Calibration Techniques for the Home Lab

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Summary

- Using a **reference multimeter** as a calibrator for less accurate instruments.
  Verify its calibration with your own standards.

- How to precisely measure low value resistors for making accurate shunts.

- Make your own AC voltage reference. Using a thermocouple to measure AC voltages / power.

- Power references and power meters for calibration.

- Linearity tests on DC, AC voltmeters and power meters.

- Accurately measure voltage ratios with a sound card.

- A GPS Frequency standard.

- Accurately measure capacitors.

Target Uncertainties

- DCV: 0.01 %
- ACV: 0.1 %
- Resistors: 0.02 %
- RF Power: 0.05 dB
- Frequency: 10e-9 to 10e-12
- Capacitors: 0.1 %

5.5 or 6.5 digit Reference Multimeter

To be used as a **calibrator** for less accurate instruments

OPTIONS

- Use Cal Lab to calibrate your Reference Multimeter (ideal, but $$$)
- Use your own DCV (ACV, R) standards, from Ebay, or voltagestandard.com, etc.
- Verify DC & AC linearity using divider such as Kelvin Varley or a Resistive Divider.
- Compare two (or more) multimeters (should agree within their spec.)

Reference Multimeter(s) Partial List

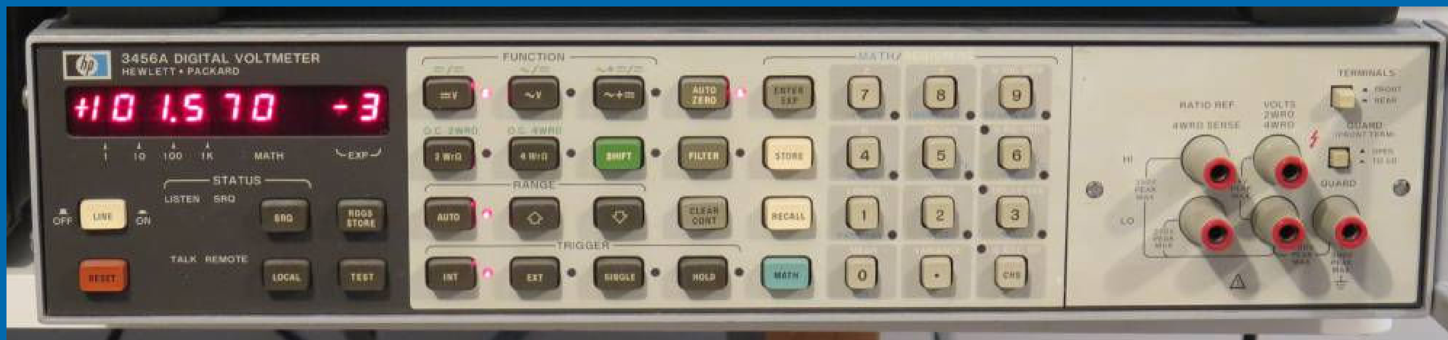
Fluke 8050A 4.5 digits Portable
Fluke 8920A 4.5 digits AC only, wideband
Fluke 8808A 5.5 digits 1/2 width
Fluke 8840A 5.5 digits 1/2 width
Fluke 8842A 5.5 digits 1/2 width
Fluke 8846A 6.5 digits 1/2 width (Competes w 34401)

Keithley 2000 6.5 digits 1/2 width
Keithley 2110 5.5 digits 1/2 width

HP 3455A 5.5 digits old
HP 3478A 5.5 digits 1/2 width
HP 3456A 6.5 digits Volt ratio, no current
HP 3457A 6.5 digits
HP 34401A 6.5 digits Volt ratio, 1/2 width

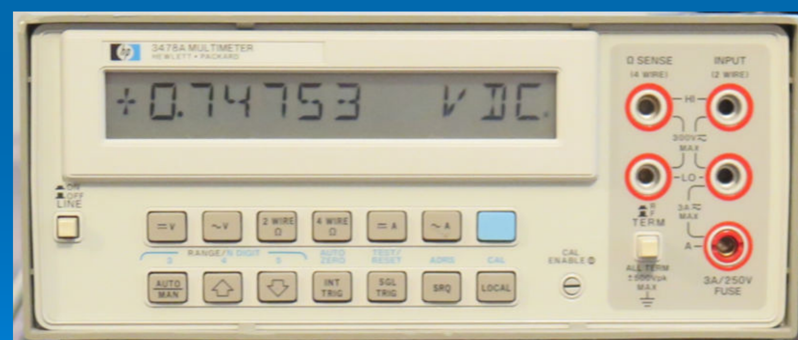
HP 3458A 8.5 digits Standards lab !

Reference Multimeters - Example



HP 3456A

HP 34401A



HP 3478A

Example of voltage references:

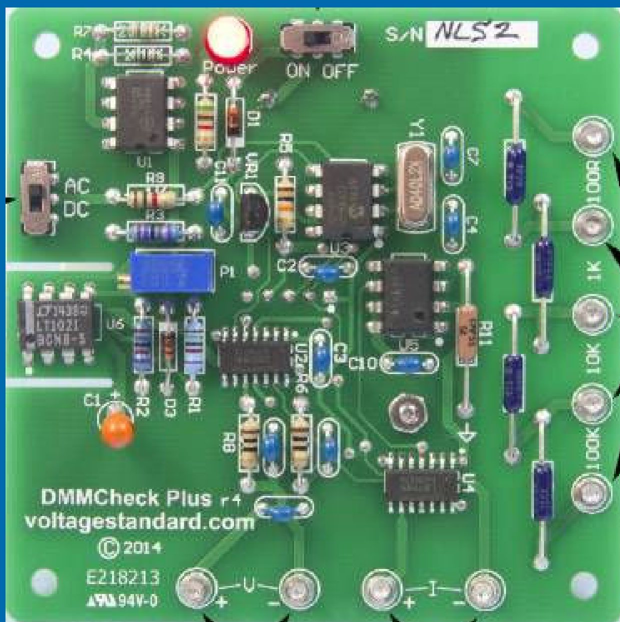
AD584 4-Channel 2.5v/7.5v/5v/10v High Precision Voltage Reference Module – From Ebay

See also: voltagestandard.com

AD584–SPECIFICATIONS (@ V_{IN} = +15 V and 25°C)

Model	AD584J Min	AD584J Typ	AD584J Max	AD584K Min	AD584K Typ	AD584K Max	AD584L Min	AD584L Typ	AD584L Max	Units	
OUTPUT VOLTAGE TOLERANCE											
Maximum Error[1] for Nominal											
Outputs of:											
10.000 V			±30			±10			±5	mV	0.05%
7.500 V			±20			±8			±4	mV	0.05%
5.000 V			±15			±6			±3	mV	0.06%
2.500 V			±7.5			±3.5			±2.5	mV	0.1%
OUTPUT VOLTAGE CHANGE											
Maximum Deviation from +25°C											
Value, T_{MIN} to T_{MAX}[2]											
10.000 V, 7.500 V, 5.000 V Outputs			30			15			5	ppm/°C	
2.500 V Output			30			15			10	ppm/°C	
Differential Temperature											
Coefficients Between Outputs		5			3			3		ppm/°C	

Using DMMCHECK Plus from voltagestandard.com



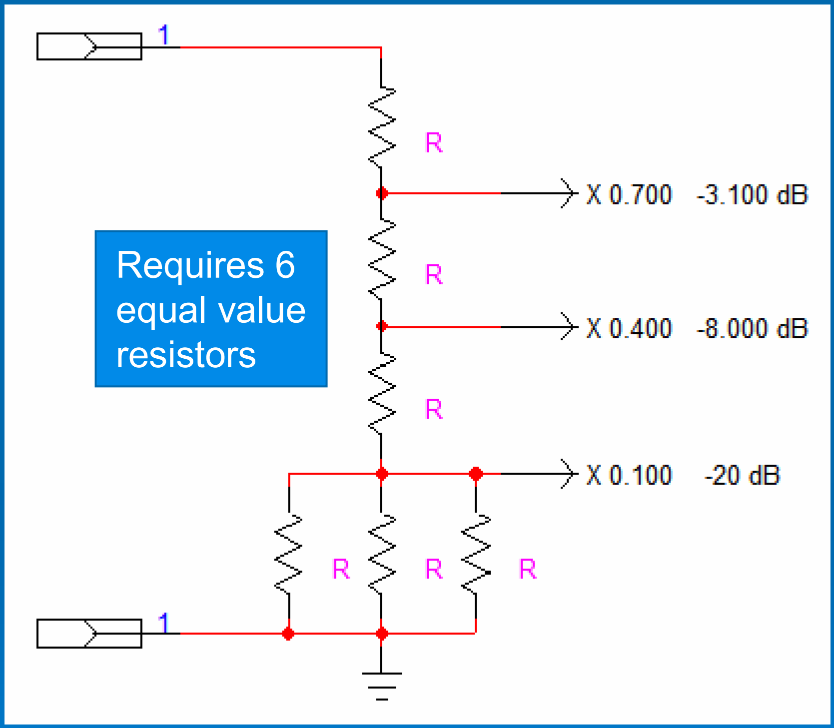
Excel sheet to log readings and compute errors – from ve2azx.net

FLUKE 8050 s/n: n/a		DATE	Nov 16 2013	T=22 C
DMM DC Input R ohms	1.0E+07	1.0E+07	1.0E+07	1.0E+07
Nominal Voltage into DMM R	0.004498	0.04949	0.49874	5.00000
Measured DCV	0.0045	0.04949	0.4987	5
Error ppm	397	-52	-71	0
Measured DC mA		20 mA range -->	1.002	1.00065
Error %			0.170	0.035
AC Input Capacitance pF	76	pF corr factor:	0.999848	
DMM AC Input R ohms	1.0E+07	1.0E+07	1.0E+07	1.0E+07
Nominal Voltage into DMM R	0.00450	0.04948	0.49865	4.9991
Measured ACV 100 Hz	0.00463	0.04968	0.5005	5.02
Error %	2.948	0.397	0.372	0.418
Measured ACV 10 KHz				4.949
Error %				-0.943
Measured AC mA 100 Hz				1.0045
Error %				0.450
Measured AC mA 10 KHz				0.9951
Error %				-0.689
Measured OHMS	99.97	1000.2	10001	100080
Error %	-0.070	-0.058	-0.010	-0.0160

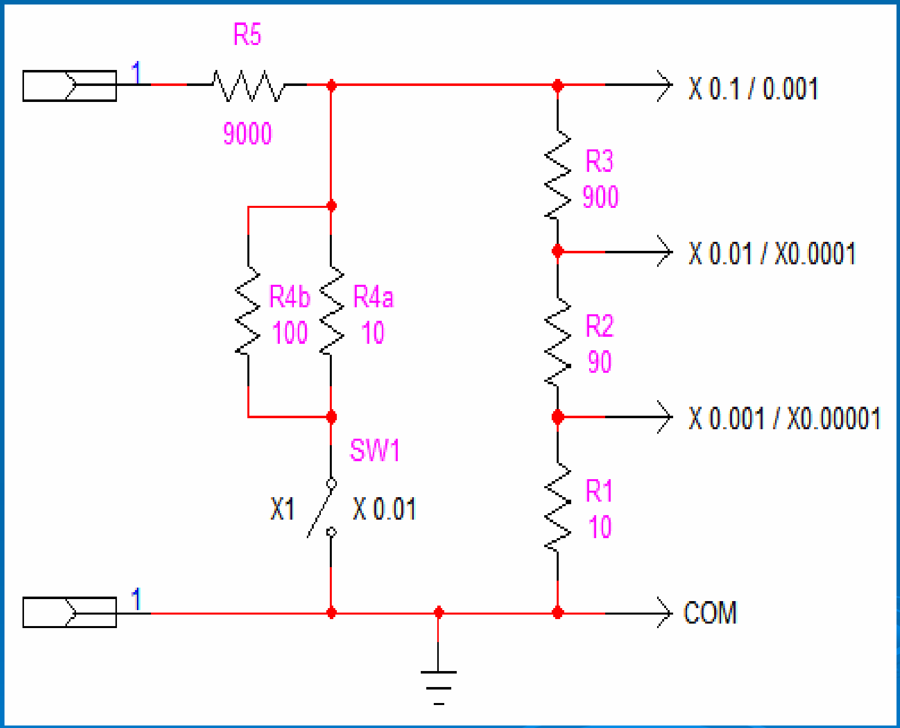
+5V out DC / AC
1 mA out DC / AC
(5) Std resistors

Simple Voltage Dividers

Connect your voltage reference and generate multiples voltages to check your multimeter



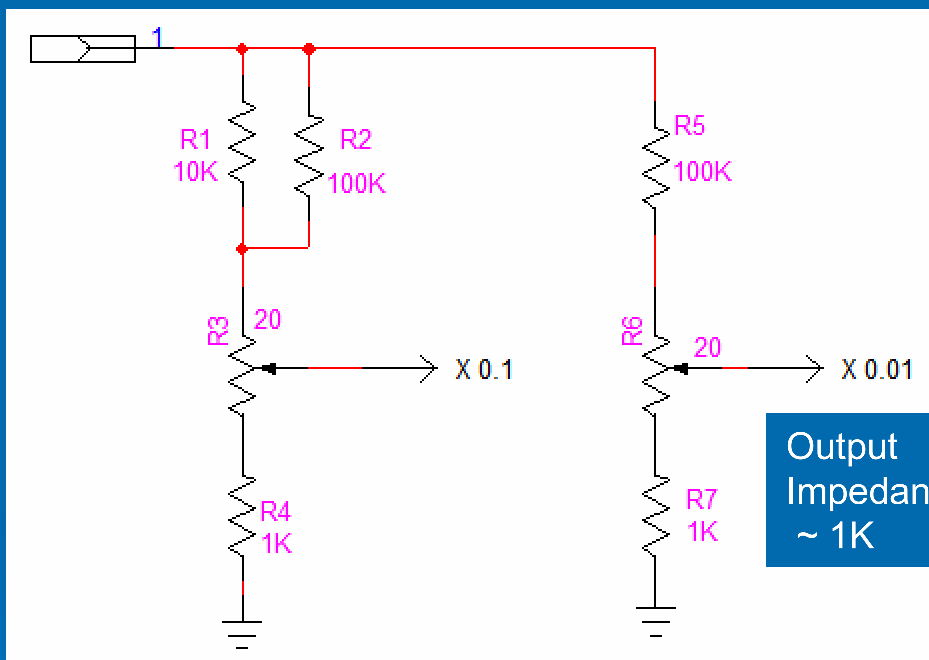
Divide by 10
(Hamon divider)



Divide by 10, 100, 1000, 10 000, 100 000
(SW1 contact resistance should be low)

Simple Voltage Dividers

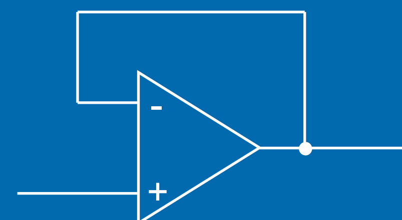
Adjustable divider provides +/- 1 % adjustment range



Output
Impedance
~ 1K

LOW OFFSET BUFFER

OPA188
OPA2188



Offset: +/- 6 μV typ.

Input impedance ~ 10^{12} Ω
Output impedance ~ 35 mΩ

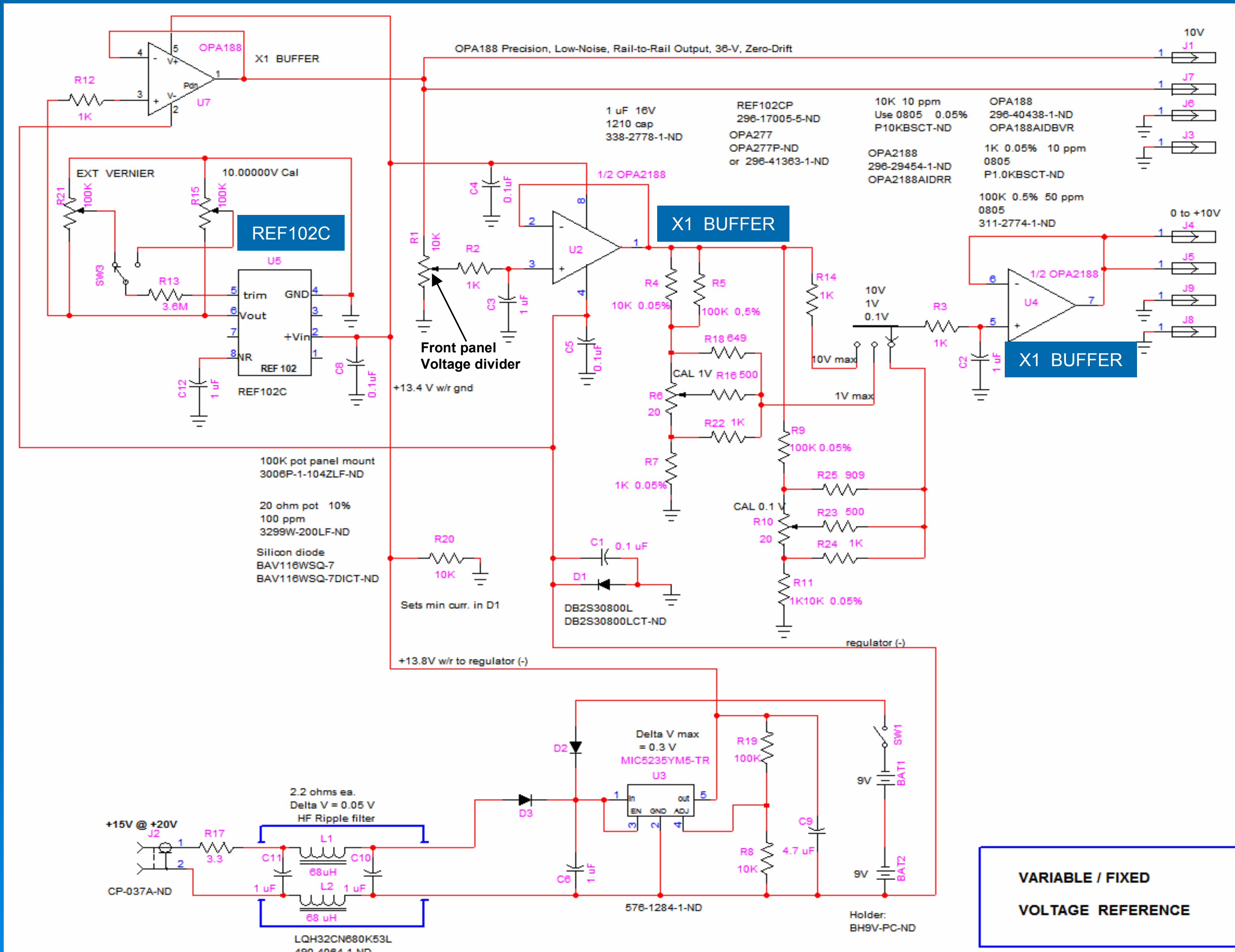
My Precision Voltage Reference

- 2.5 ppm **max.** 10V reference (uses REF102C)
- Measured +3.2 ppm with HP3456A
  +2.9 ppm with HP34401A
- Floating source from 2X 9V batteries.
- External supply for long term use.
- 3 precise adjustable decade dividers.
- 10 turn pot generates buffered voltages.
- 10V buffered output adjustable +/- 10 mV.
- Battery test led.

Boonton calibrator does all the functions of Boonton 2500 calibrator.

My Voltage Reference

Uses REF102C 2.5 ppm /°C 10 V out



10V
Fixed
Output

0 – 0.1V
0 – 1V
0 - 10V
Variable
Output

VARIABLE / FIXED

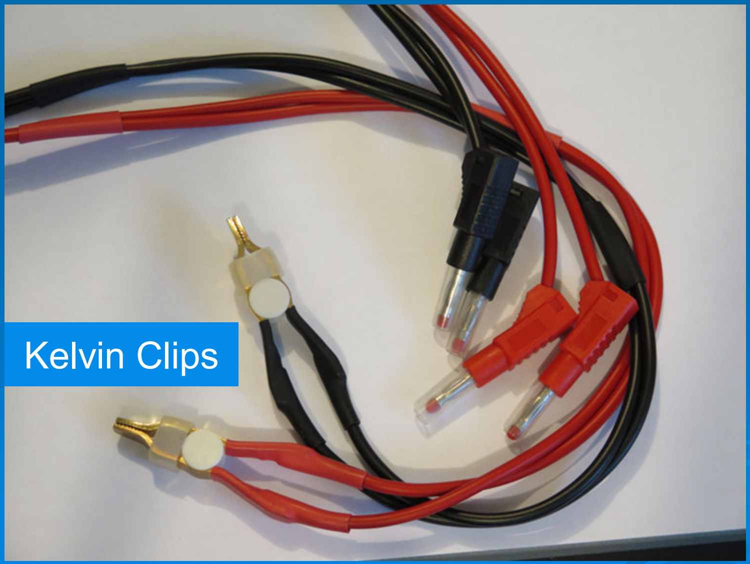
VOLTAGE REFERENCE

Verify DVM DC linearity using divider such as Kelvin Varley

- Check/adjust the previous dividers in **ratio mode** if possible
- Reference should be between 1 to 12 V

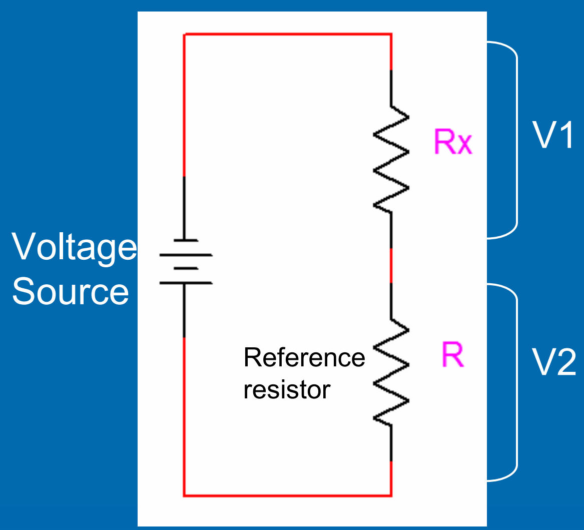
Standard Resistors and Shunts:

- Standard resistors allow periodic checking of your DMM.
- Testing multimeter current scales using standard resistors.
- Eliminate lead resistance by using Kelvin connections with reference multimeter. Check measured values on more than one instrument.
- Compare resistor ratio using multimeter ratio mode or computed manually.
- How to make low value shunts. Used for checking multimeter HI current ranges by monitoring voltage across the shunt.



Comparing Resistors

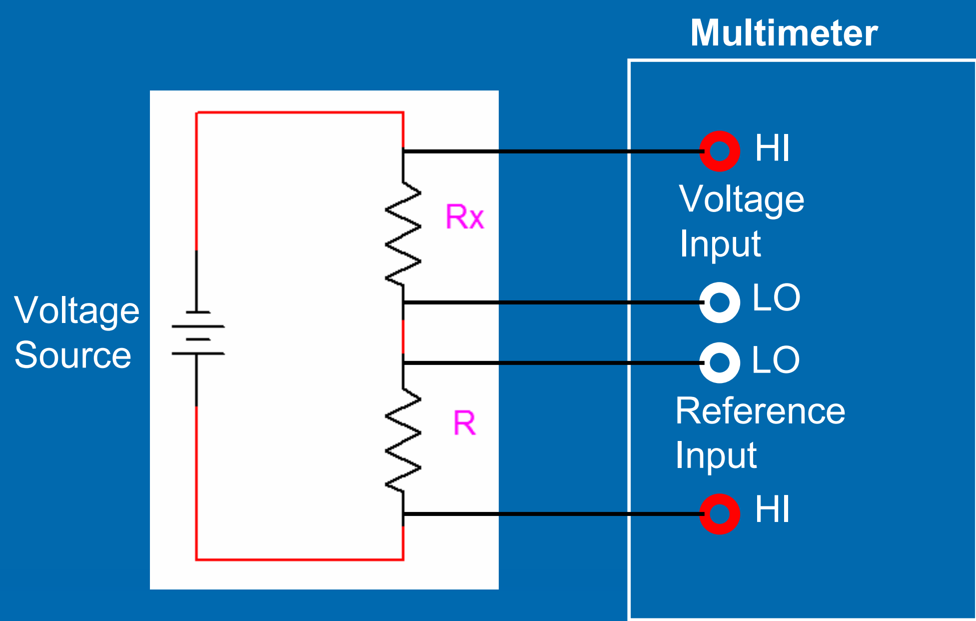
Measure V1 and V2 separately



$$Rx = R * \frac{V1}{V2}$$

Independent of multimeter input resistance

Using Ratio Mode



Rx = R * Abs(Ratio)

DC / DC Ratio mode

Reference input voltage: 1 to 12V

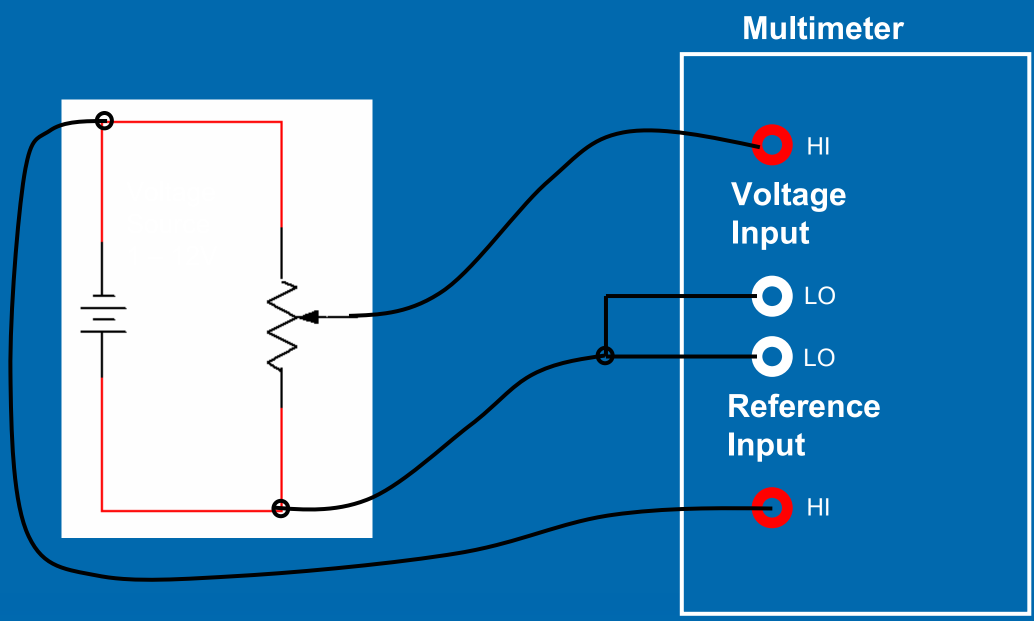
More accurate: one reading req'd

Reference R has highest value: RX <= R

Use four wire connections !

Comparing Resistors

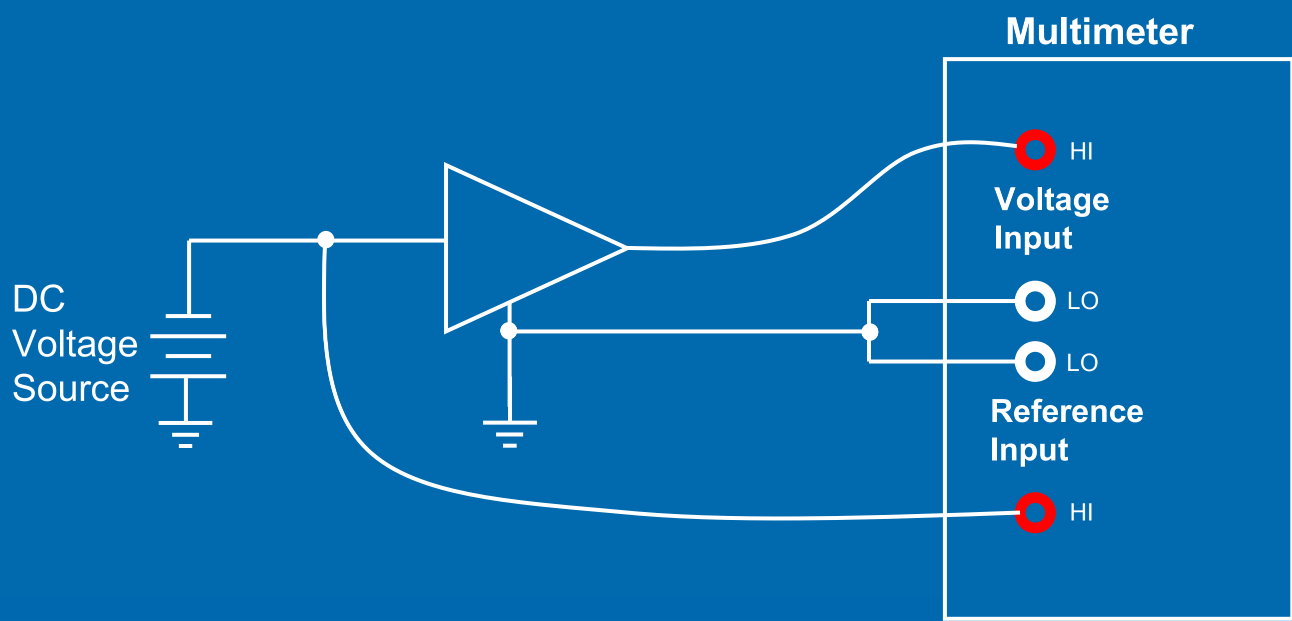
Using Ratio Mode to verify Potentiometer Linearity



DC / DC Ratio mode

Resistance ratio shown on DVM
Reference input voltage: 1 to 12V
Easily checks 10 turn pot linearity

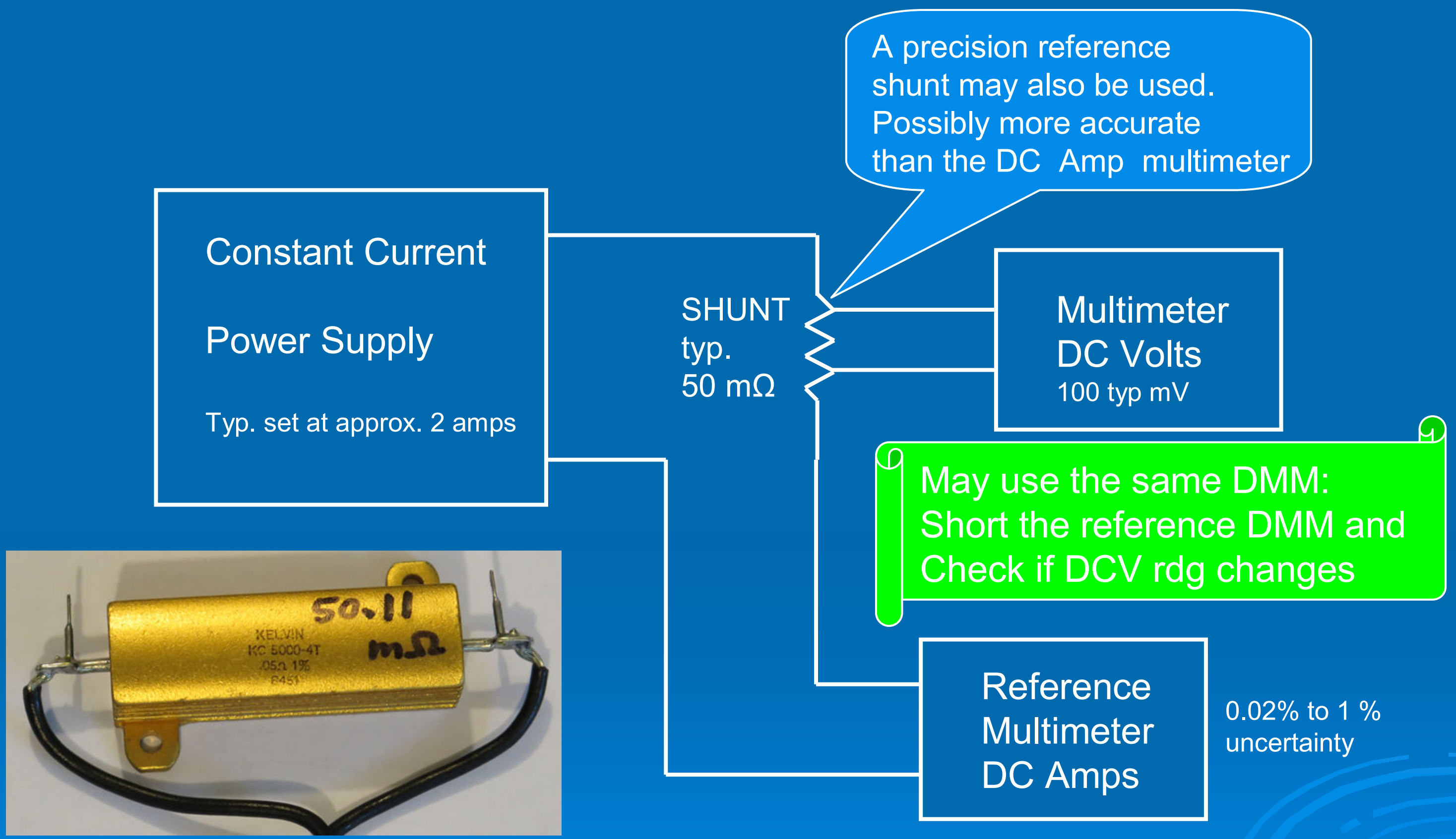
Using Ratio Mode to verify DC Amplifier GAIN



DC / DC Ratio mode

CALIBRATING THE **REFERENCE** SHUNT

Typically even 6.5 digits multimeters are not accurate in measuring low values of resistance say below 1Ω
These shunts may be used to ckeck multimeter current accuracy in measuring 10 mA to 10 Amps.

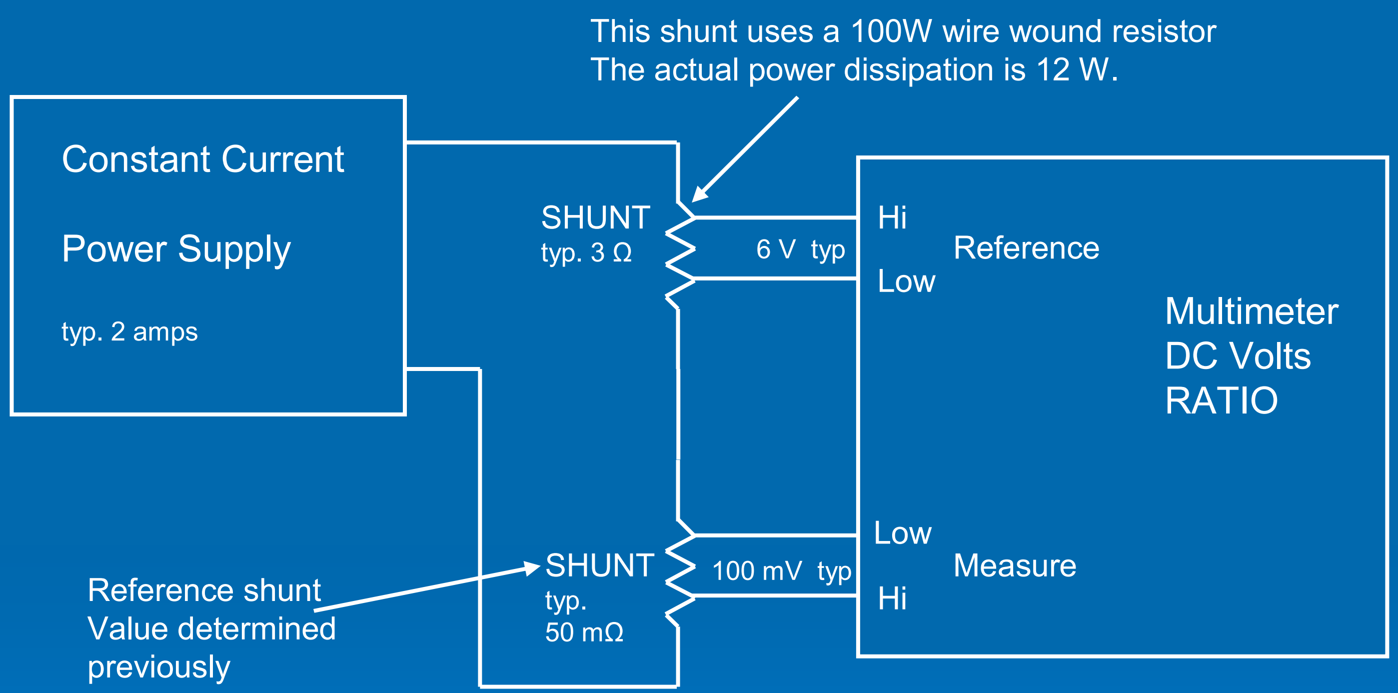


Reference shunt

$$\text{Shunt R} = \frac{0.1\text{ V}}{2\text{ A}} = 0.05\ \Omega$$

CALIBRATING A HIGH RESISTANCE SHUNT

Ref.: ShuntRes_3_ohms-RatioMode.xls



Use ratio mode here if possible.

$$\text{Shunt R} = \frac{0.05\ \Omega \times 6\ \text{V}}{0.1\ \text{V}} = 3\ \Omega$$

$$\text{Shunt R} = \frac{0.05\ \Omega}{|\ \text{Ratio}\ |} = 3\ \Omega$$

Power dissipation in the reference shunt: 0.2 W.

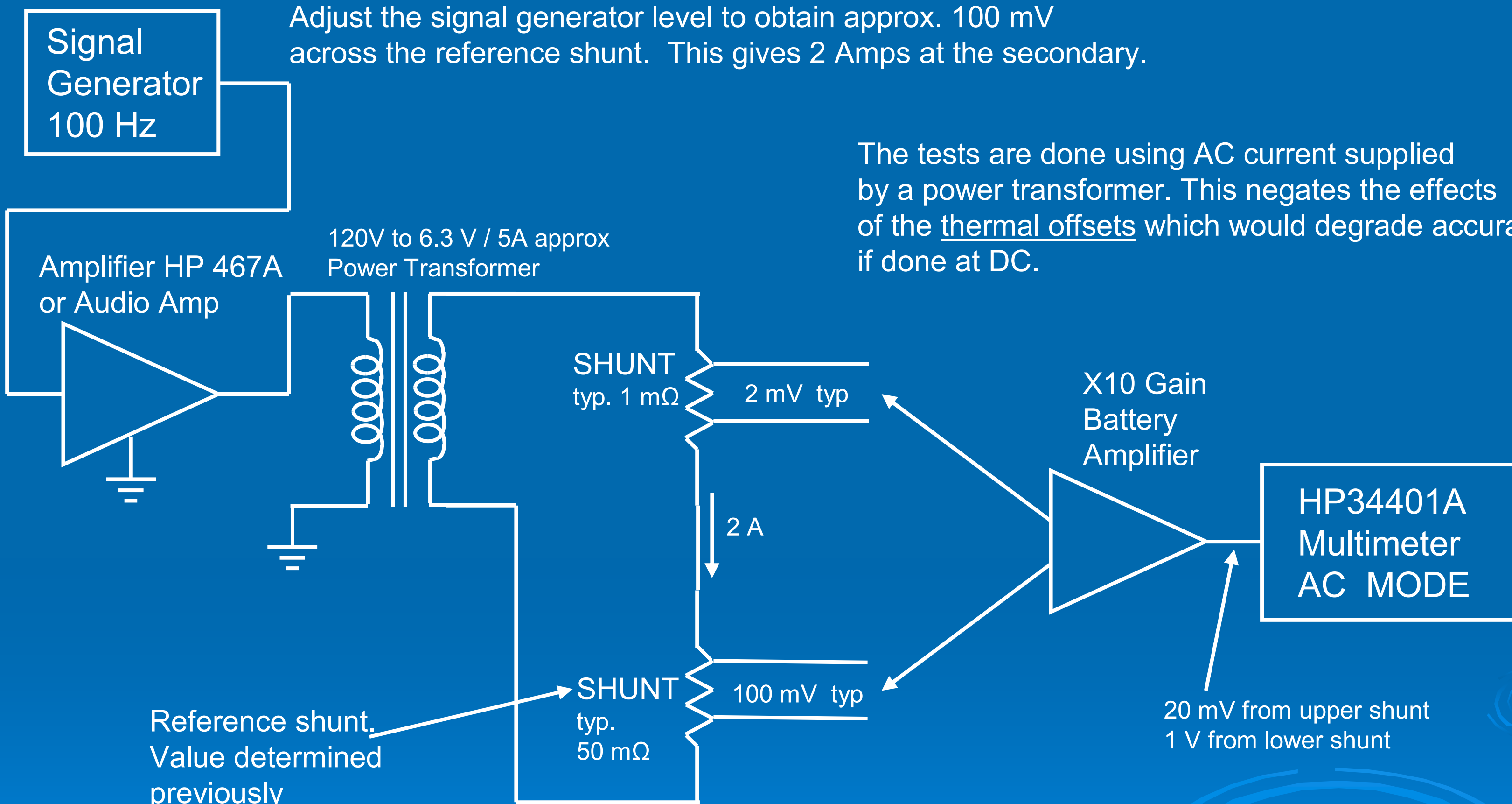
Power Resistor Terminal Modifications for four wire connections

Open terminal
One side for current,
The other for voltage

CALIBRATING A **LOW RESISTANCE** milli ohm SHUNT

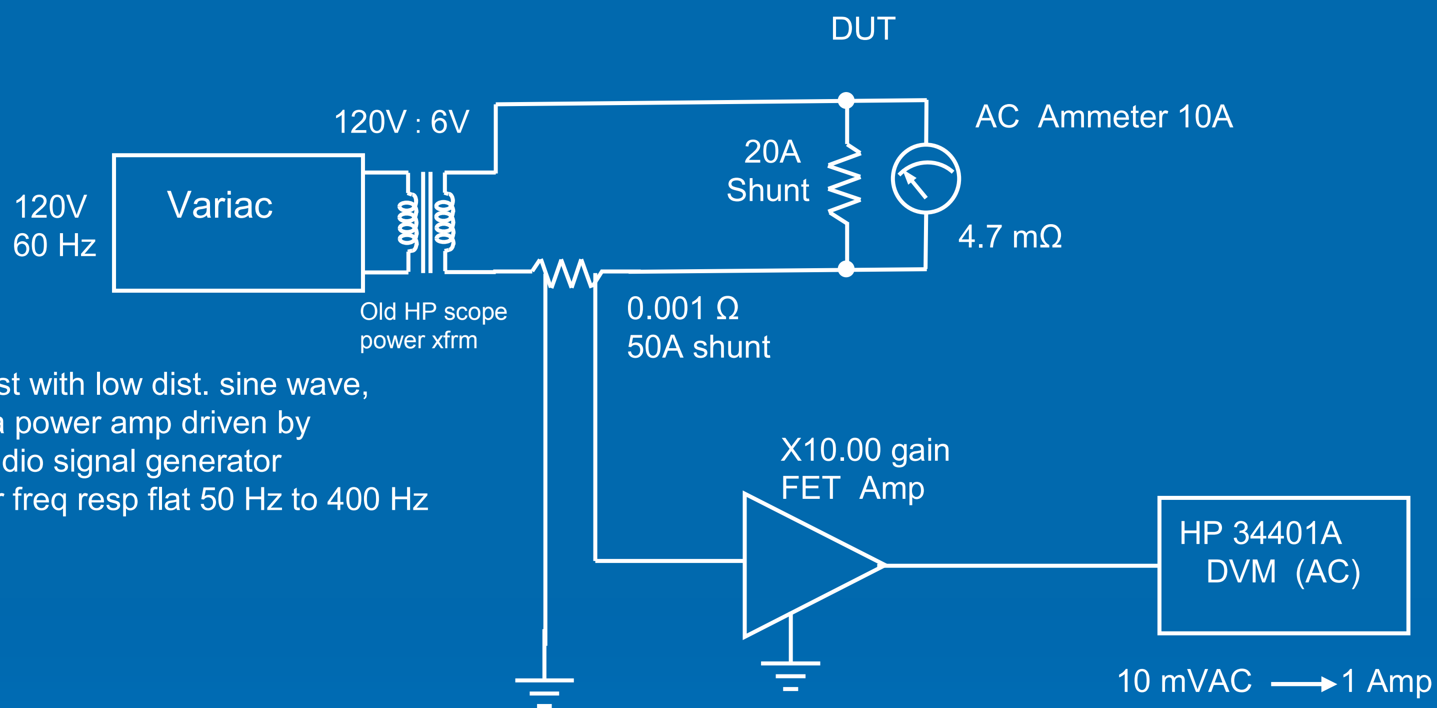
Adjust the signal generator level to obtain approx. 100 mV across the reference shunt. This gives 2 Amps at the secondary.

The tests are done using AC current supplied by a power transformer. This negates the effects of the <u>thermal offsets</u> which would degrade accuracy if done at DC.



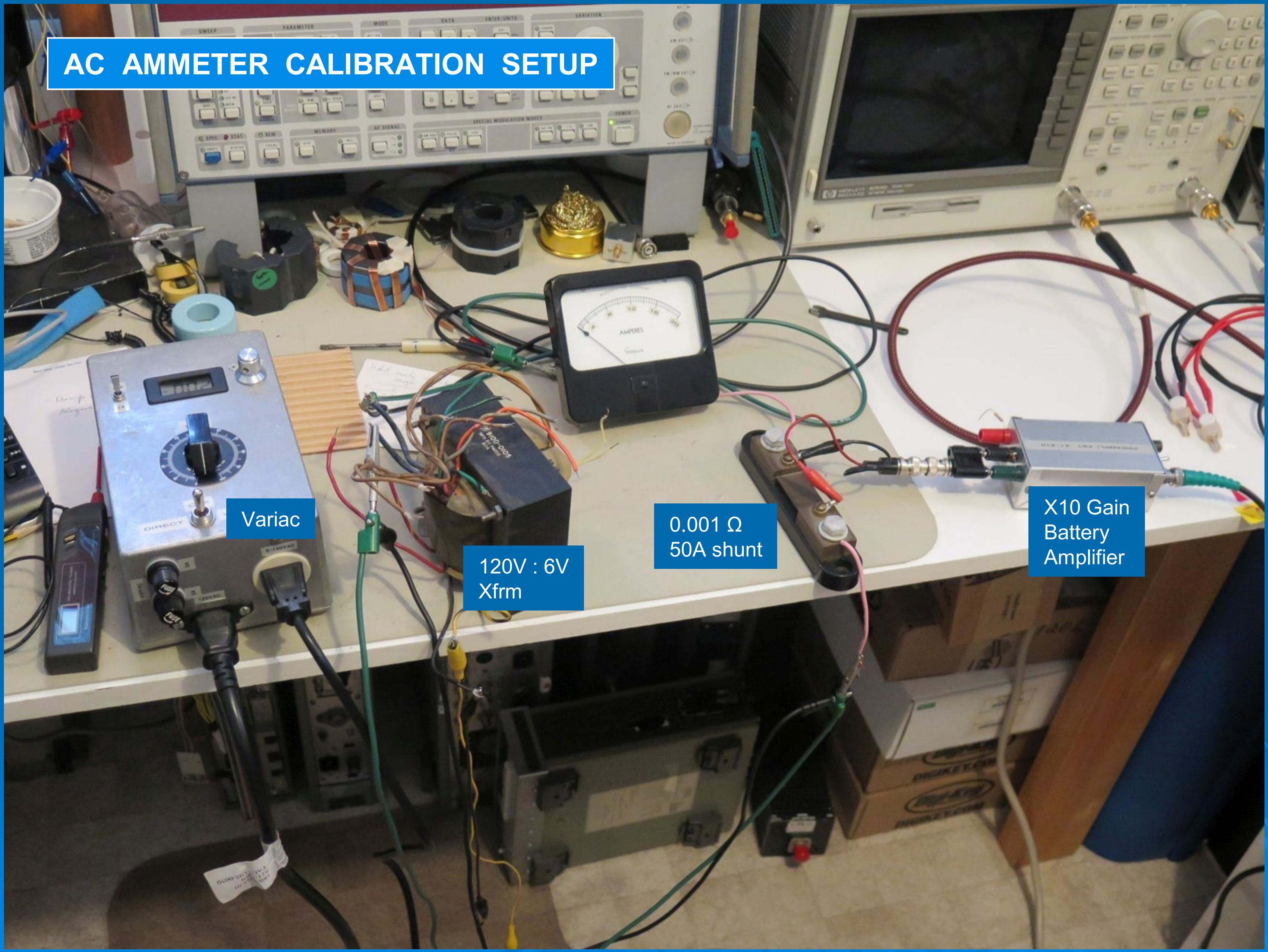
$$\text{Shunt R} = \frac{0.05\ \Omega \times 0.02\ \text{V}}{1.0\ \text{V}} = 1\ \text{m}\Omega$$

Making a shunt to read 20 A on a 10 A ammeter

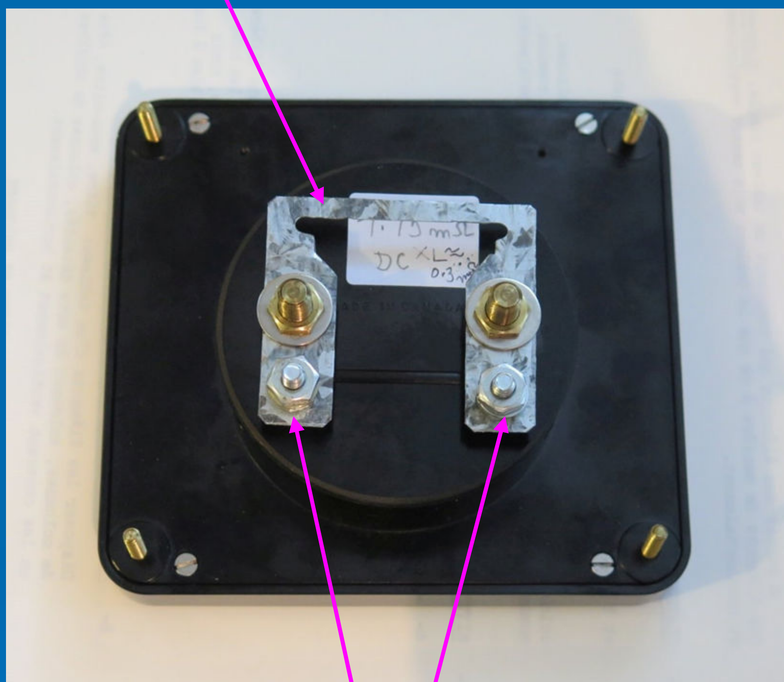


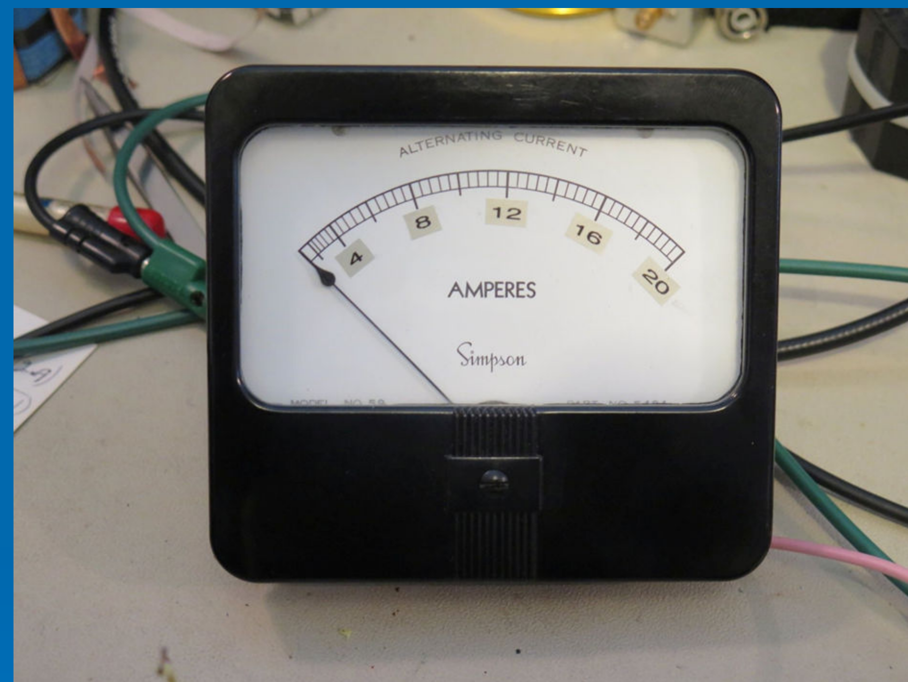
To test with low dist. sine wave,
Use a power amp driven by
an audio signal generator
Meter freq resp flat 50 Hz to 400 Hz

1 mΩ 50A shunt.
Verified with
1.000 Amp AC, as measured with HP 3478A in-circuit
While the HP 34401A measures 10.00 mV AC at amp out


AC AMMETER CALIBRATION SETUP
Variac
120V : 6V
Xfrm
0.001 Ω
50A shunt
X10 Gain
Battery
Amplifier

Shunt made of galvanized steel (heating duct galvanized steel)





Terminals

AC voltage references

Not so precise (0.5%)
And very expensive: $200

Calibrated voltage reference.

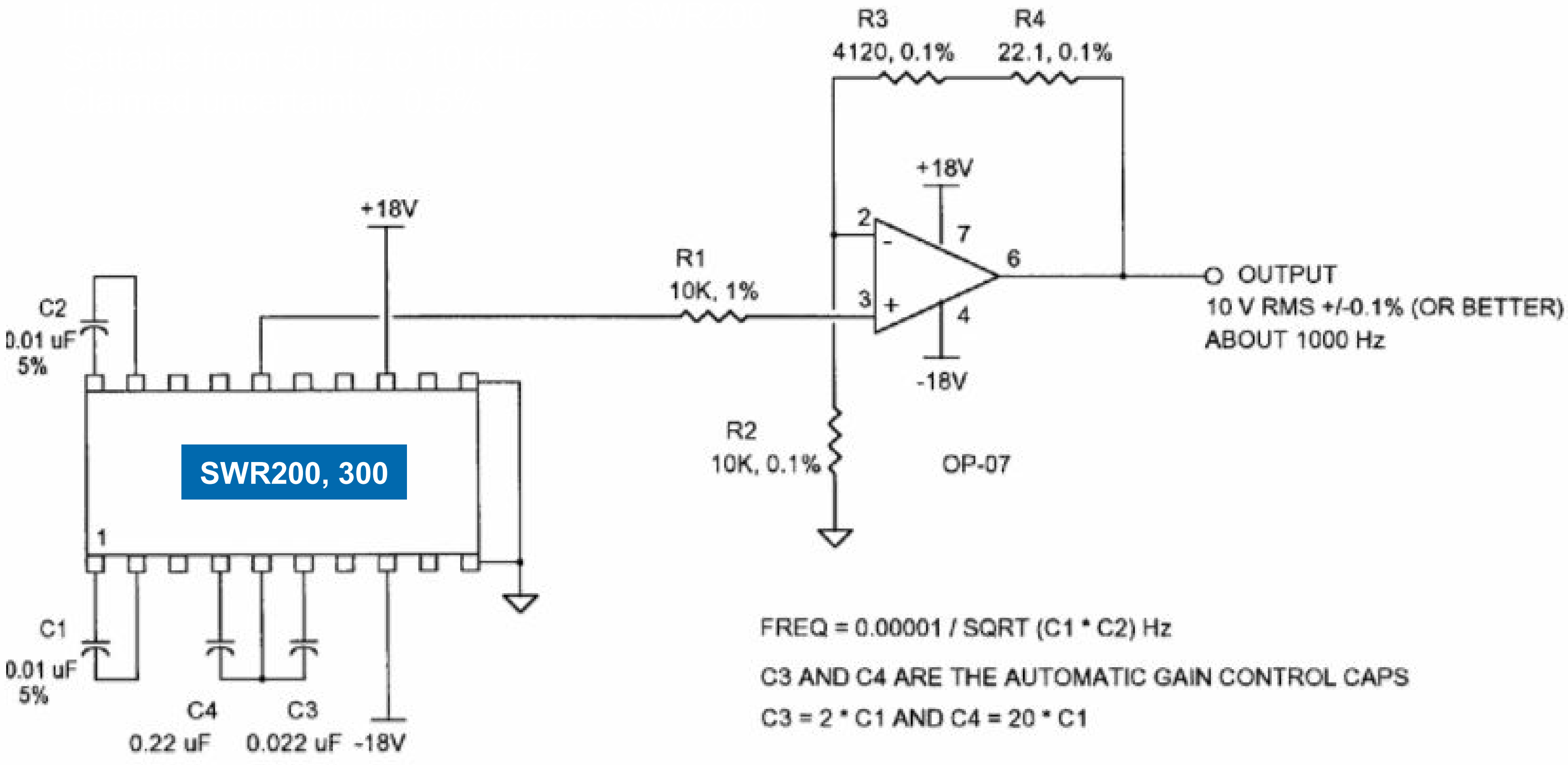


FIGURE 10. AC voltage reference using Thaler Corp. SWR300. Gain set resistors (R2, R3, R4) should be 0.1% or better with low temperature co-efficient.

From: http://www.nutsvolts.com/magazine/article/the-ac-volt

Use op-amp full wave precision rectifier below 100 KHz.

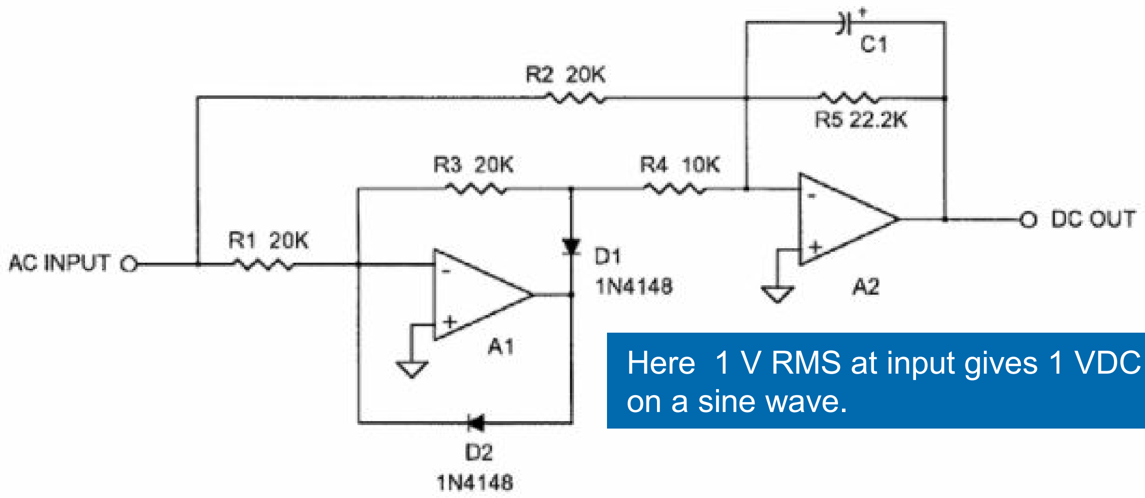
Build with precision resistors (0.1% or better), low offset op-amps.

Allows measuring the AC value (RMS or Average) by measuring the rectified DC output.

This is an averaging detector. It does NOT respond to the RMS value.

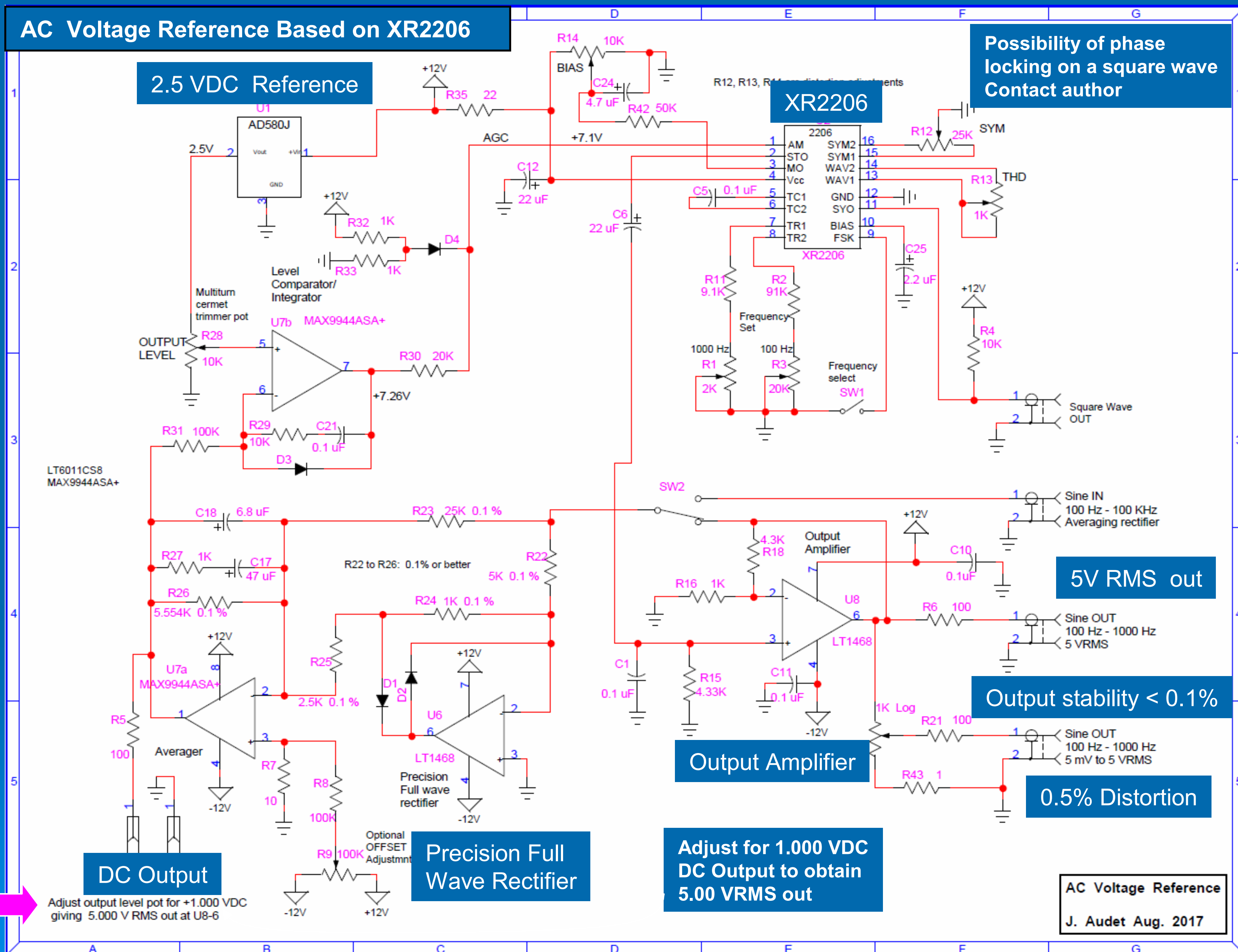
Requires < 1% sine wave distortion.

Ref: http://www.nutsvolts.com/magazine/article/the-ac-volt



Here 1 V RMS at input gives 1 VDC at the output on a sine wave.

FIGURE 1. Precision rectifier. Typical resistor values shown aren't critical, but should be closely matched for best accuracy (0.1% or better).


AC Voltage Reference Based on XR2206
2.5 VDC Reference
XR2206
Possibility of phase locking on a square wave
Contact author
R12, R13, R14 are distortion adjustments
Level Comparator/ Integrator
Multiturn cermet trimmer pot
OUTPUT LEVEL
LT6011CS8
MAX9944ASA+
R22 to R26: 0.1% or better
Frequency Set
Frequency select
Square Wave OUT
Sine IN
100 Hz - 100 KHz
Averaging rectifier
Output Amplifier
5V RMS out
Sine OUT
100 Hz - 1000 Hz
5 VRMS
Output stability < 0.1%
Sine OUT
100 Hz - 1000 Hz
5 mV to 5 VRMS
0.5% Distortion
Averager
Precision Full wave rectifier
Optional OFFSET Adjustmnt
DC Output
Precision Full Wave Rectifier
Adjust for 1.000 VDC DC Output to obtain 5.00 VRMS out
Adjust output level pot for +1.000 VDC giving 5.000 V RMS out at U8-6
AC Voltage Reference
J. Audet Aug. 2017

AC Power Reference – Frequency Response & Linearity

Use power meter cal output (0 dBm, 50 MHz).

- Compare cal outputs of various power meters (at least 2), such as HP 435A…468A, Boonton 4200
- Measured +/- 0.01 dB delta between ***four*** power meters. Spec is 0 dBm +/- 0.05 dB

Reference level generator (Ex.: HP 3335 / 3336 with HI accuracy attenuator option.)

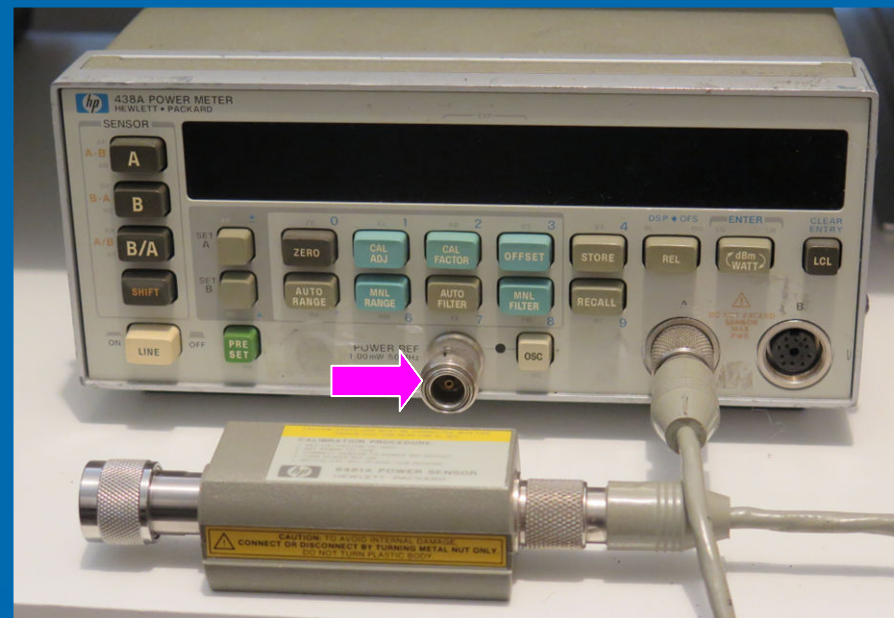
- Provide wide range of precise output levels. Useful for linearity and frequency response tests.
- Flat frequency response. Useful for freq. response tests, up to 50 / 21 MHz.
- Needs calibration

Reference attenuators

- For generating known power levels.
- Nice to have: HP 355C+D and / or HP 8494B + 8496B step attenuators.
- One may do 3 resistance measurements to calculate all low freq. attenuator characteristics. *
- Reference:

* http://ve2azx.net/technical/ComputeLowFrequencyParametersofResistiveAttenuatorswithThreeDCResistanceMeasurements.pdf

Power meter cal outputs (0 dBm, 50 MHz).



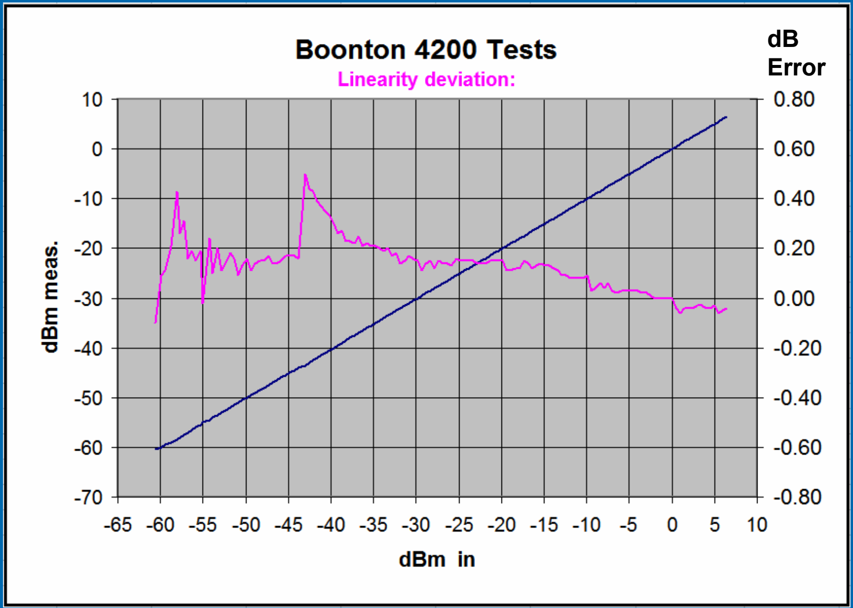
Boonton 4200

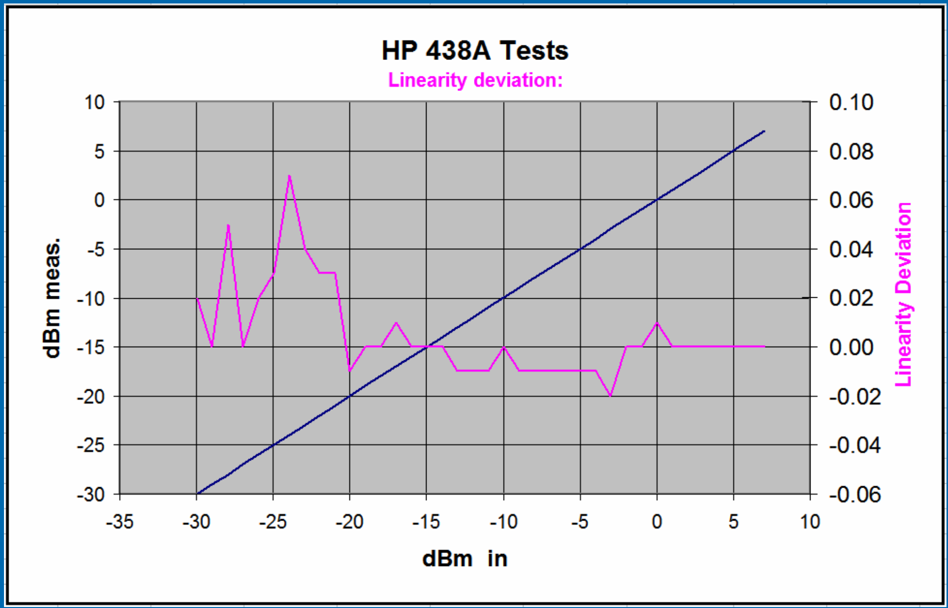
Diode sensor. 50Ω DC coupled
- 60 dBm to +13 dBm
RMS response below -25 dBm
Response from 10 KHz to > 10 GHz

HP 468A

Thermocouple sensor (HP8481A).
AC Coupled. -30 dBm to +22 dBm
RMS response
Most accurate ! … and most $$$
Response from 10 MHz to > 10 GHz

Linearity Comparisons





HP 438A is my most accurate level meter
Excellent linearity above -20 dBm

Calibrated Thermocouple (needs calibration, Useful from DC to 50 MHz)

Also called Thermal Converters such as: HP 11049A, 11050A, 11051A and Fluke A55
RMS responding.

My home made thermocouple

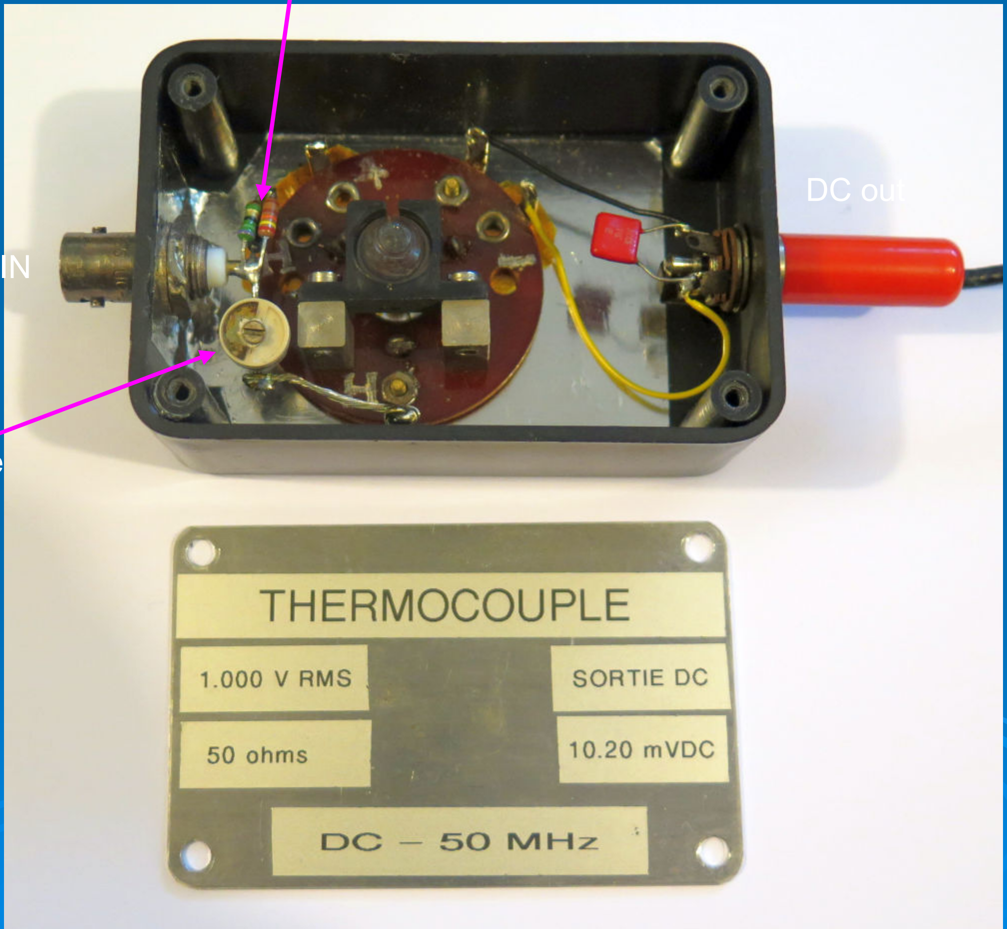
From Boonton Q meter

Series resistors selected to get 50Ω at input

DC to 50 MHz IN

Input Impedance optimization

DC out



Thermocouple Calibration

Calibrated at DC, using power supply and a precision 0.1% 50Ω resistor in series:

Measure DCV at supply output, before the 50Ω resistor.

Compute power into thermocouple.

Measure corresponding mV DC at thermocouple DC output. Remove multimeter DC offset.

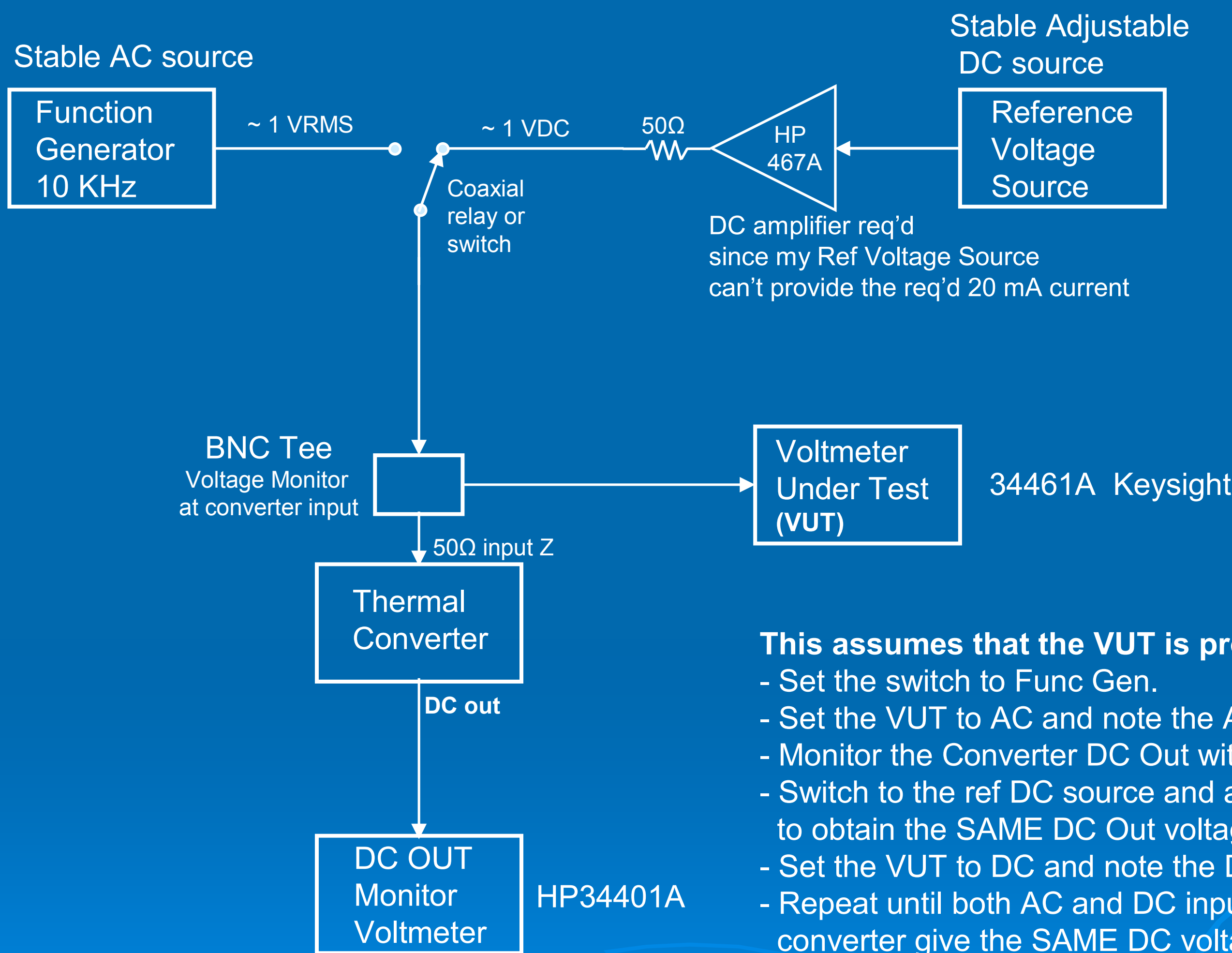
Repeat for thermocouple input powers from 1 to 10 mW.

Plot DC out vs input power

Fit curve to enable measuring any AC power from DC mV measurements.

Voltmeter DC to AC Calibration with a Thermal Converter

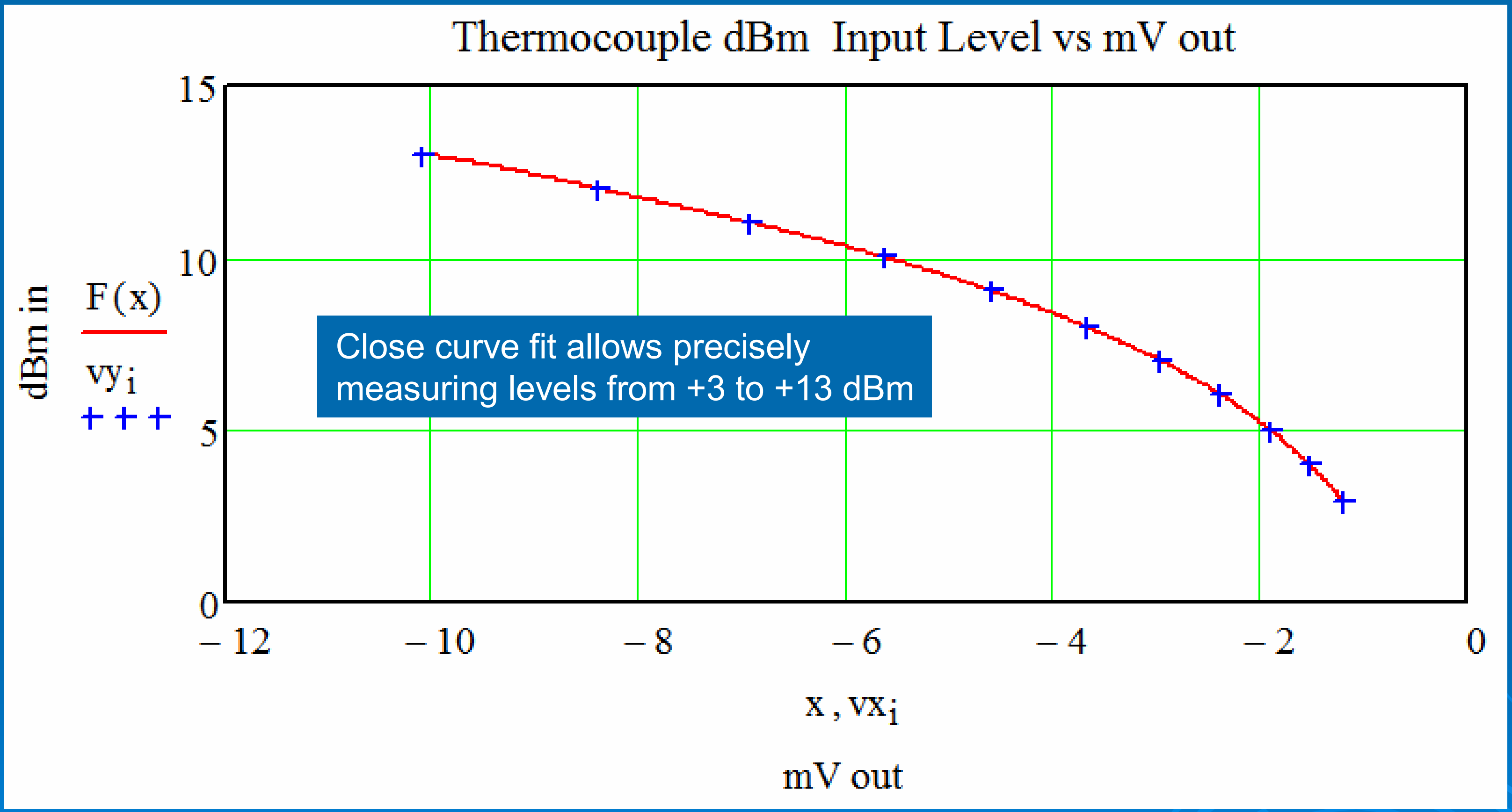
J. Audet
Mar 2022



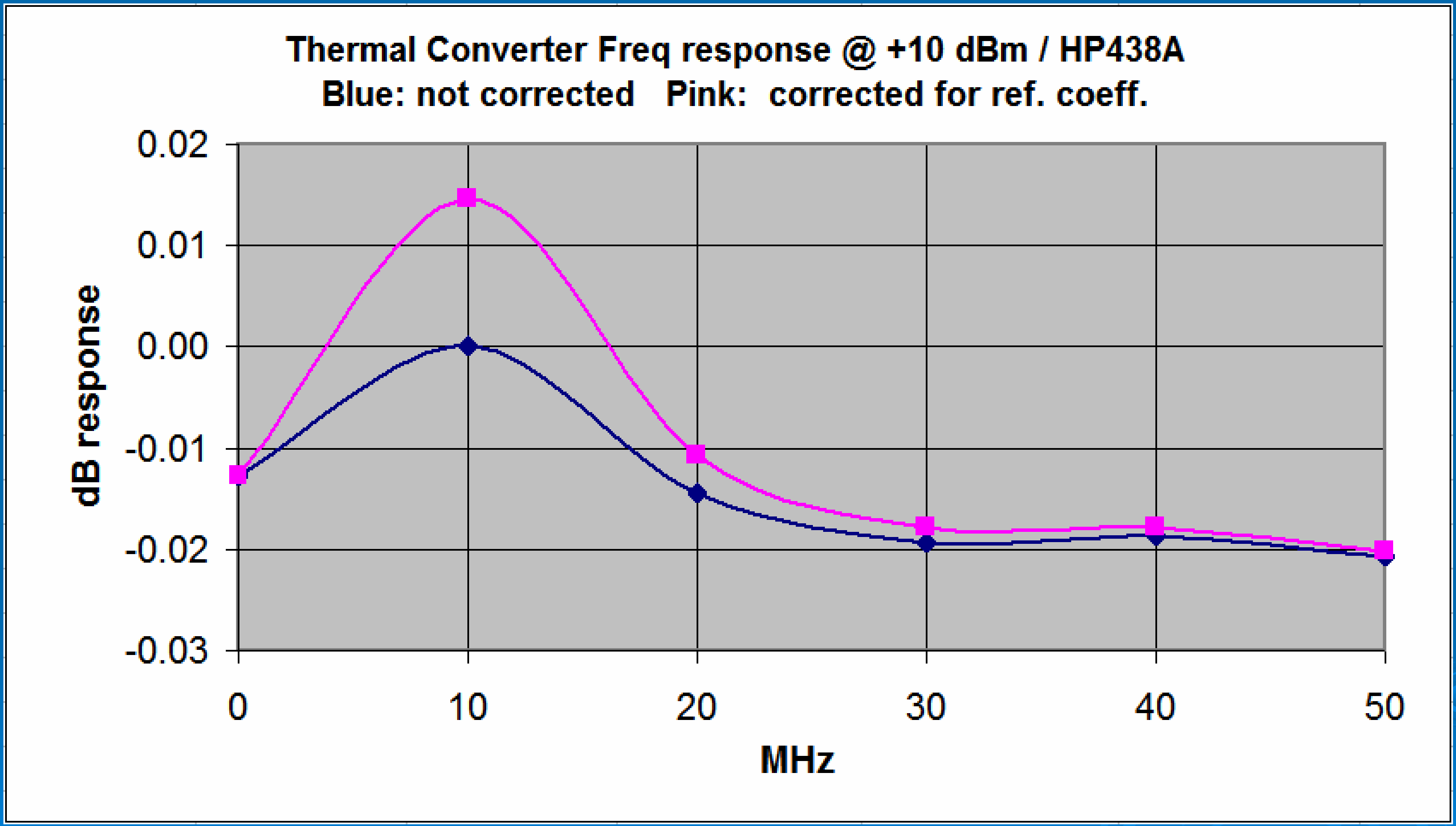
This assumes that the VUT is properly calibrated at DC

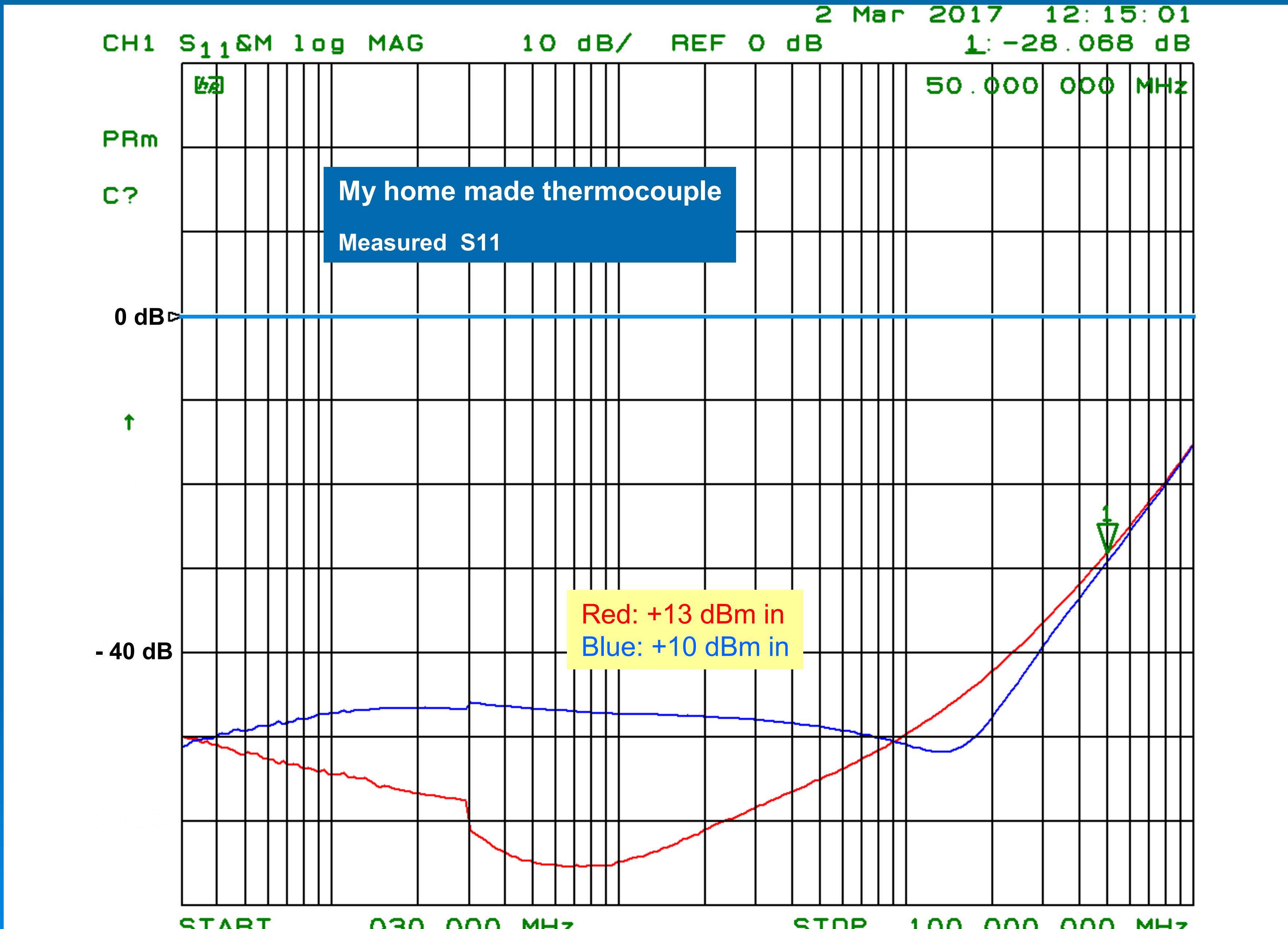
- Set the switch to Func Gen.
- Set the VUT to AC and note the AC voltage.
- Monitor the Converter DC Out with the 2nd voltmeter.
- Switch to the ref DC source and adjust it to obtain the SAME DC Out voltage.
- Set the VUT to DC and note the DC voltage.
- Repeat until both AC and DC inputs to the converter give the SAME DC voltage on the monitor voltmeter.
- Read and record the DC and AC voltages on the VUT.

Thermal converter Response



Response of my thermal converter from DC to 50 MHz as verified with HP438A




2 Mar 2017 12:15:01
CH1 S11&M log MAG 10 dB/ REF 0 dB 1: -28.068 dB
50.000 000 MHz
PRm
C?
My home made thermocouple
Measured S11
0 dB
- 40 dB
Red: +13 dBm in
Blue: +10 dBm in
START .030 000 MHz STOP 100.000 000 MHz

RMS Power detector based on the AD8362

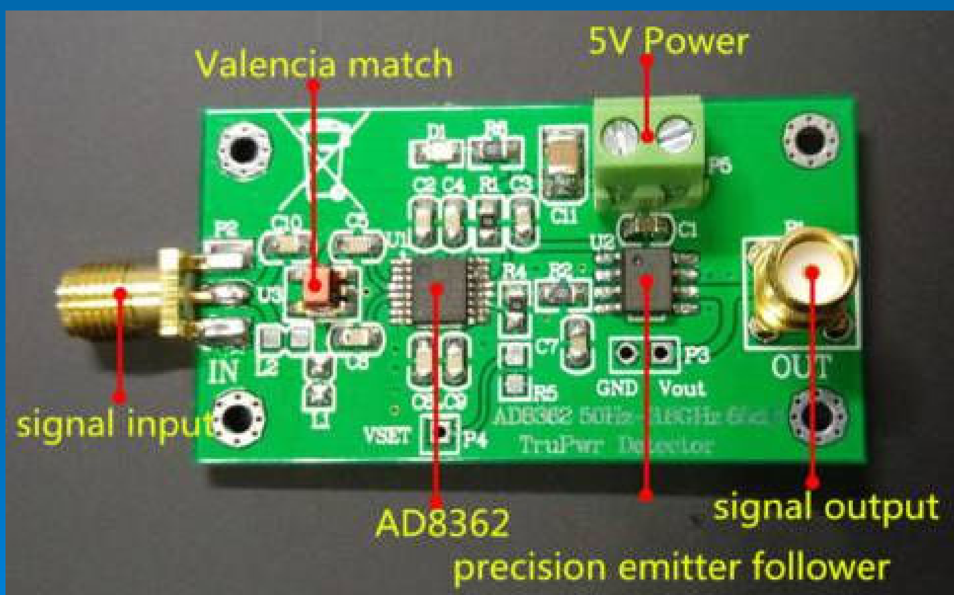
Operating frequency can be 50Hz to 3.8GHz, suitable for wideband power detector, having a flat input and output response.

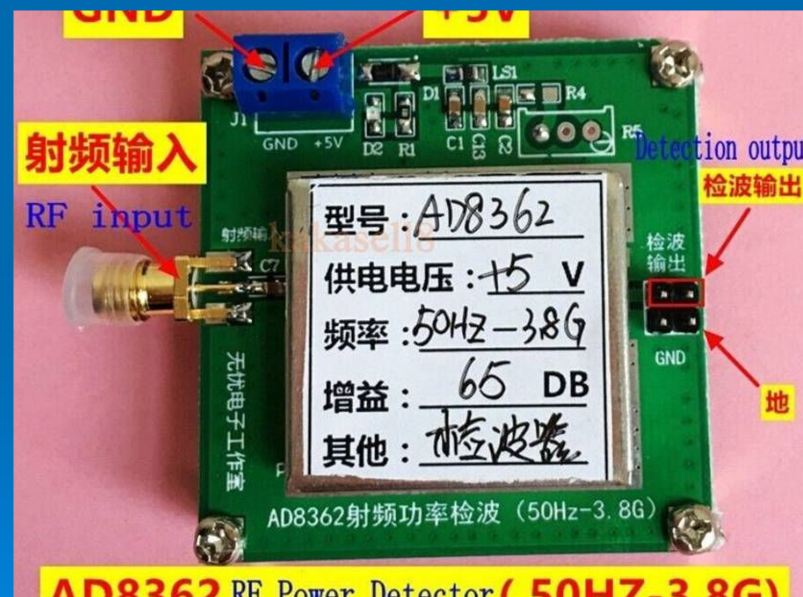
Dynamic range of 60dB, in a 50Ω system, the input signal from -52 dBm to + 8dBm.

Precision, high linearity to provide an accurate decibels (dB) as the unit of linear output voltage, 50mV / dB.

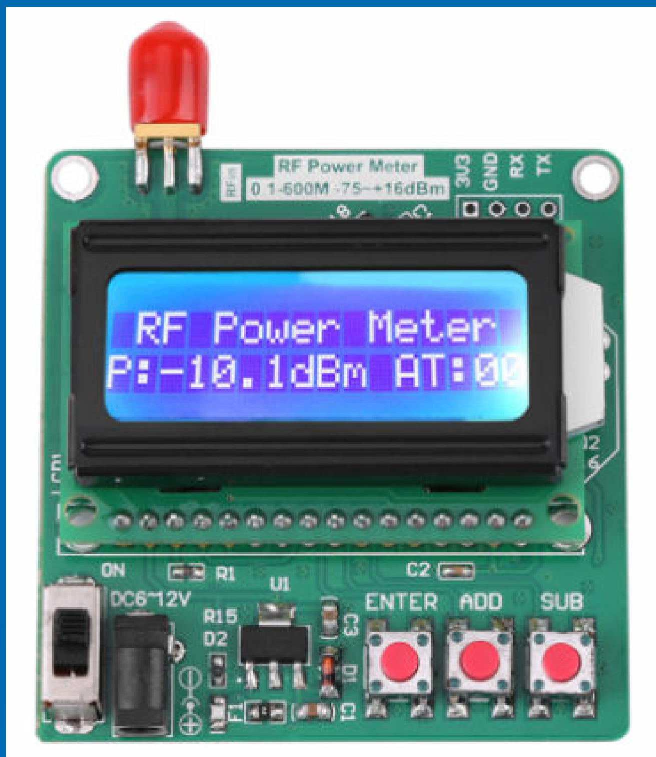
Approx. $15 to $20

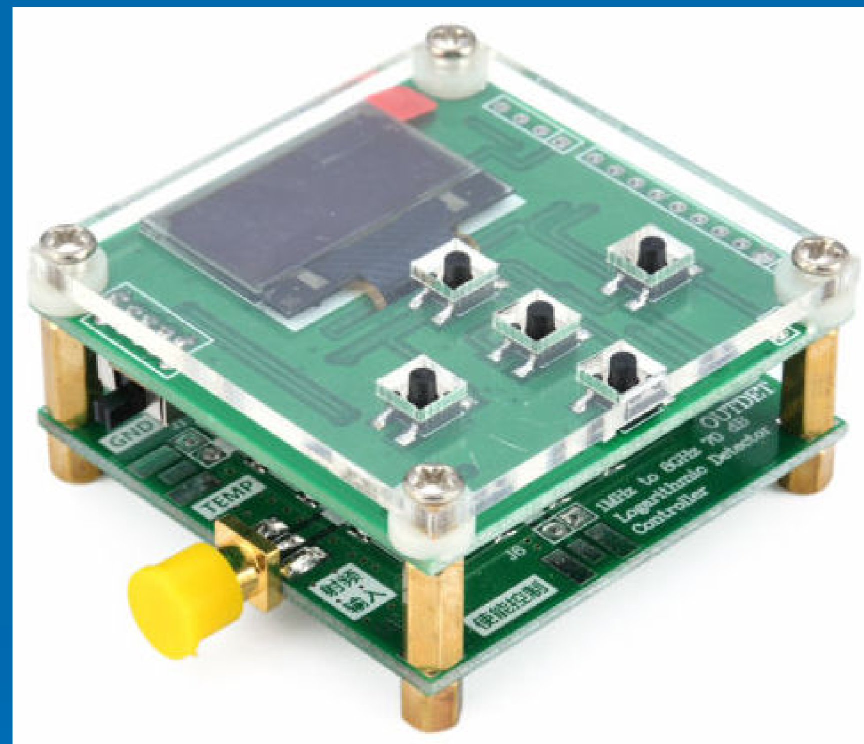
From Ebay





Mini Power Meters (from Ebay)





Digital LCD RF Power Meter
-75 to +16 dBm 1- 600MHz
6 to 12V $21

8GHz RF Power Meter 1-8000Mhz OLED -55～-5 dBm
+ Sofware RF Attenuation Value Kit $33
USB powered. Sends data to serial port.

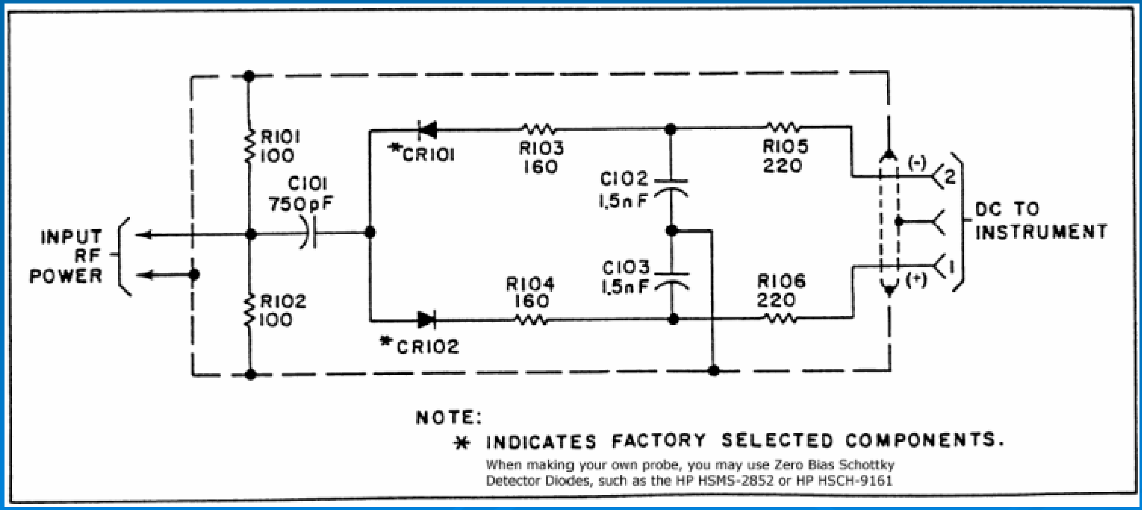
Diode Power Sensor Calibration

Peak responding. Error in measuring NON sinusoidal signals with a diode peak sensor.

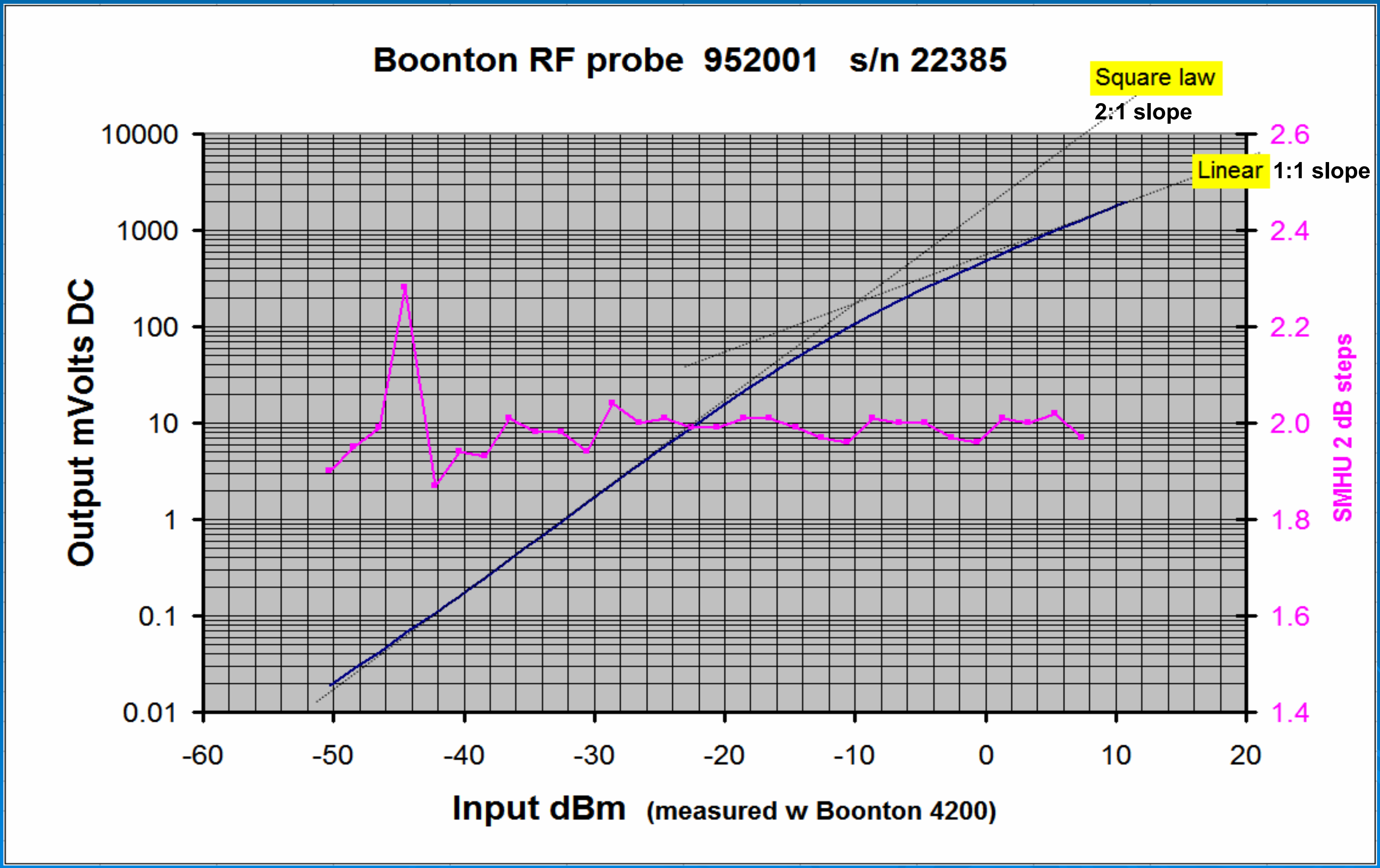
- If the sensor is DC coupled, insure no DC offset from generator on the RF input port.

- It must NOT allow any RF to enter the DC out port.
  Use shielded RF generator / attenuator and RF feedthru decoupling on the DC port.

- Example of test results with a Boonton probe. Done with SMHU sig gen or HP3336 / opt 5.



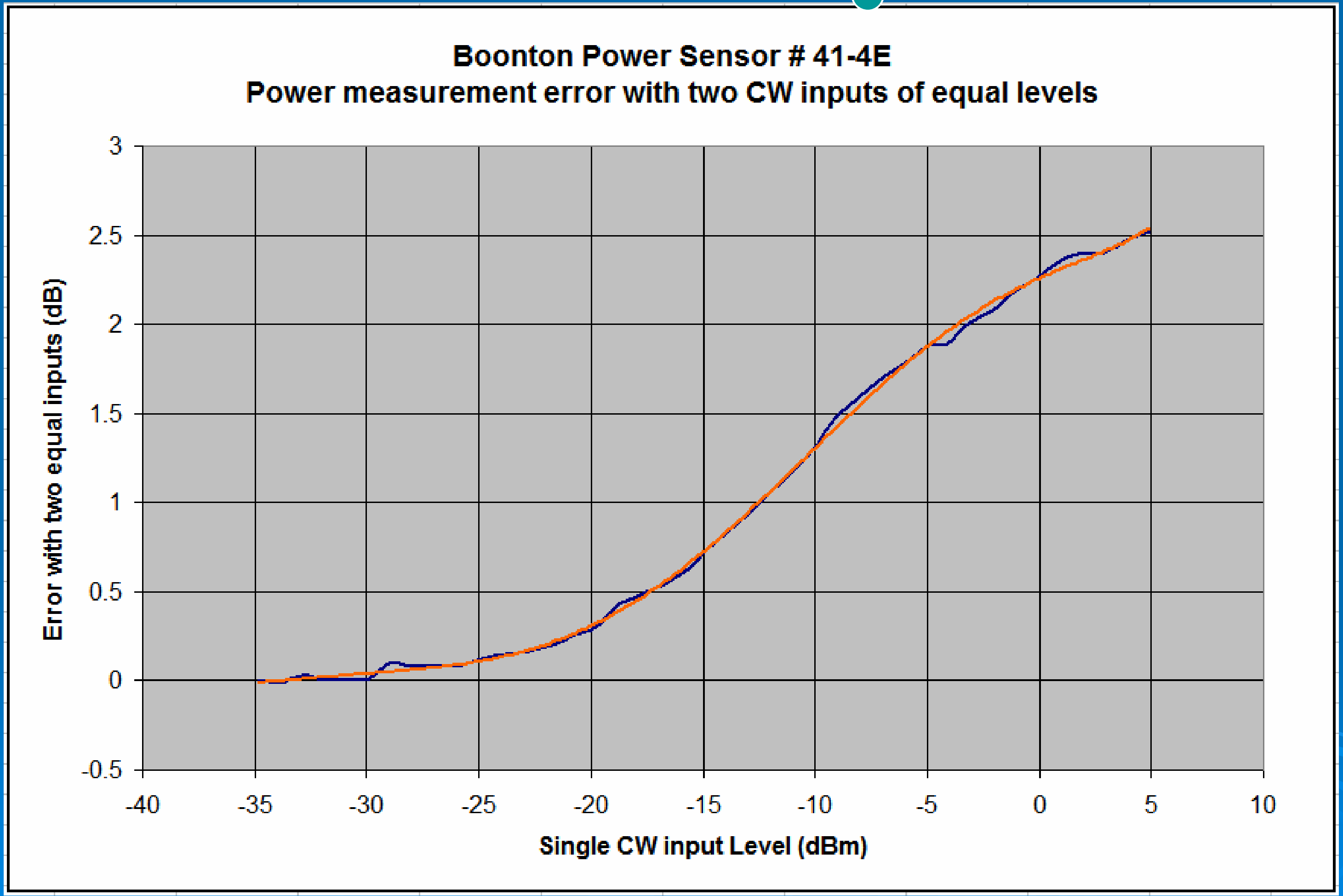
Measured Response of my Boonton RF Probe



Boonton Power Sensor

Measured error in measuring NON sinusoidal signals with a **diode peak sensor**

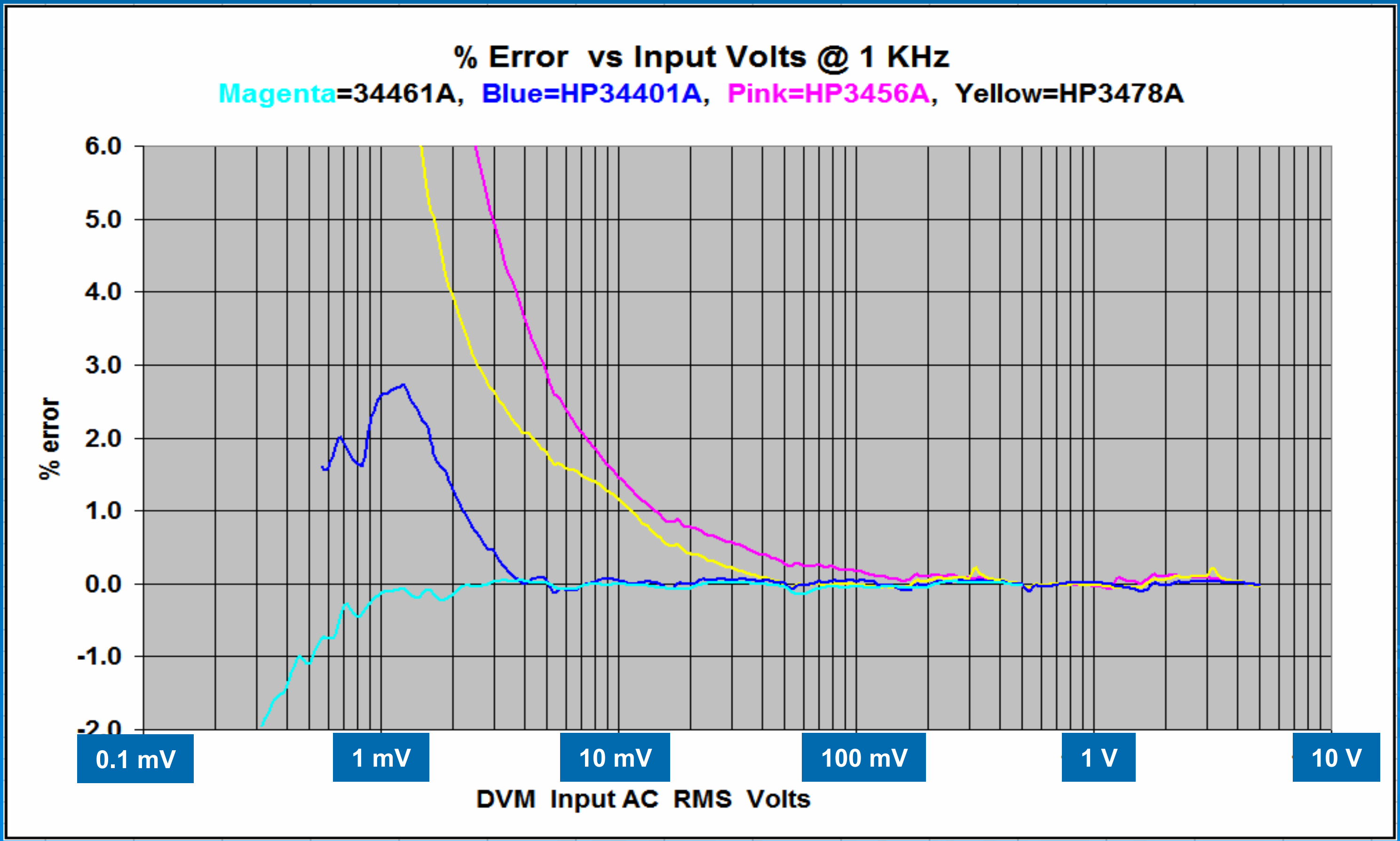
Adding two equal power signals increases the power by 3 dB Diode peak detectors show a larger increase above -25 dBm.



How's my Multimeter Linearity at AC ?

5 and 6 digit multimeters in AC mode can measure voltage ratio accurately.

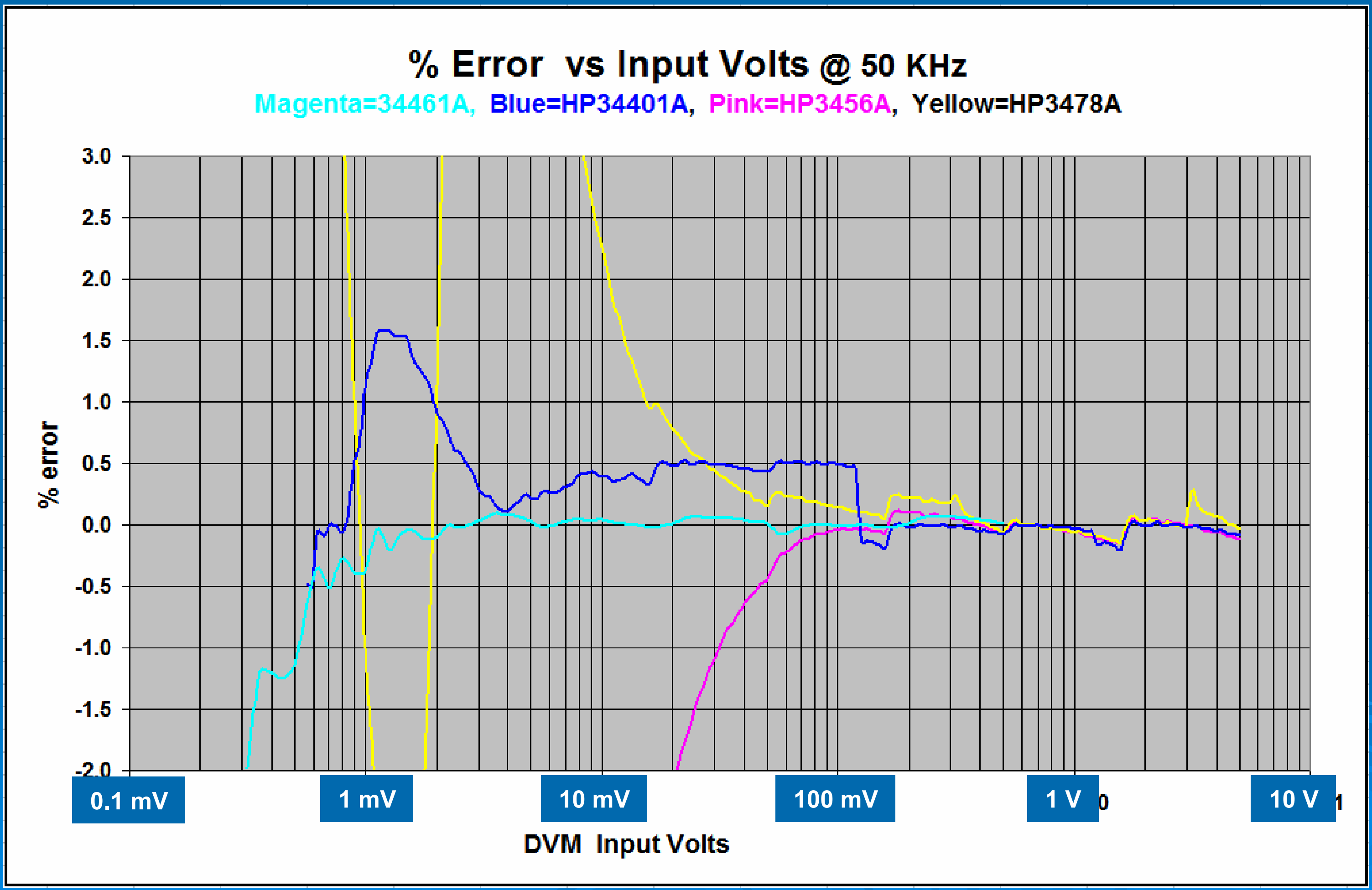
Measured with HP3336B level generator, term 50Ω and X10 gain amp



AC Linearity @ 50 KHz

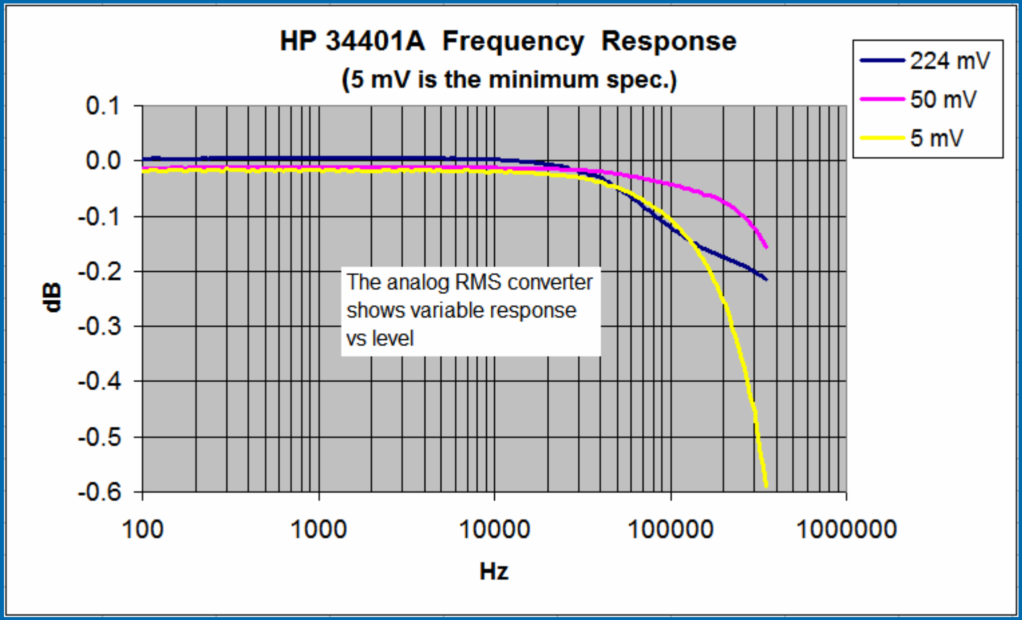
Multimeters in AC mode. **50 KHz**

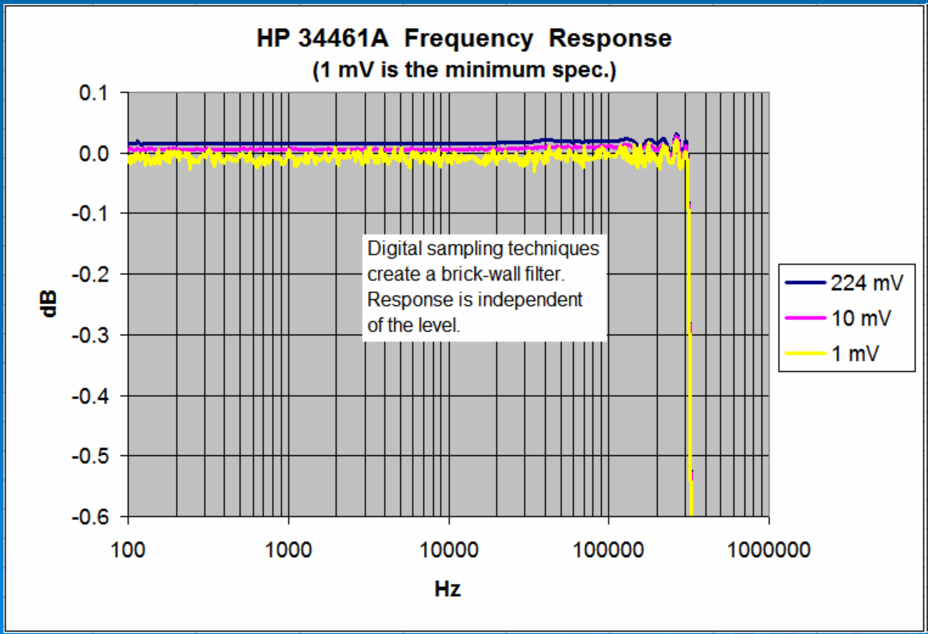
The 34461A has similar curves all the way to 300 KHz. Its response cuts sharply above 300 KHz.

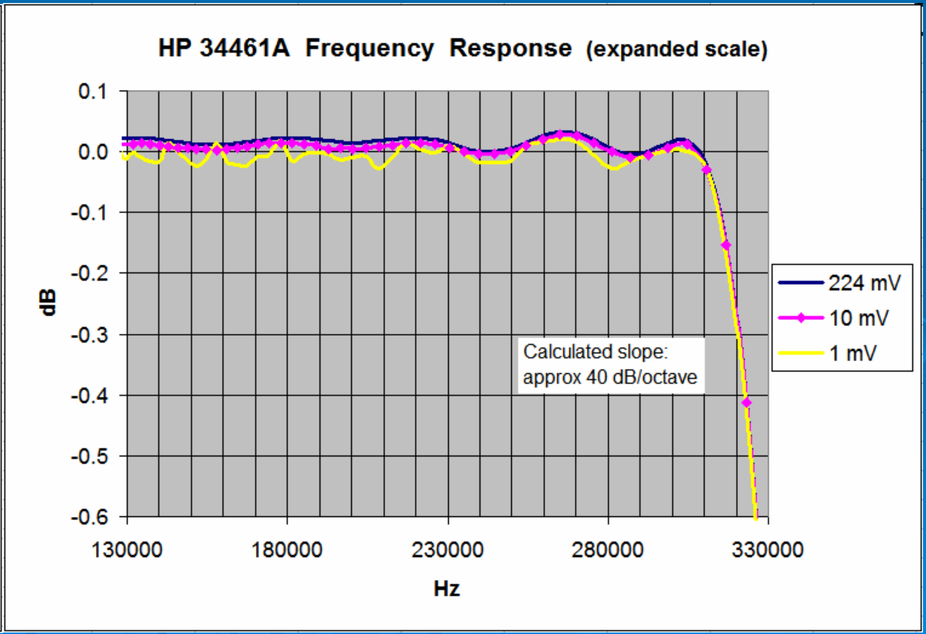


HP 34401A and Keysight 34461A

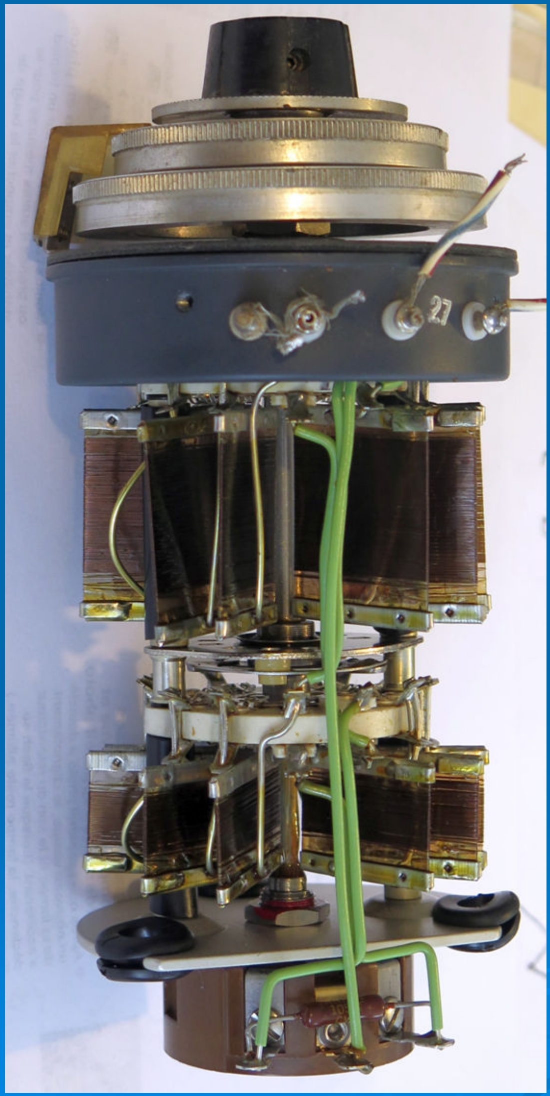
Frequency Response Comparisons

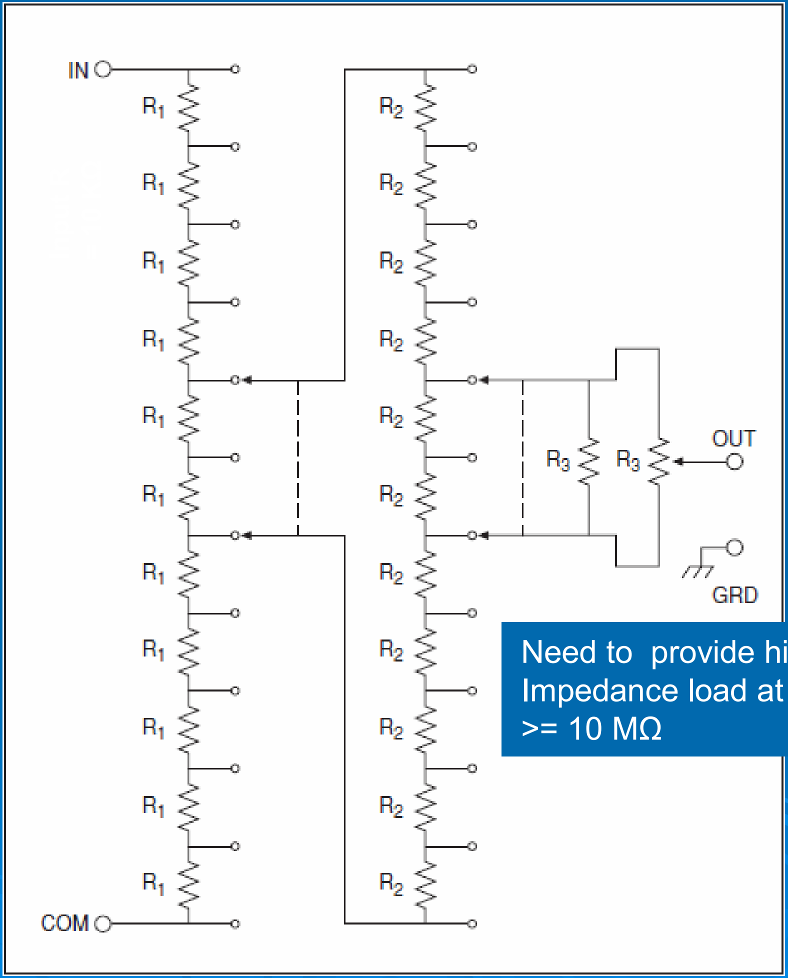






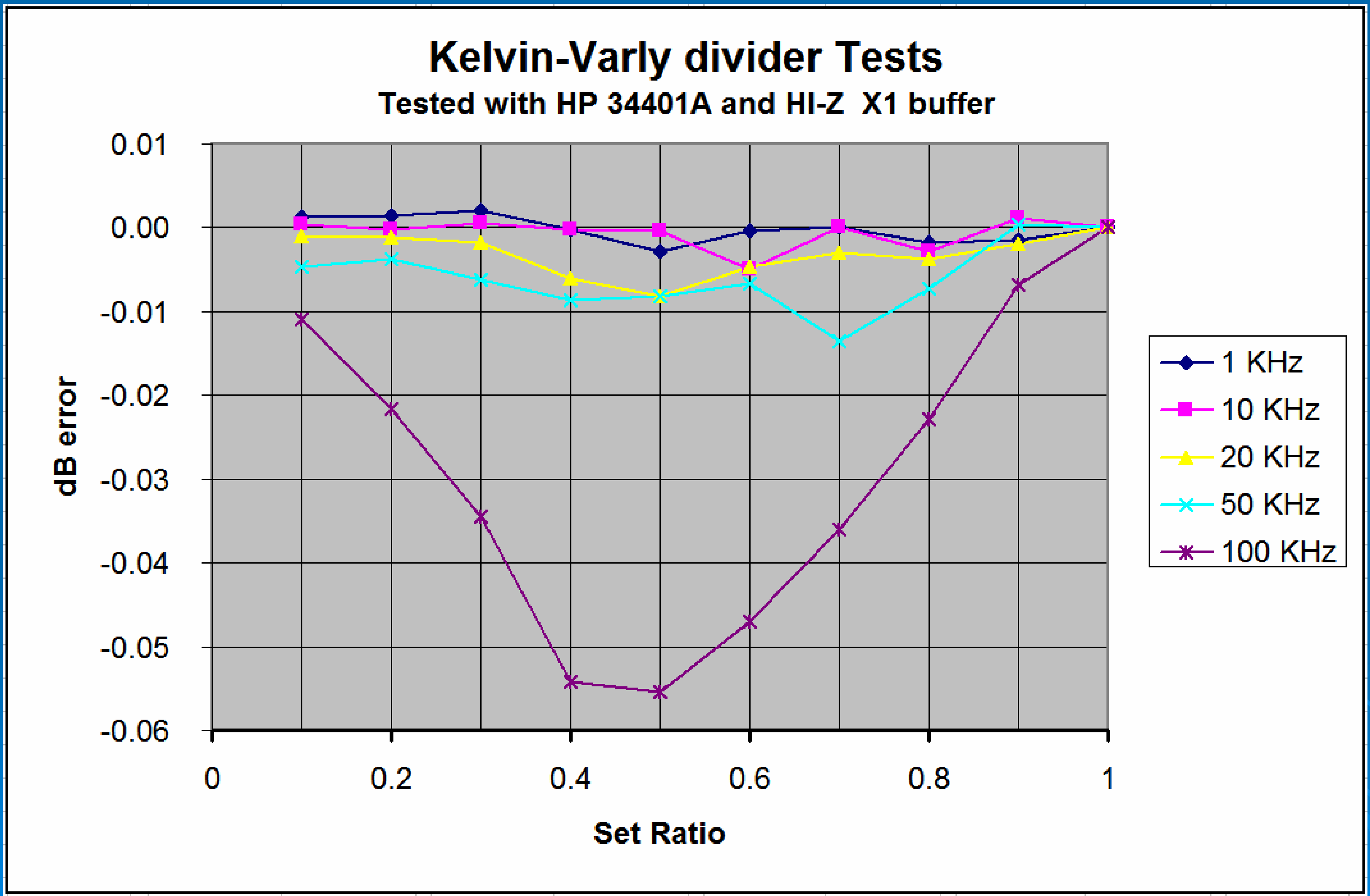
Kelvin Varley Divider for linearity testing





Need to provide high Impedance load at output >= 10 MΩ

AC Response Tests using a Kelvin Varley Divider



Measure voltage ratio accurately using a 24 bit sound card with Spectrum Analyzer software

Over a 80 dB range:

A 16 bit card gives 1.2 dB resolution at the bottom of this range.

A 24 bit card gives 0.005 dB resolution at the bottom of this range.

May have to use an external buffer

Examples:

- Spectrum Lab See: http://www.qsl.net/dl4yhf/spectra1.html

- Audio Meter: measure band limited RMS of audio signals with a sound card
  See: http://www.dg8saq.darc.de/AudioMeter/index.shtml

- ARTA Audio Measurement and Analysis Software See: http://www.artalabs.hr/

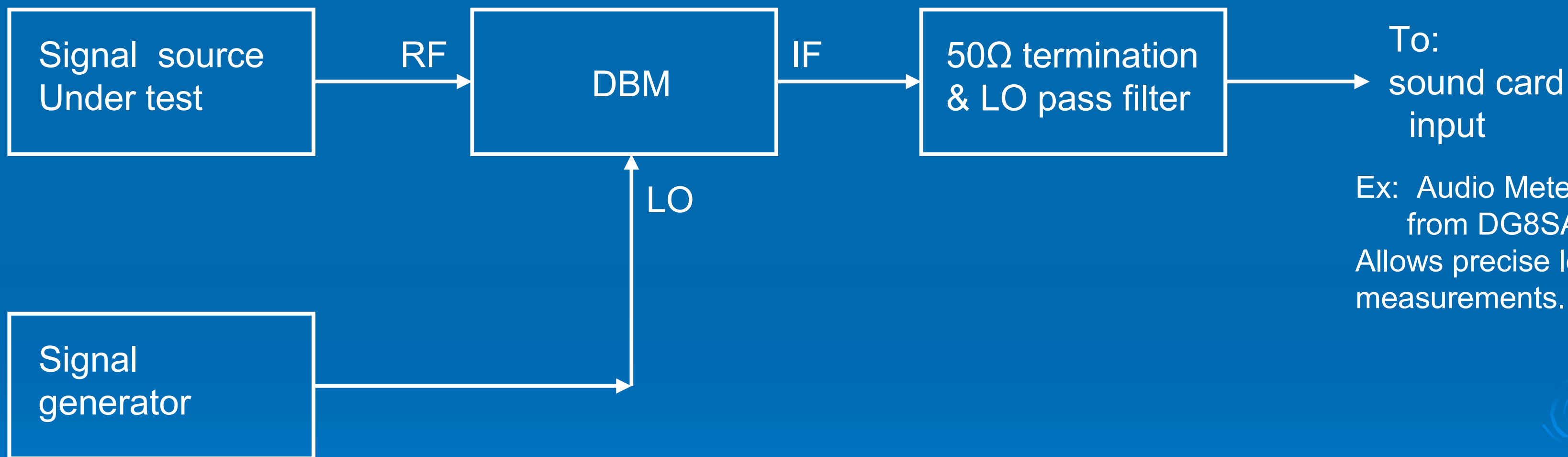
Checking Voltage / Power Ratio at higher frequencies / Output Attenenuator

Check relative level errors of a signal source.

Down-convert the high frequency using a double balanced mixer (DBM) mixer

By converting to audio, and using 24 bit sound card with Spectrum Analyzer software.

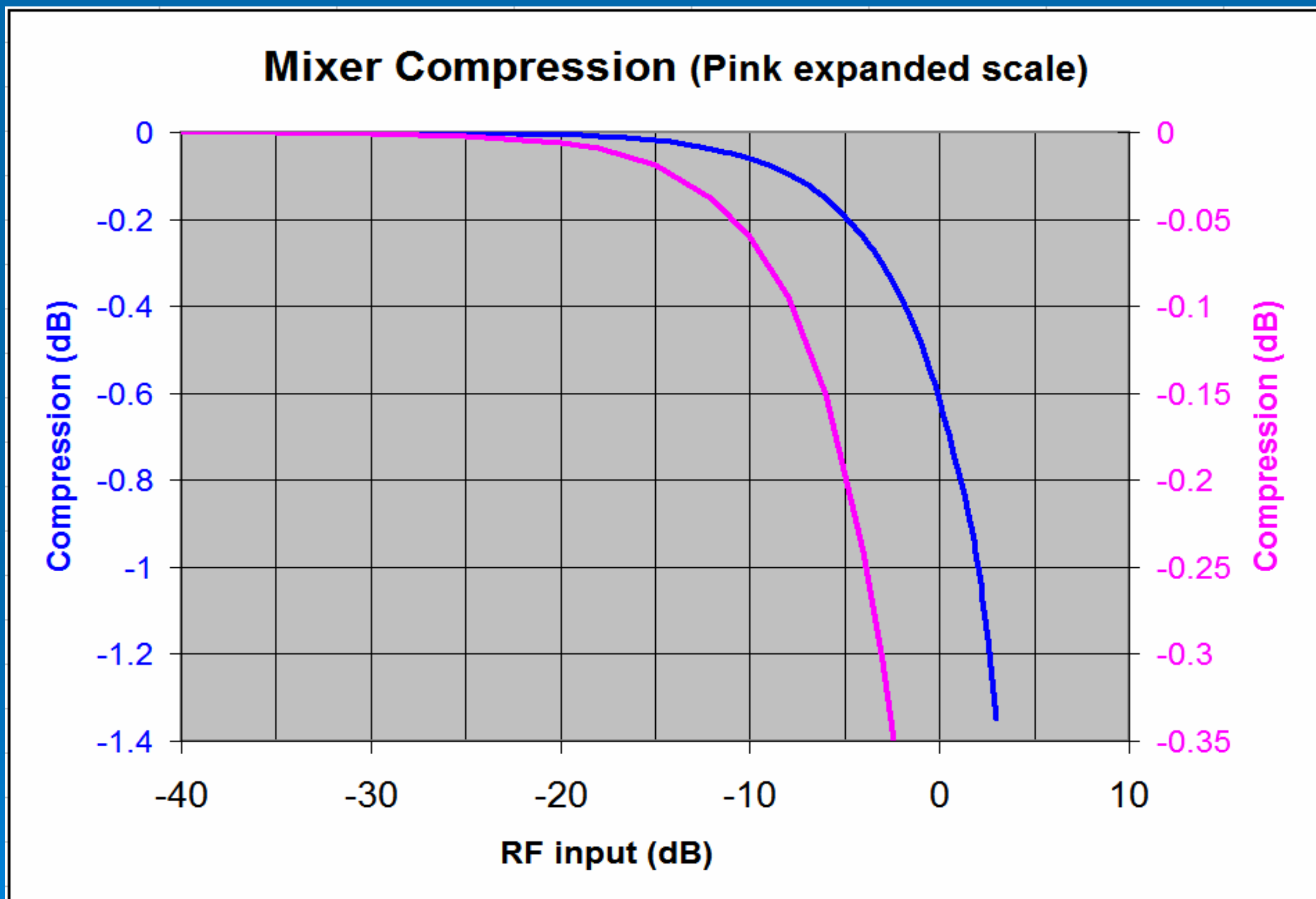
Allows checking attenuator accuracy of a signal generator.



Ex: Audio Meter s/w from DG8SAQ
Allows precise level measurements.

Set F +/- 10 KHz from signal source

Level 7 Mixer Compression vs RF port Level (from simulations)



Frequency Response Testing

- Use Precision op-amp full wave rectifier below 100 KHz. (AC/DC ratio depends on resistors)

- Calibrated Thermocouple (needs cal, Useful from DC to 50 MHz)

- Above 100 KHz Use diode power sensor (EX.: Boonton 41-4E power sensor)

- Above 10 MHz Use thermocouple power sensor (Ex.: HP8481A).
  If possible… compare with Boonton sensor above 10 MHz.

Reference level generator (HP 3335A / 3336A/B/C with HI acc. atten opt. 005)
Useful for freq. response tests, up to 50 / 21 MHz.

OPTION 005, HIGH ACCURACY ATTENUATOR **HP 3336**

Attenuation	10Hz – 20MHz
10 to 19.99 dB	± .035 dB
20 to 39.99 dB	± .06 dB
40 to 79.99 dB	± .1 dB

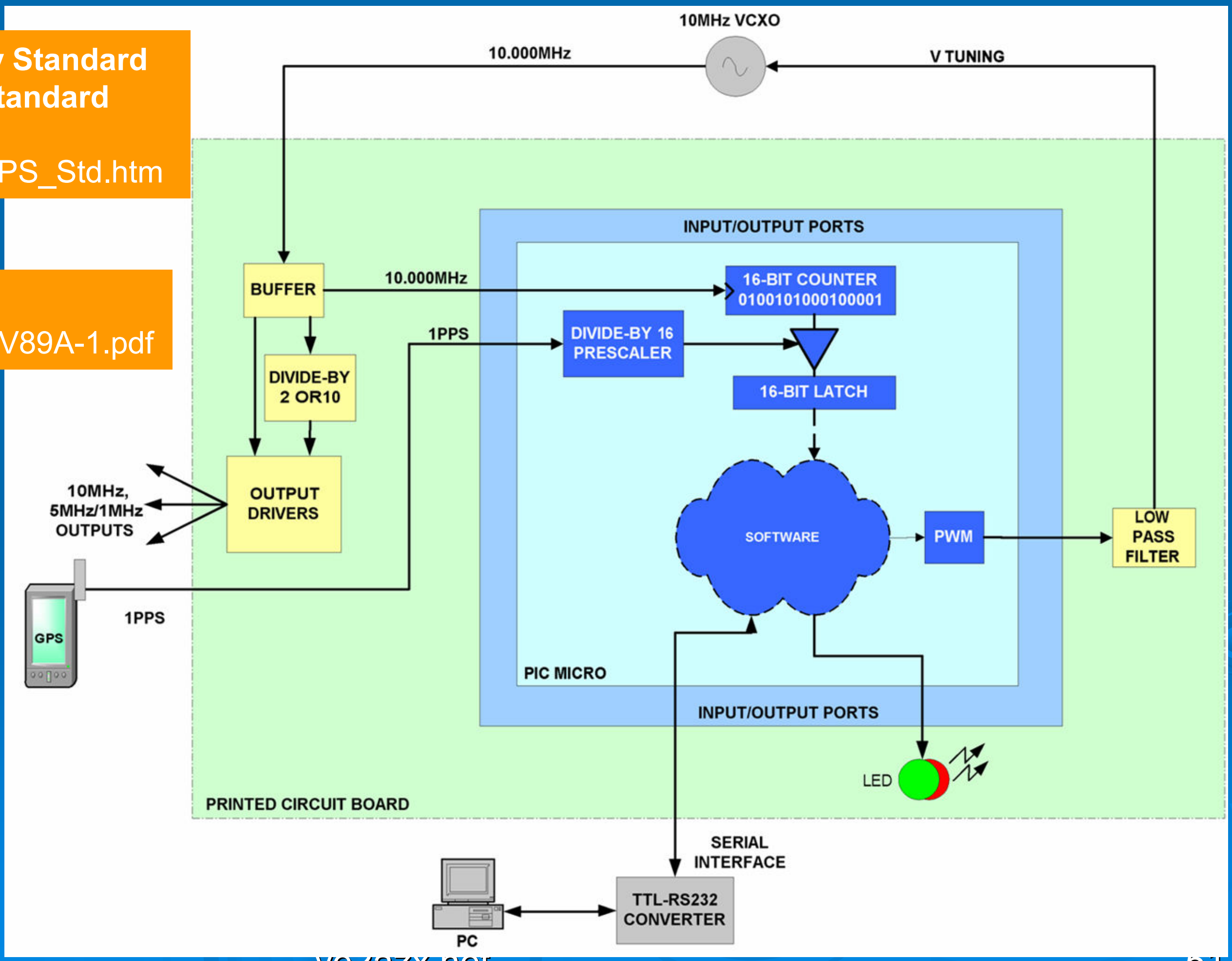
Reference level generator (HP 3336B with HI acc. atten opt. 005)

Frequency Standard:

- GPS frequency standard is self calibrating. It does NOT require periodic calibration.
- Accuracy 10e-9 to 10e-12
- Multi output buffer for distribution to signal generators, spectrum analyzer, VNA etc.

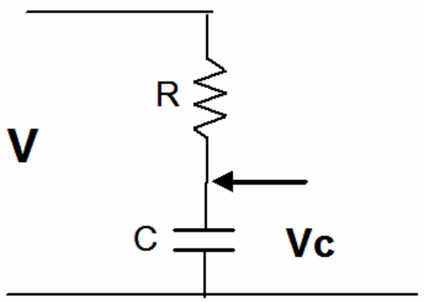
Example of GPS Frequency Standard from VE2ZAZ Frequency standard Documentation. Ref: http://ve2zaz.net/GPS_Std/GPS_Std.htm

See also: http://ve2azx.net/technical/MV89A-1.pdf



Measurement of Capacitance

- Create your own standard reference capacitors for checking capacitance meters
- Voltage ratio and series resistor allows measuring the capacitance value.
- Need <u>stable</u> cap's with Q > 100



$$K = \frac{Vc}{V}$$

Measured attenuation ratio, normally a scalar value

$$C = \frac{\sqrt{1 - K^2}}{2 \cdot \pi \cdot F \cdot K \cdot R}$$

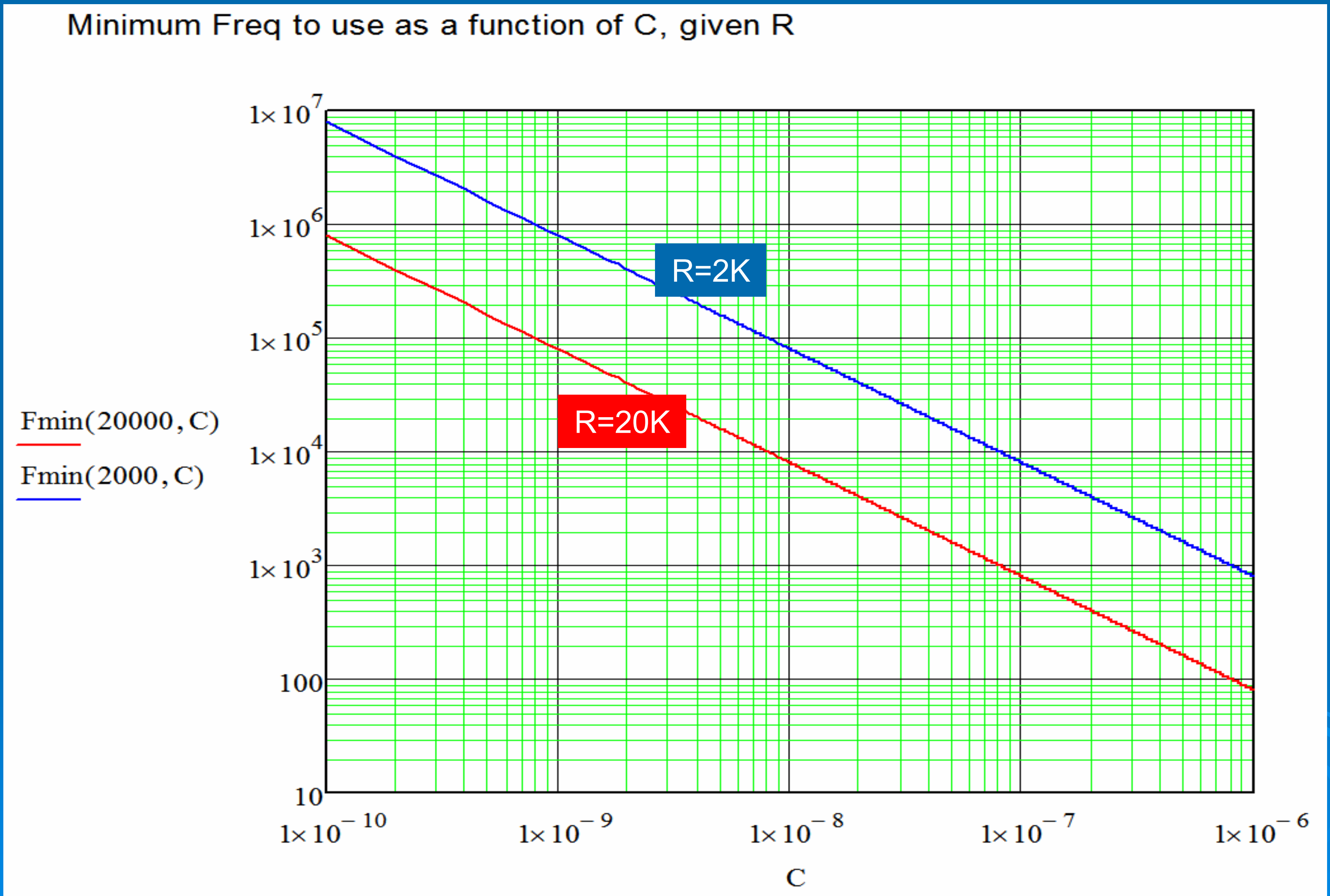
Allows finding C if Q > 100
See below

Substract the multimeter input capacitance.
A FET probe may be used

For 0.1 % error the ratio R to Xc must be >= 10 and the Q of the cap >= 100

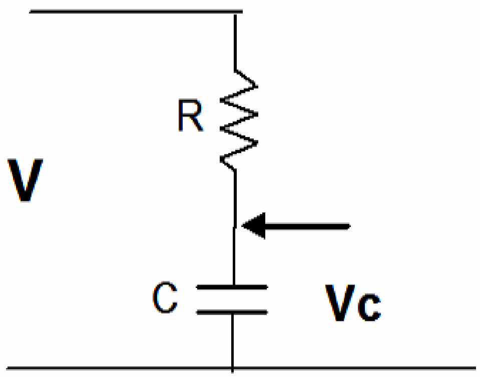
$$Fmin := \frac{10}{2 \cdot \pi \cdot R \cdot C}$$

Minimum Frequency to be used for R=2K and R=20K



Excel spreadsheet to calculate the capacitor value

Capacitance Measurement Aug. 2017 J. Audet ve2azx.net



$$K = \frac{Vc}{V}$$

Measured attenuation ratio, normally a scalar value

Q factor of capacitor > 100

A FET probe may be used when C is less than 1000 pF

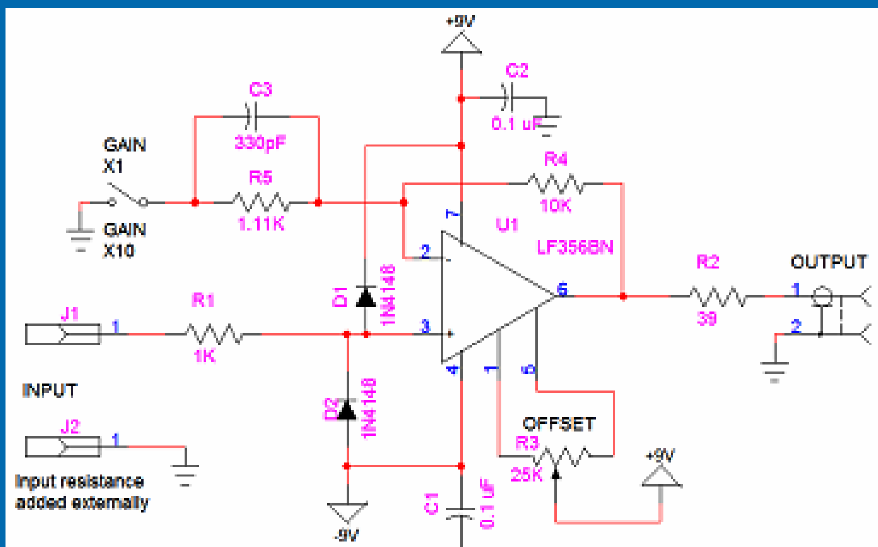
Enter data in the green cells

Measured Voltages V	Vc	Test Freq. KHz	Approx C (nF)	R ohms	C probe (pf)
1228.4	65.066	1	150	20022	49.5

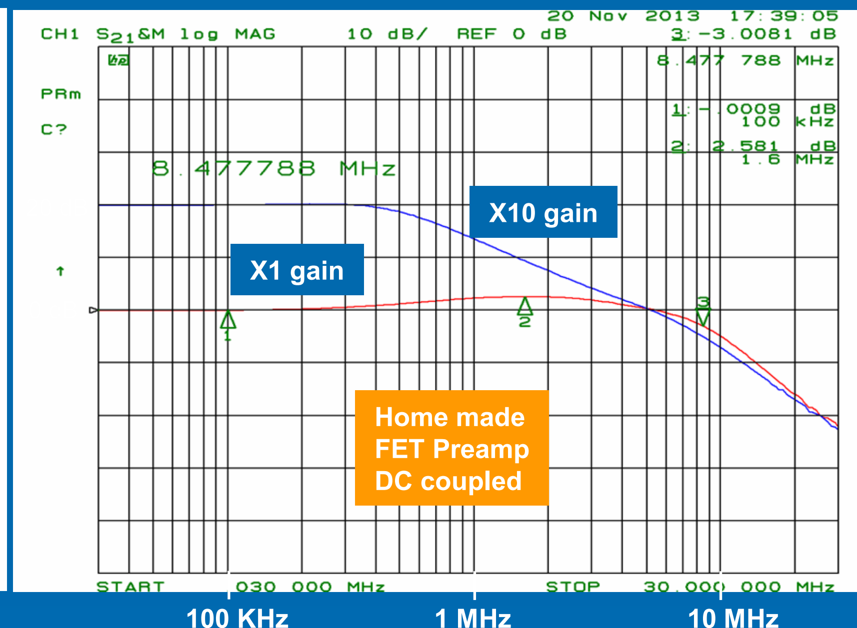
Calculated Values

Minimum Freq (KHz)	0.530
Capacitance (nF)	149.81

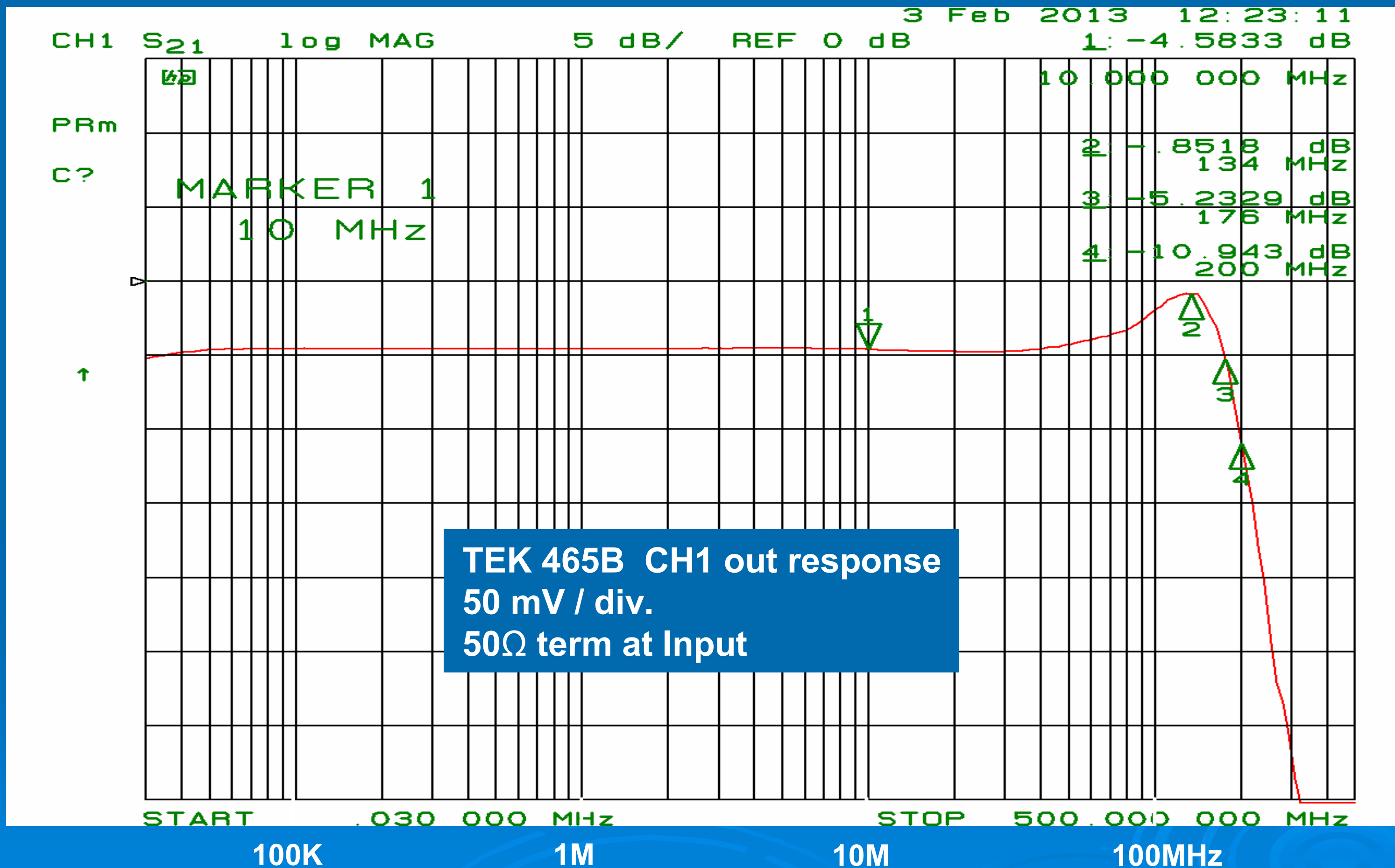
My X1 – X10 FET Input Utility Preamplifier (DC Coupled)



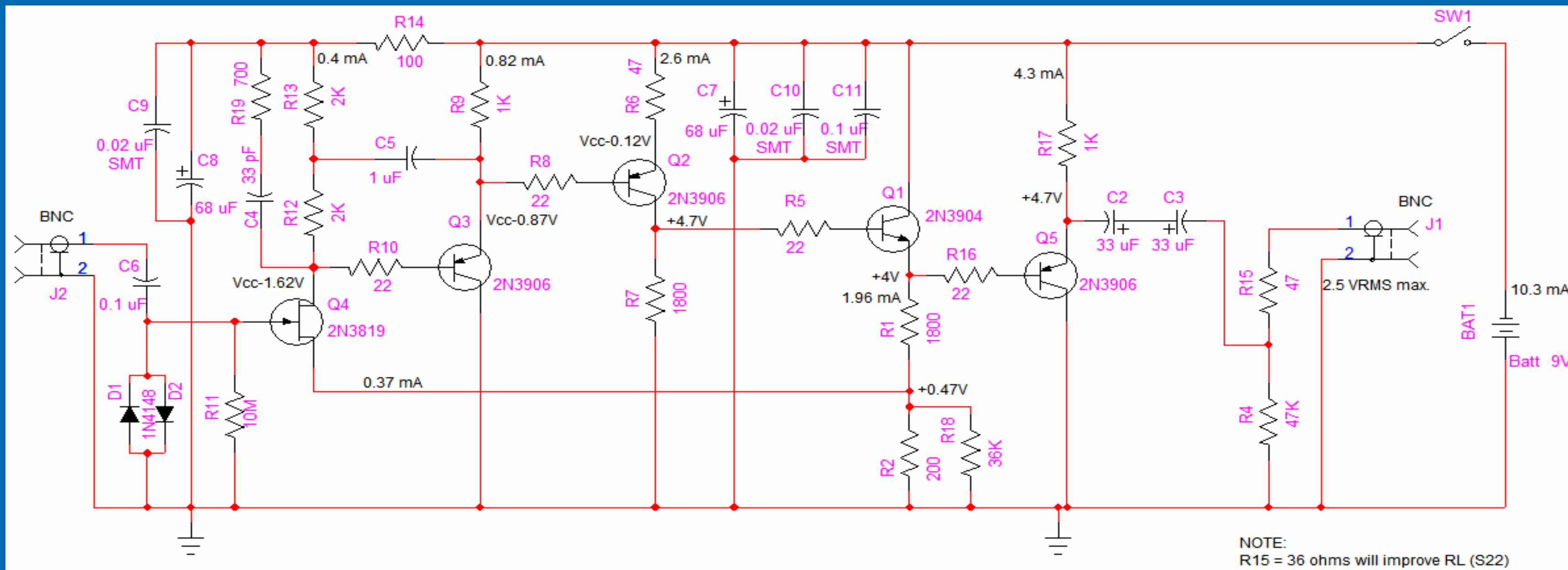
R1, D1, D2 added for protection



An Amplifier for free…If you have a TEK 465B



Low Noise 30 MHz X10 Amplifier



Wideband Amplifier
DC > 200 MHz

Conclusion

- Using a **reference multimeter** as a calibrator for less accurate instruments and verify its calibration with your own standards.

- Hi performance 6.5 digit multimeters are available on the surplus market

- Accurate DC voltage references are available at reasonable cost. Using dividers will allow you to cover a wide range of voltages.

- Use ratio mode on your DMM for best accuracy.

- AC voltage references may consist of a precision rectifier for low frequencies or a 0 dBm power reference at RF frequencies.

- Precise low resistance shunts are useful for measuring high currents. Available as surplus.

- Reference level generators (like HP3335, 3336) are useful for frequency response measurements and precise level generation.

- It's a good idea to check the AC voltmeter linearity, at the frequencies it's used.

- Don't neglect your computer sound card. It allows making precise ratio measurements.