are averaged, which takes 533 mS; very close to twice per second

# What’s this Root Mean Square stuff, anyway?

- The method just described calculates the average of a number of readings of how far the AC sinewave instantaneous voltage is from the midpoint, either positive or negative.
- A true measure of the “heating value” of the sinewave waveform of an AC power line is more complicated. Turns out you need to calculate the RMS voltage – root of the mean of the squares
- Squares: Each reading is multiplied by itself. This also takes out any minus signs
- Mean: The samples are added and divided by the number of samples to get the “average”, technically this is the “mean”
- Root: The square root of the result is the RMS value

# Why are we subjecting ourselves to this abuse?

- In a DC circuit, the power is E X I, or V squared over R. Note the "square law" relationship
- The same concept occurs for AC power; the higher voltages get an advantage
- The calculations of the previous slide do more than drive us crazy; they compensate for the square law effect
- All that number crunching takes a fairly complicated computer. A $7 multimeter can't afford that
- So, we cheat. An AC voltage reading almost always has a 60Hz power line, which is a clean sinewave.
- If the waveform is a clean sinewave, all we have to do is multiply the average by 1.11, which can be done by adding the average, 1/16$^{th}$, 1/32 and 1/64. Dividing by powers of 2 is easy in a simple computer.
- If you don't like that, expensive meters are always "true root mean square"

# Measuring SWR

## Three different SWR bridges

# Antennas

- Every antenna at every frequency has an impedance, consisting of a resistance (the “real” part) and a reactance – either a capacitance or inductance (the “imaginary” part) …
- This can also be expressed as an impedance and a phase angle.  Either way; whichever is more useful.
- At certain frequencies (“resonance”) the impedance of an antenna becomes primarily resistive at a particular number of ohms (e.g., a 67 foot long dipole resonates and presents 50 ohms resistive at 7 MHz)
- A dipole will also resonate when the length adds a full wavelength
- So it is also resonant at the odd harmonics – such as 21, 35, 49 MHz etc.)

# Antennas - 2

- The antenna and transmission line from the transmitter need to be at roughly the same impedance.
- Back in the 1920s ladder line had a 300 or 600 ohm impedance
- As a result, antennas were often folded dipoles and the like because they had an impedance at resonance of about those values

# Antennas, cables, transmitters

- Once coaxial cable was developed during WW2, it was less expensive and much easier to use, and such cables tend to have impedances around 50 ohms, so hams started using antennas that resonated at 50 ohms, like a simple dipole
- With antennas designed to have a 50 ohm resistive impedance, and a 50 ohm coax cable, the output impedance of the transmitter is set to match 50 ohms
- Back in the day, vacuum tube power amplifier circuits had an output impedance of a few thousand ohms. They had an impedance matching circuit to transform it down to 50 ohms
- The matching circuit used large air variable capacitors, to make it tunable. Non-resonant antennas could often be “matched” and operated

# More on Transmitters

- With the development of transistor finals, transmitters became much smaller, and lower impedance, so as the units became much smaller, they needed even larger variable capacitors.
- Manufacturers threw up their hands and designed the transmitters for a non-adjustable 50 ohm resistive load.
- You need an external antenna tuner to match non-resonant loads
- Modern transmitters are designed to handle a lot of power in a small box.  If the antenna is not properly matched, the transmitter will exceed its heat dissipation and overheat.
- The antenna is fine with a mismatch; the weak link is the transmitter overheating

# Antenna tuners

- Antennas that are off resonance can be resonated with an antenna tuner.
- Long antennas can be easily matched with an antenna tuner; short antennas require a wider adjustment range
- Inexpensive narrow range antenna tuners are fine for random length long wires, while short antennas may need larger, more expensive tuners
- Automatic antenna tuners tend to be narrow range and can be erratic in matching highly reactive (especially short) antennas

# Effects of SWR mismatch

- An antenna will perform off-resonance just fine
- Same for the coaxial cable or other transmission line
- The problem with a SWR mismatch is the transmitter
- Transmitters typically dissipate one watt of heat for every watt radiated. Getting rid of that heat is a challenge for a small solid state rig
- In the case of a SWR mismatch, the transmitter dissipates significantly more heat than with a match. Overheating is a real risk
- So transmitters reduce power or shut down entirely with a large SWR mismatch; THAT is why we watch our SWR
- And you will note that receiving at high SWR is not a problem

# So, how to we handle this?

- Either we use a resonant antenna providing a 50 ohm resistive load, or we use an antenna tuner to transform the impedance to 50 ohms resistive
- There are manual and automatic antenna tuners that due pretty much the same thing, but the automatic ones are much more expensive than the manual ones, and to hold the cost down they often cannot tune as wide a range of impedances.
- In any event, we need to have equipment available to at least occasionally verify that our antenna system is providing a proper 50 ohm resistive load to the transmitter

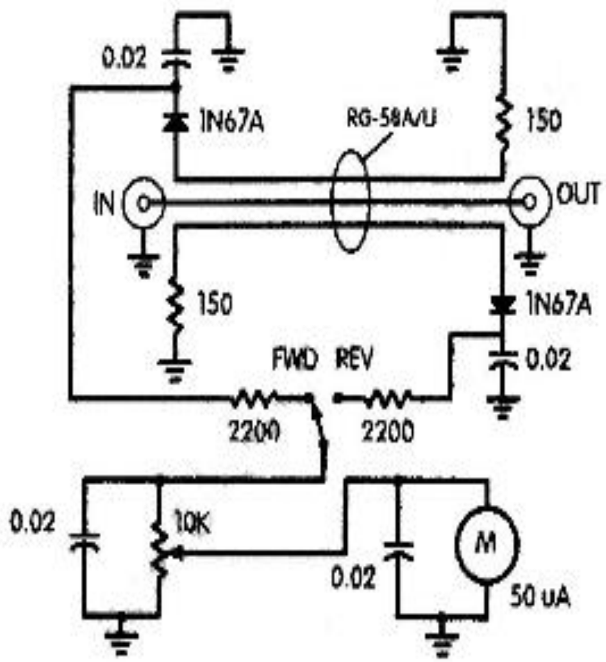
# How do we measure antenna impedance?

- There are several ways to measure antenna impedance, but they tend to be fairly expensive and knowing your antenna is presenting an impedance of 31 ohms resistive and -216 ohms reactive is not very easy to wrap your mind around. Gotta be some easy-to-use shortcut
- A transmitted signal in a coaxial cable produces something called standing waves, which have voltage peaks and valleys at different locations. With a matched antenna, these peaks and valleys disappear; as the errors increase, so do the peaks and valleys.
- Interesting, but how are we supposed to measure these invisible effects?

# How to measure standing waves?

- There is something called a directional coupler used to measure standing waves, but they are expensive
- Forget that.  Can we cheat and slap something together?
- So glad you asked.
- Take a foot or so of RG-8 coax.  Remove the outer cover. The outer conductor shield braid has a kinda sloppy fit.  Push the braid together enough to slip a nice thin insulated wire under the braid through a small hole ½ inch in, and comes out ½ inch before the other end.  Now, straighten the braid back out.
- Now connect the RG-8 so that it is inbetween the transmitter and the antenna.
- See the next slide for a diagram of what to do with the thin wire

# A cheap-and-dirty directional coupler in a SWR bridge



# Classic SWR bridge

- A classic SWR bridge places a diode rectifier and a capacitor on each end of the thin wire.  This takes a tiny sample of the signal and generates a DC voltage
- The rectifier on the transmitter side produces a DC voltage indicative of the forward power going from the transmitter to the antenna
- The rectifier on the antenna side produces a DC voltage indicative of power reflecting back from the antenna
- The idea is to adjust the complete antenna system to maximize the power going to the antenna (forward) and minimize the power coming back (reflected).
- Either two voltmeters or a single meter and a switch can be used

# Classic SWR bridge -2

- The forward power is brought to a meter. It can be calibrated to show the watts output at a specific frequency, or a specified range of frequencies
- The rectifier on the antenna side generates a voltage proportional to the reflected power. It can go to a second meter or a second position on the switch puts it on the single meter
- The idea is to make sure the expected power is going to the antenna while keeping the reflected power to as low as possible, as a percentage of the forward power
- An adjustment is used to vary both voltmeter sensitivities.
- The switch is set to “forward” and the adjustment is used to set the meter to full reading

# Classic SWR bridge - 3

- Now the switch is set to the reflected position and the meter reading is compared to the full-scale forward power
- The dial scale includes a range from SWR=1.0 at minimum, up to infinity at maximum.
- Usually, an SWR from 1.0 is ideal, 1.5 is good,. 2.0 is questionable, and 3.0 and above is unacceptable
- Now, THIS is a nice and inexpensive way to measure and easy to understand
- Today, with microcontrollers, we can buy inexpensive digital readout power / SWR meters that do all the math and display both power and SWR as numbers

# Antenna Analyzer

# Antenna Analyzer

- An antenna analyzer is used to measure the impedance or SWR of an antenna without applying transmitter power
- Such units typically cost about $300
- It has a tunable low-power frequency source and a digital frequency readout.
- There is a processor to determine the impedance and SWR of whatever is connected (usually an antenna)
- Some provide the resistance and reactance; others provide a single combined impedance. All provide SWR
- By slowly tuning the frequency over a desired band, it is easy to determine how the SWR varies
- It is very useful in determining how to add or decrease element length to obtain the best SWR over the entire band

# OSCILLOSCOPE


# What is an Oscilloscope?

- An oscilloscope lets you see how a voltage varies with time
- An oscilloscope has two critical parameters – number of channels and frequency
- The number of channels is how many signals can you display and compare.
- The frequency is the highest frequency signal that can produce a meaningful display
- A single channel, low frequency oscilloscope can be quite inexpensive, while a really nice hobbyist oscilloscope that sells today for $250 or so will have two channels and a bandwidth of 100 MHz.  Anything more than that is for specialized use

# Time Base

- If you are looking at a 60Hz waveform, consider it takes 16.66 milliseconds to complete one cycle, so you would likely want to see about 25 or 50 milliseconds worth (2 cycles?)
- Oscilloscope time bases generate a dot that moves across the screen at the speed determined by a switch. On some oscilloscopes that dot speed can be from well under a microsecond up to tens of seconds.
- The moving dot "paints" a line as it moves across the screen. And then it goes back to the start and may overwrite the old one
- Options include overwrite and show multiple sweeps, erase the old and just show the new, and just do one sweep and keep it

# Signal level

- Like a voltmeter, you have to set a switch to select the expected input voltage so that the variations of the signal voltage are displayed over as much of the screen as possible, but stays on the screen
- A switch is provided to select the appropriate range
- An adjustment is provided to move the display up and down to allow it to be positioned on the screen
- The input voltage is shown changing with time as the dot moves across the screen
- The input signal channel is usually good from DC up to some specified maximum; typically 100 kHz for an inexpensive scope and typically 70 MHz for a mid-priced one
- A switch allows for AC coupling to allow such things as looking closely at power supply ripple.

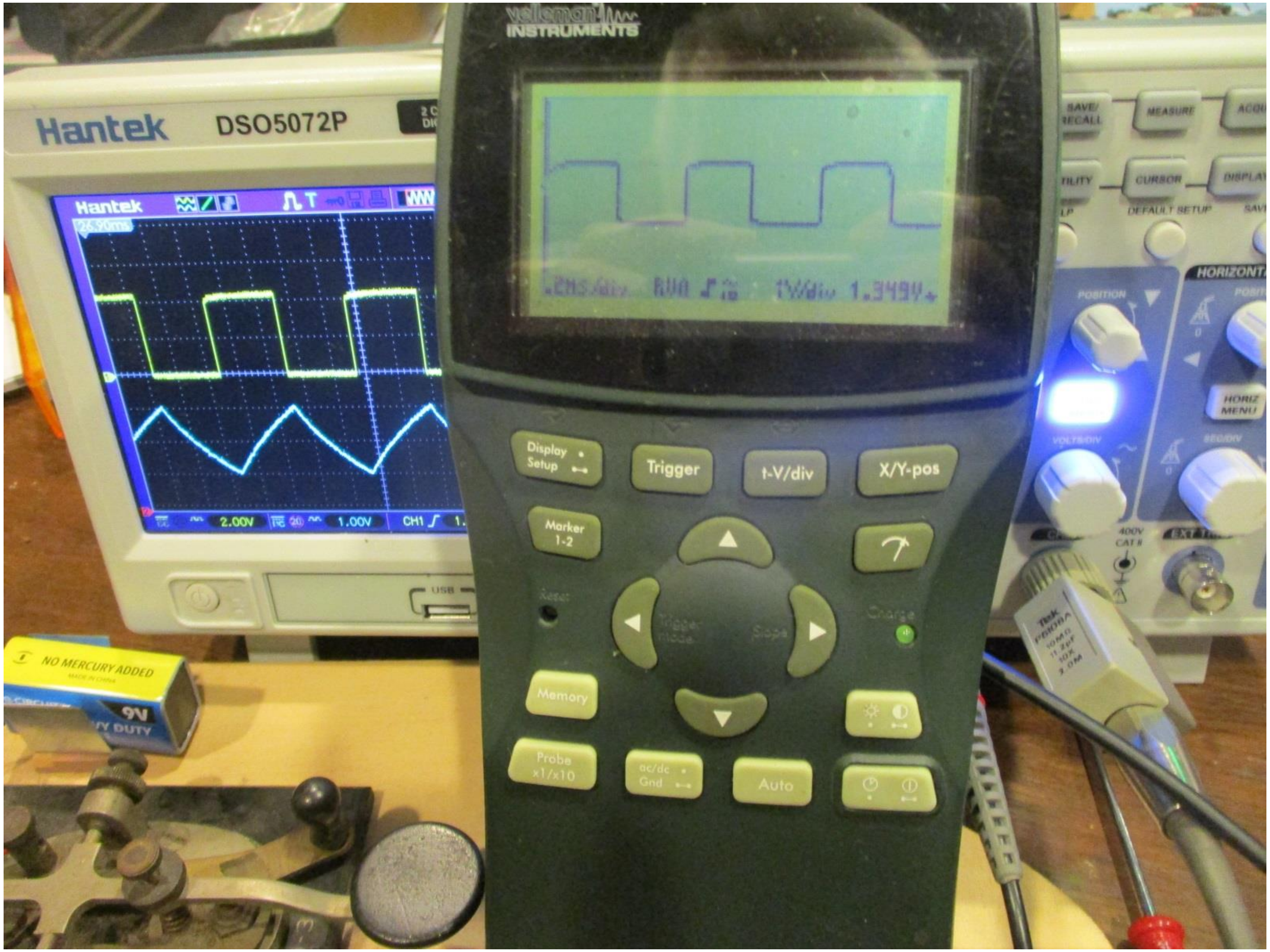
# A basic oscilloscope

- The most basic oscilloscope has one input channel, probably good from DC up to something like 100 kHz
- It is likely hand-held, battery operated, with a screen around 2X3 inches, and is quite inexpensive
- Such scopes are good for looking at a single waveform; For example is the pulse generator putting out the pulse waveform I want
- In some cases they can be extremely valuable; In some others they just don’t cut it
- Of course there are high quality, handheld, battery operated oscilloscopes too, but the idea here is to show what to expect for a modest price

# Triggering

- For an oscilloscope to show a meaningful display, the waveform on the screen must start at the same time for every sweep of the time base, or the pattern runs across the screen and getting any useful data like time or voltage is impossible
- Every oscilloscope has a triggering circuit, and it is absolutely key to creating a meaningful display
- On an inexpensive oscilloscope, each sweep will wait until the input crosses an adjustable level – either going up or going down – to start the sweep

# An inexpensive oscilloscope



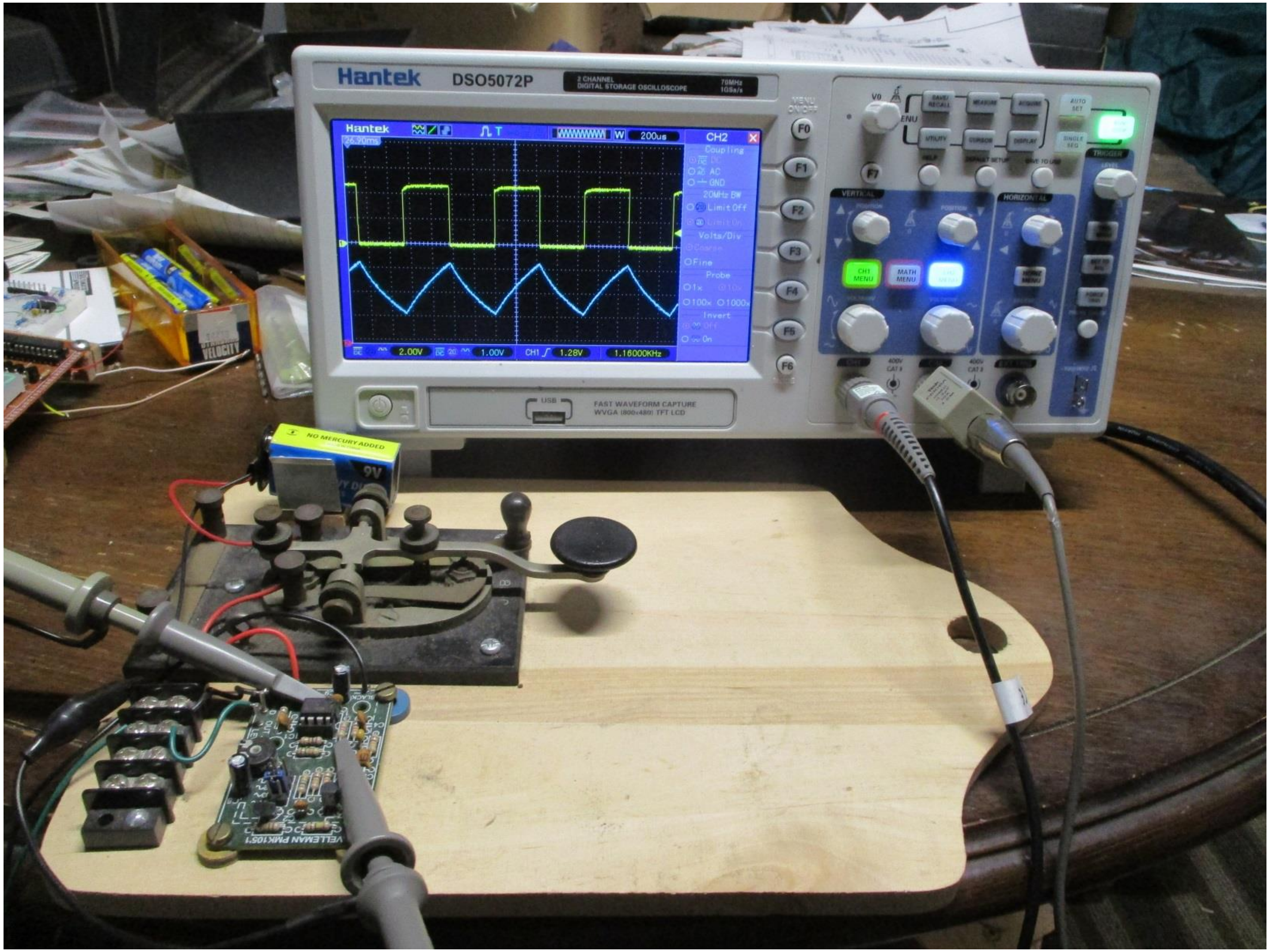
# A mid-range oscilloscope

- A very nice piece of benchtop test equipment can be bought for around $250 today
- It has a screen around 4X6 inches, is AC powered and sits on the workbench.  It has two input channels plus a third option for a non-displayed trigger.  It will have an input frequency bandwidth of about 70 or 100 MHz to show high frequency waveforms clearly, especially useful for the rise and fall times of digital signals.
- The two channels can be selected separately; Each has 1 Megohm input impedance, but probes with 11 Megohm impedance are supplied to minimize effects on the circuit under test.
- The main advantage of such an oscilloscope is to allow you to see two separate waveforms in such a manner that you can clearly see them both on the same time scale.
- Usually one channel or the other is selected as a trigger. Usually you select the input that has an easily detected feature that occurs before something interesting happens on the other channel

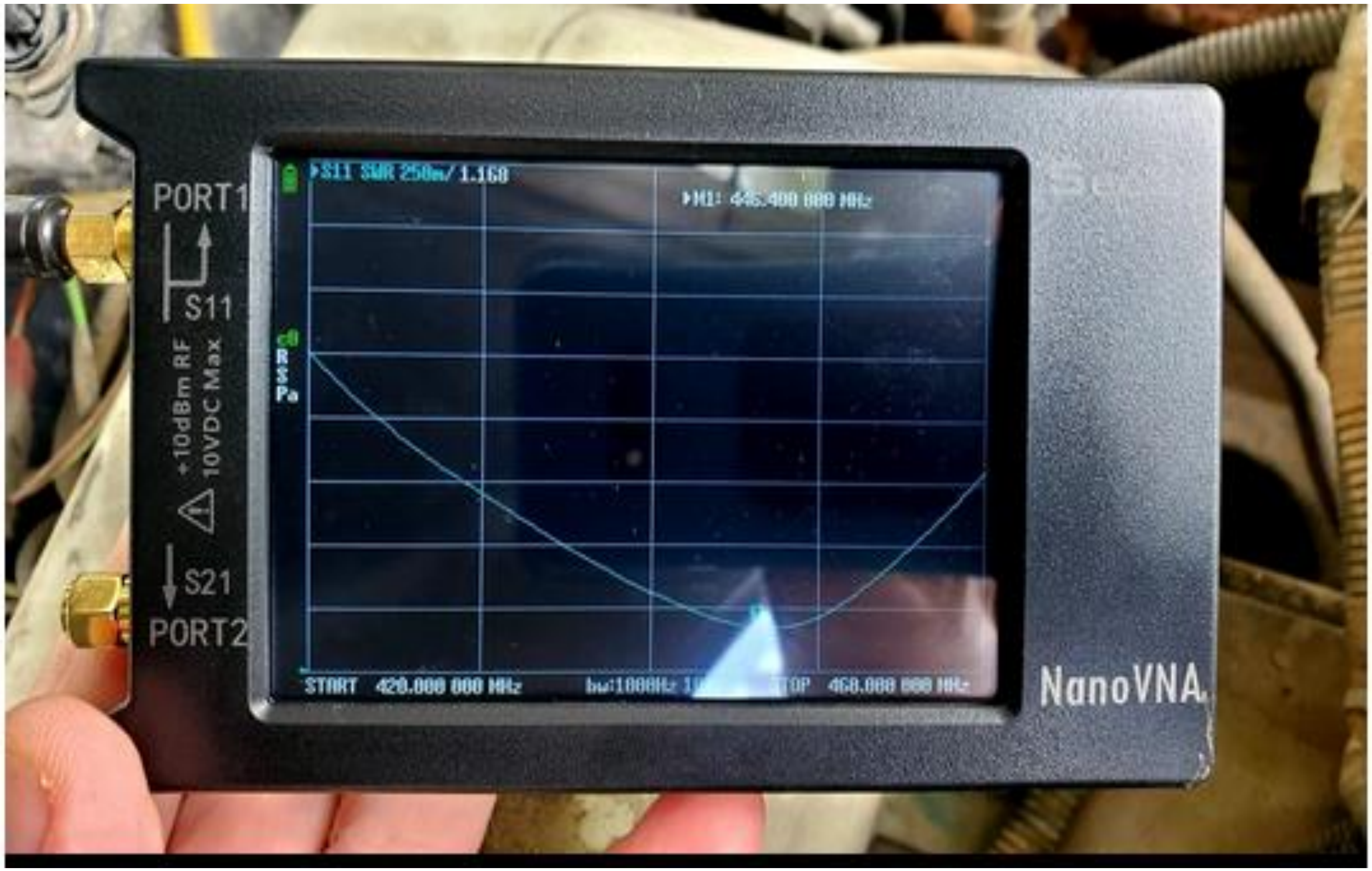
# A mid-range oscilloscope - 2

- Many such oscilloscopes have a third input that is not displayed
- It is a dedicated trigger signal input to trigger the two displayed signals, while not visible itself.
- Triggering has an entire menu of possible settings, but if "the proof of the pudding is in the eating", getting a good display is the desired result of all the playing around
- One last time – an improperly triggered signal can lie to you. Be suspicious and don't fall for it

# Mid-range oscilloscope



# Vector Network Analyzer (VNA)



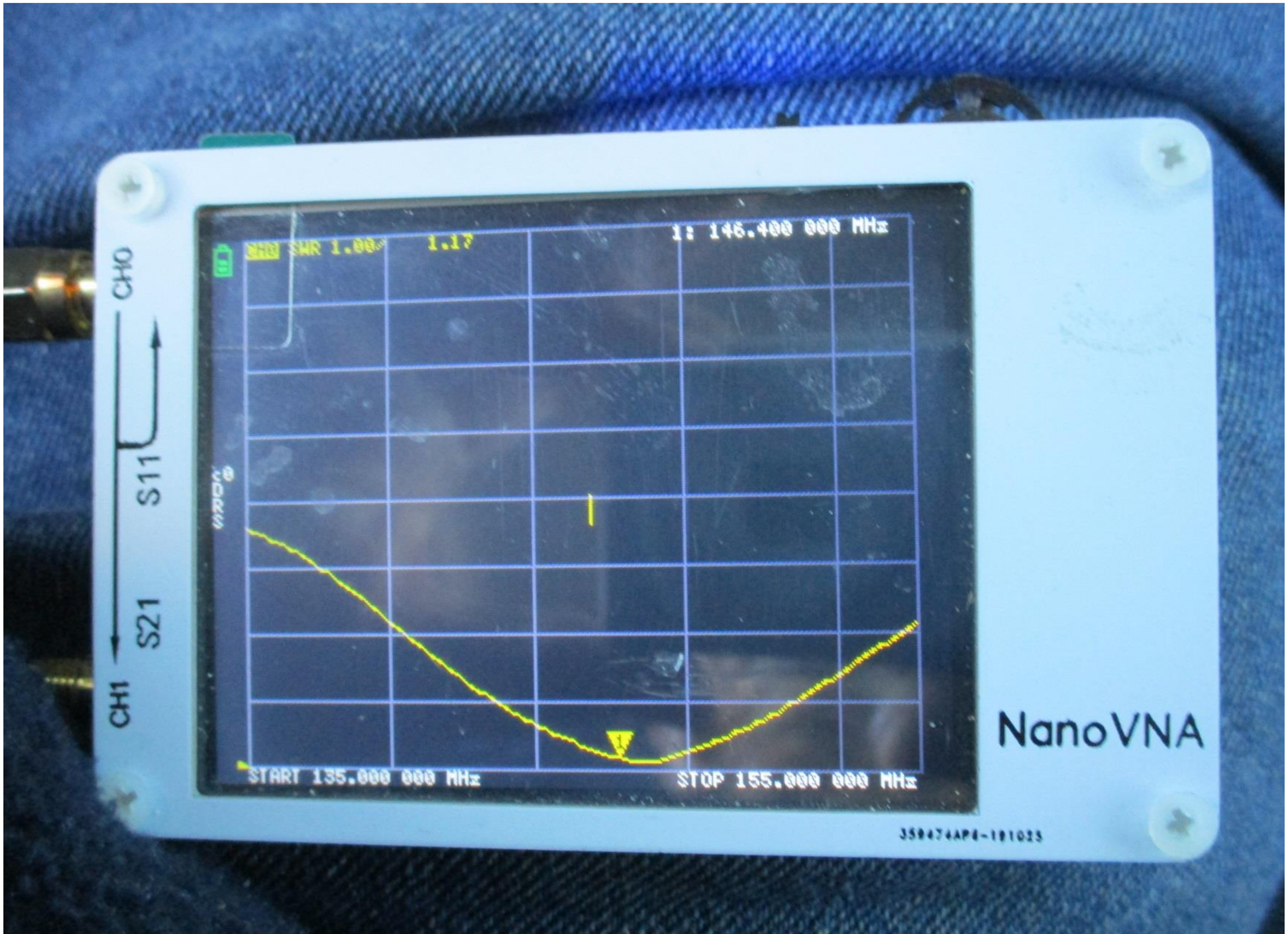
# Vector Network Analyzer (VNA)

- VNAs used to cost tens of thousands of dollars. The world was taken by storm with the introduction of the cute little “Nano-VNA” for as little as about fifty bucks. Yes, it actually DOES work
- A vector network analyzer has two modes – one port (one coax line) and two-port (two coax lines)
- In the one-port mode you can connect the VNA to a passive network (i.e. one that does not produce power)
- You then set a range of operating frequencies of interest
- Where an antenna analyzer has to be manually tuned, a VNA is preprogrammed over the band of desired frequencies, similar to an oscilloscope display

# Vector Network Analyzer (VNA)-2

- Like an oscilloscope, the display screen parameters can be set to show the most useful display
- Various displays of real and imaginary impedances, Smith charts, etc. are available, but hams tend to go right to the SWR display setting
- NOTE: WE DO NOT HAVE TIME TO GO INTO SETUP DETAILS; LET ME KNOW IF YOU WANT A DEDICATED TALK NEXT YEAR
- For example, connecting the VNA to a 2 meter mobile antenna can be set to display the impedance as VSWR over any selected frequency range.
- If we set the range to be from 135 to 155 Mhz we can see the SWR of the antenna over the entire 2M band at one glance

# Typical VNA 1-port display: SWR of an antenna from 135-155MHz

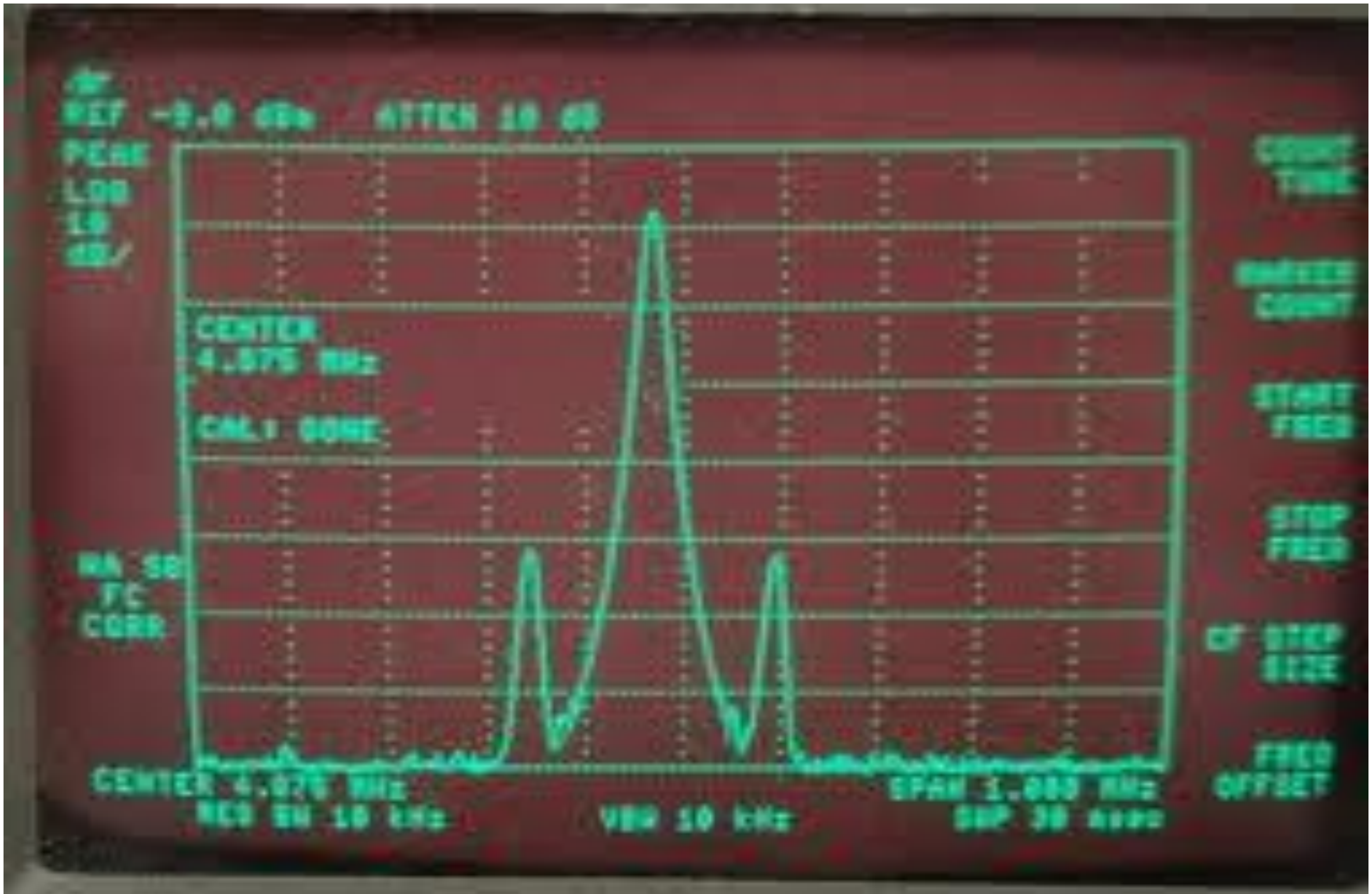


# Spectrum Analyzer

# Spectrum Analyzer

- A spectrum analyzer is similar to an oscilloscope, but the horizontal axis is not time but frequency and the vertical axis is not voltage but RF power level
- The “waterfall” display on some new HF transceivers is a form of spectrum analyzer, showing the signals across the band
- Like a VNA, spectrum analyzer input signals must be very low power
- A spectrum analyzer can also be narrowed down to show the spectrum of a single signal. An AM signal containing the carrier as well as upper and lower sidebands can be shown.
- The next slide is a typical display taken off the internet

# Spectrum of an AM signal



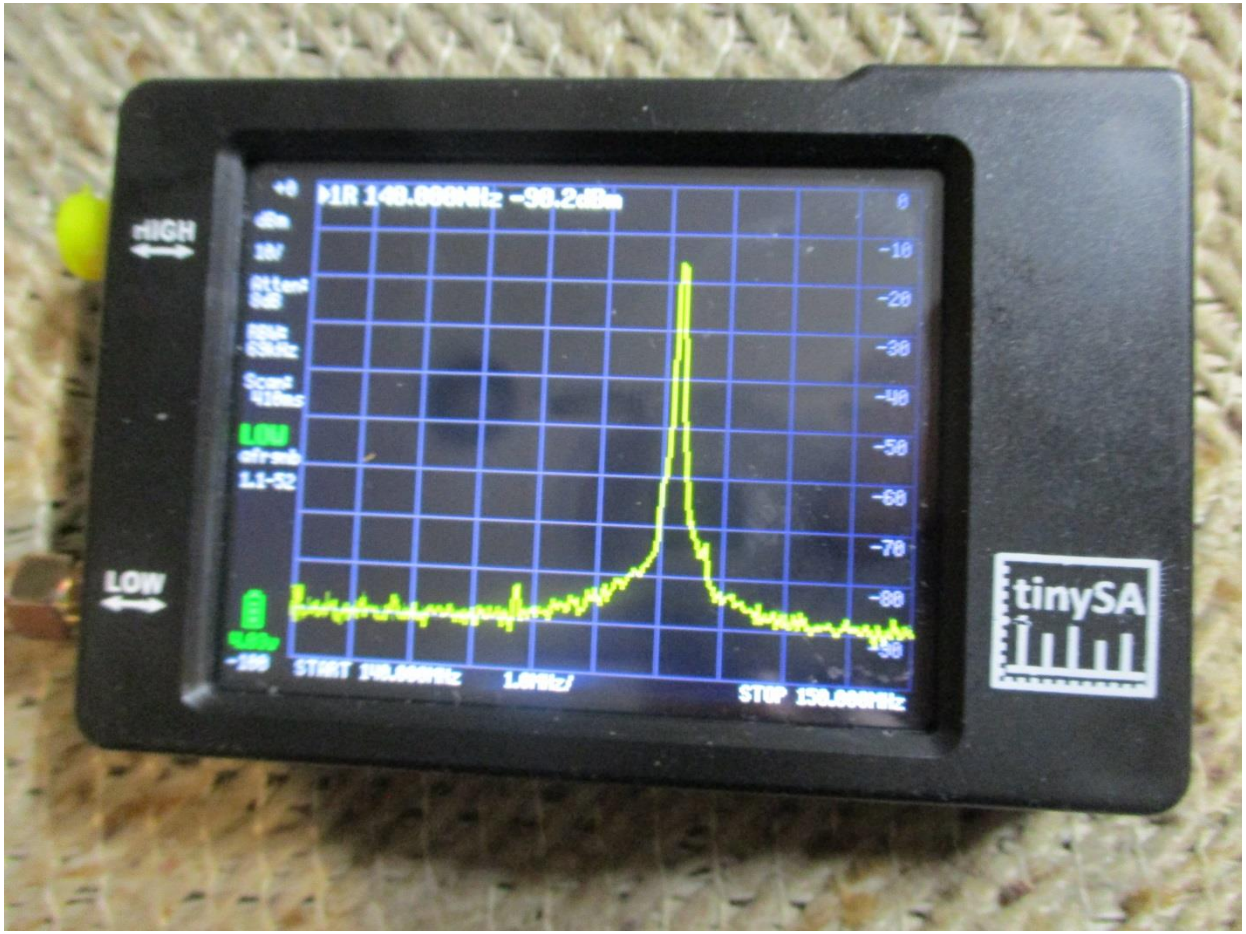
# Using a Spectrum Analyzer

- Much like using an oscilloscope, where multiple settings must be adjusted to provide the desired display, a spectrum analyzer must also be set up for a clear display
- If a spectrum analyzer is not set properly, the display can be misleading, so be careful
- The center frequency and the span must be set.  Also the input attenuator must be set to provide the proper dynamic range of the signal.
- The scan speed and the bandwidth must be synchronized to provide an accurate display; the narrower the bandwidth setting, the slower the display must scan

# TinySA

- Similar to the nanoVNA, there now is the TinySA - A small, inexpensive spectrum analyzer that really works
- It can be connected to an antenna and used to see what signals are coming in strong, their frequencies, and bandwidth
- It can be used to monitor a transmission frequency and spectrum (by using a separate receiving antenna – DO NOT connect directly to a transmitter)

# Tiny SA:   140-150 MHz / 146.25 signal



END