A Simple USB RF Power Meter

W.J. Riley
Hamilton Technical Services
Beaufort, SC 29907 USA

● **Introduction**

This paper describes a simple USB-powered RF power meter that covers a 500 kHz to 500 MHz frequency range, a -70 dBm to +13 dBm power range, and interfaces with a custom PC application via a USB connection that powers it. The device is packaged in a small Pomona 3230 box as shown in Figure 1. The PC application provides single or continuous readings of dBm, µW, mW, µV, mV or V rms into 50 Ω with adjustable averaging that can be manually read, copied to the Windows clipboard or recorded to a disk file. The program also supports device calibration at up to 24 selectable frequencies.

Figure 1. The USB RF Power Meter

● **Background**

The Analog Devices AD8307 [1] is an attractive device as the basis of a simple RF power meter, and several previous designs have been reported [2-8]. This paper describes a similar unit which emphasizes simplicity, software compensation, and maximum utilization of both PC software and its USB interfacing to substitute for instrument hardware.

● **RF Power Measurements**

A good introduction to RF power measurements will be found in References [9] and [10]. The three classic methods for measuring RF power use diode detectors, thermistors and thermocouples, using the square-law characteristic of a semiconductor diode for the former and RF heating for the latter two. This device uses another method, a cascade of six RF logarithmic amplifier stages that use progressive compression and a summation of full-wave detectors to produce a log-linear response [11-14]. That technique implements a monolithic RF level detector having a wide dynamic range and which, if calibrated, can give reasonably-accurate results.

● **Power Meter Description**

The RF power meter comprises an AD8307 logarithmic RF power detector, a PIC16F688 microcontroller [15] and a FT232 USB converter [16]. The AD8307 provides a log-linear DC output voltage proportional to the RF power in decibels that is digitized by a PIC 10-bit ADC channel whose readings are accessed via the USB port. The microcontroller also provides a command interface and a means for storing calibration data in its EEPROM. The system is powered by the USB 5 VDC line, while a 3.3 VDC regulator in the FT232 device supplies the ADC reference voltage. A block diagram of the unit is shown in Figure 2.
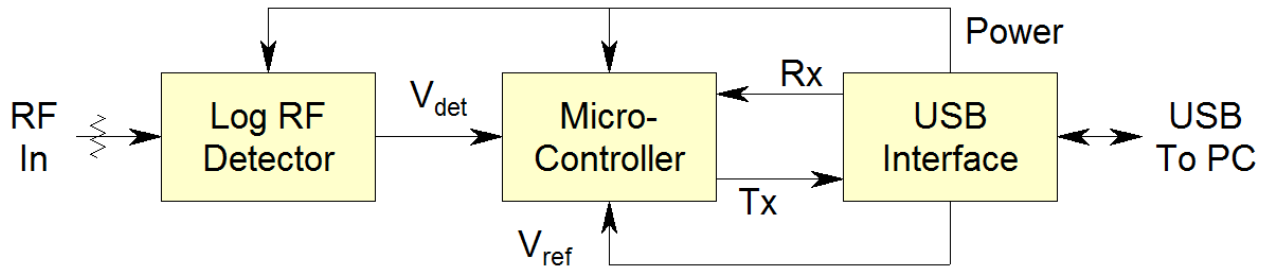
Figure 2. RF Power Meter Block Diagram

● **Power Meter Circuit**

Schematics of the RF power meter detector and interface circuits are shown in Figures 3 and 4. It is a very straightforward application of the three devices used, with no adjustments or frequency compensation since those aspects of the unit's accuracy are handled by calibration. The detector input termination includes a series inductor to provide return loss compensation. The AD8307 is quite insensitive to supply voltage and temperature variations, and the FT232 3.3V regulator provides a stable ADC reference at a voltage consistent with good ADC resolution.

The four 1/8 Watt 0805 SMT resistors can handle a maximum power of +27 dBm, but is it reasonable to impose an input power limit of +20 dBm since useful measurements cannot be made at that level. The input is DC-coupled to these resistors, so no significant DC component should be applied (5V maximum).
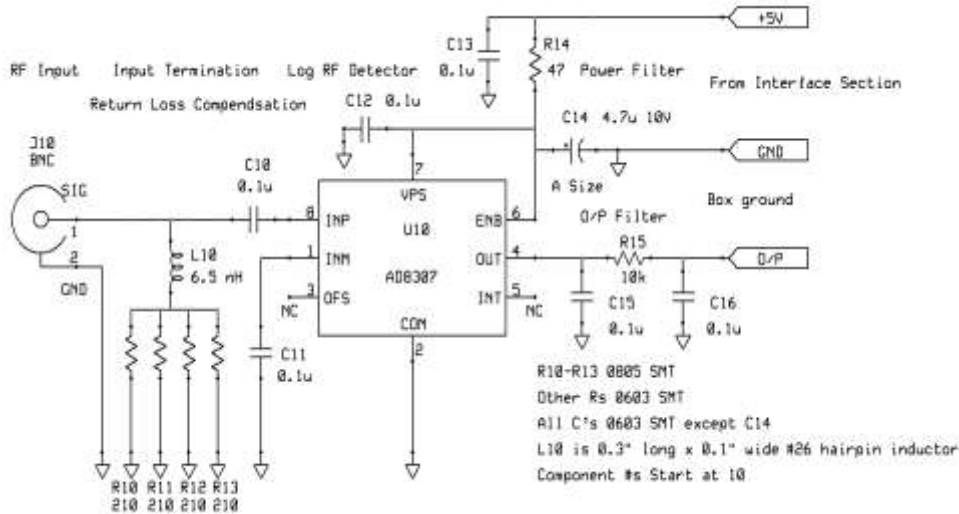

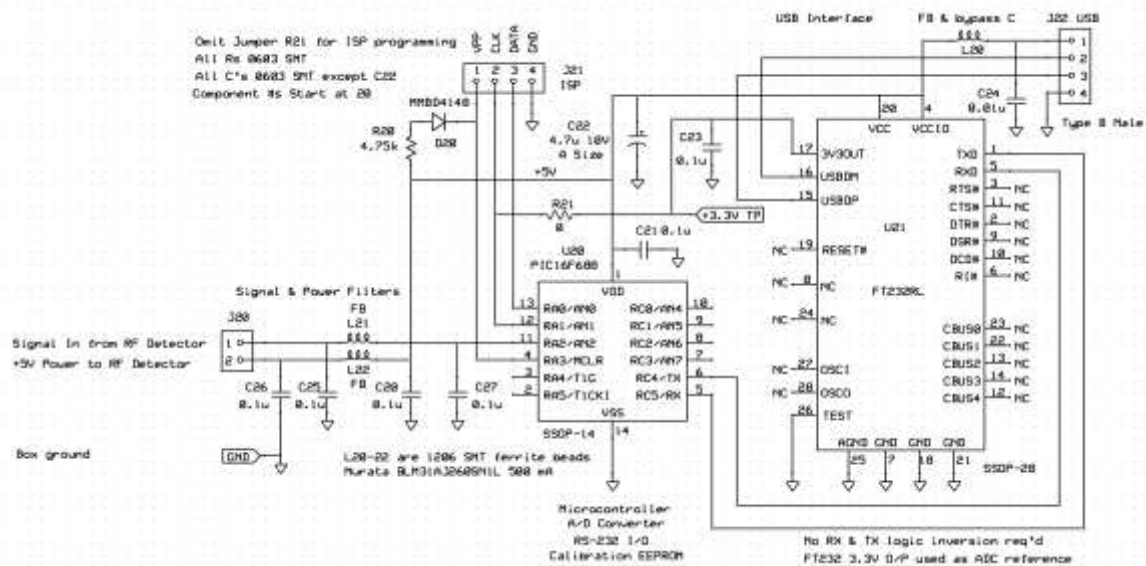
Figure 3. Detector Section Schematic

Figure 4. Interface Section Schematic

● **Board Layout**

The circuit board layout of the USB RF power meter is shown in Figures 5 and 6. It uses the smallest-available surface mount components for the ICs, and fits into a small Pomana box with a soldered connection to the RF input BNC connector at one end and a board-mounted Type-B USB female connector at the other end. Four 0805 resistors are used as the input termination for power handling, while the ground plane is removed under them to reduce shunt capacitance. Terminals are provided for in-circuit programming of the PIC microcontroller, and there is a test point for measuring the ADC reference voltage.
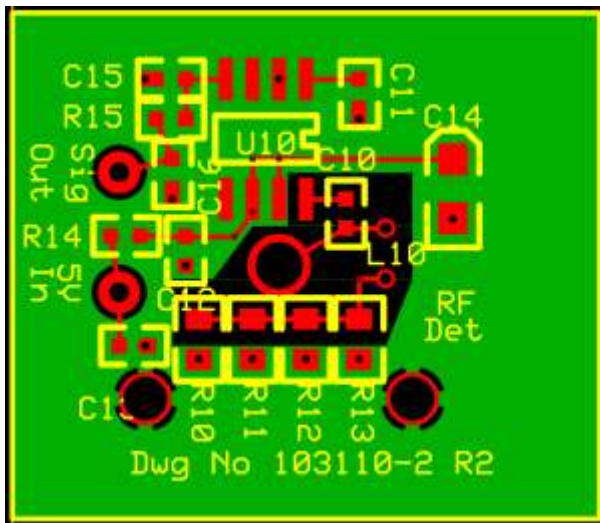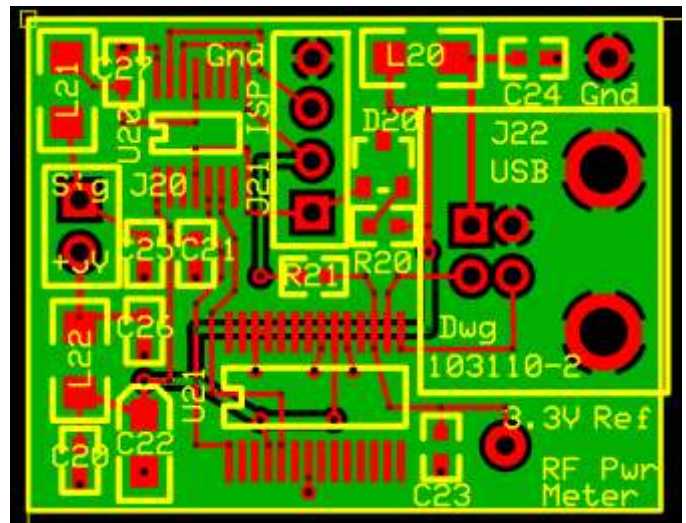

Figure 5. Detector Section PWB Layout

Figure 6. Interface Section PWB Layout

● **Power Meter Construction**

The main consideration is constructing the power meter is to use good RF practices at the input so that the unit presents a broadband 50 Ω input impedance. It is also important that the RF detector be well-shielded to avoid stray pickup.

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A breadboard USB RF power meter was constructed by using a PICPROTO 4 [17] prototyping board and a FT232R RS-232 to USB board [18], as shown in Figures 7 and 8.

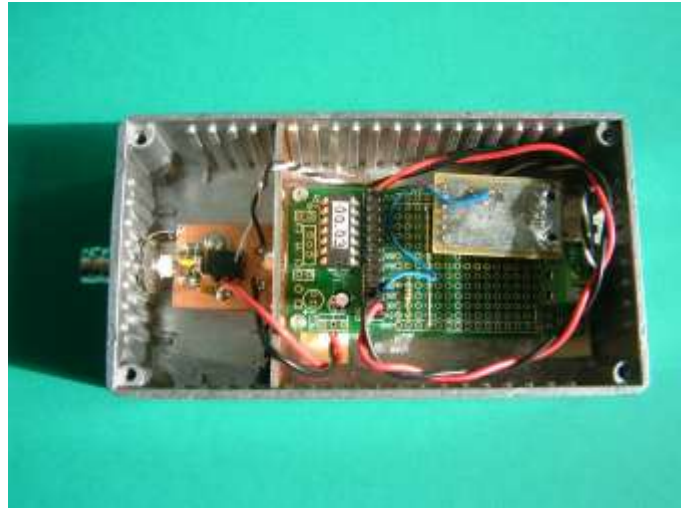Figure 7. RF Power Meter Breadboard - Closed

Figure 8. RF Power Meter Breadboard - Open

The final design uses a 2.25" x 1.38" x1.13" Size B Pomona 3230 box [19] with two flange mounting BNC receptacles as a suitable (albeit quite expensive) housing for the USB RF power meter, as shown in Figure 9. One BNC connector is used for the RF input, while the other BNC connector is replaced with a Type B female USB connector. The original hole is simply filed square to accommodate the plug on the USB cable, and the USB connector is attached completely inside the box with its pins upward by two 4-40 mounting screws. The paint is scratched away inside of the box where the body of the USB connector contacts the box to assure good grounding. The four original BNC flange mounting holes can be left empty or filled with short 4-40 machine screws.

Figure 9. Pomona 3230 Box with Connectors

A photograph of the assembled USB RF power meter is shown in Figure 10. The detector section is mounted vertically directly behind and facing the input BNC connector and the interface section is mounted upside-down at opposite end of the box, supported by the USB connector. The two sections are connected by three short wires (+5V, signal and ground). The power and signal leads are filtered by ferrite beads and bypass capacitors on the interface board, and there is no evidence of stray RF pickup. Use of a USB cable with a ferrite bead is recommended to avoid spurious components from the computer.

Figure 10. Assembled USB RF Power Meter

● **Calibration**

Calibration using an RF source with an accurately-known power output at the frequencies of interest is required to make absolute measurements with the USB RF power meter. Two accurate power levels, e.g., 0 dBm and -10 dBm, are needed at each frequency to determine the slope and intercept of the detector log-linear response. An HP 8640B RF signal generator and an HP 436A RF power meter with an HP 8482A power sensor are ideal for that purpose, and are used for the testing described here. They cover the desired 500 kHz to 500 MHz frequency range, the sensor can measure from +20 dBm to -30 dBm, and the power meter has an internal 50 MHz, 0 dBm calibration source. The HP 8640B or another equivalent calibrated signal generator alone is quite sufficient, while the HP 436A or another equivalent 50 MHz power reference is excellent at that single frequency. Access to those widely-available instruments is needed only for a short time while performing the calibration. The W1GHZ 50 MHz RF power standard [20] is low-cost alternative to the HP 436A, but has a rather low -10 dBm nominal output, and the one unit tried here had a power output that was high by about 1.5 dB. Another alternative is an uncalibrated source along with a calibrated RF spectrum analyzer. An accurate fixed attenuator between 10 to 20 dB is useful accessory, especially for a reference source having a fixed output. Higher powers are best handled with an external attenuator, which can be corrected for by applying an offset in the user interface.

The general calibration procedure is to:

1. Calibrate the HP 436A RF power meter and HP 8482A sensor using the internal 50 MHz 0 dBm calibration source.
2. Set the HP 8640B signal generator to the desired frequency.
3. Adjust the HP 8640B output to 0 dBm as indicated on the HP 436A power meter.
4. Use the HP 8640B 10 dB step attenuator to set the input to the USB RF power meter under test. Power settings of 0 dBm and -10 dBm are generally used for linear calibration and 0, -20 and -40 dBm for quadratic calibration.
5. Use the calibration screen of the USB RF power meter application to measure its response at the desired frequency and two input levels, and apply those measurements, thus storing them in the unit's EEPROM memory. The measurements should be averaged by at least a factor of 100, and a factor of 500 is recommended.
6. Repeat the calibration at all frequencies of interest. The standard frequencies are 0.5, 1, 2, 5, 10, 20, 30, 40 50, 75, 100, 125, 150, 175, 200, 250, 300, 350, 400, 450 and 500 MHz. Use the closest value if

they cannot be set exactly. The resulting calibration slopes in mV/dB and intercepts in dBm can be examined in the linear listing screen.

A full linear calibration can be done in about 15 minutes, and quadratic calibration takes only slightly longer. If the calibration is done at only one frequency (e.g., 50 MHz) then consideration could be given to compensating the detector response as has been described by others []. When testing the low power response with an HP 8640B signal generator, it was found better to use BNC attenuators directly at the USB RF power meter input because of a 140 kHz -60 dBm spurious component from the generator. Examples of linear and quadratic calibrations listings are shown in Figures 11 and 12 respectively.

USB RF Power Meter Calibration Listing

Index	MHz	MJD	Slope, mV/dB	Intercept, dBm
0	Uncal	55534	25.00	-84.00
1	0.5	55570	25.53	-86.40
2	1.0	55570	25.42	-86.73
3	2.0	55570	25.46	-86.59
4	5.0	55570	25.55	-86.29
5	10.0	55570	25.46	-86.49
6	20.0	55570	25.32	-86.84
7	30.0	55570	25.27	-86.90
8	40.0	55570	25.56	-85.81
9	50.0	55570	25.76	-85.01
10	75.0	55570	25.79	-84.59
11	100.0	55570	25.70	-84.62
12	125.0	55570	25.93	-83.61
13	150.0	55570	26.04	-82.83
14	175.0	55570	25.85	-83.17
15	200.0	55570	25.41	-84.37
16	250.0	55570	25.94	-81.97
17	300.0	55570	26.37	-79.82
18	350.0	55570	25.51	-81.76
19	400.0	55570	25.32	-81.30
20	450.0	55570	24.98	-81.74
21	500.0	55570	24.83	-81.04
22	Aux 1			
23	Aux 2			
24	Aux 3			

Close

Figure 11. Linear Calibration Listing

USB RF Power Meter Calibration Listing

Index	MHz	MJD	A, dB/V²	1/B, mV/dB	C, dBm
0	Uncal	55534		25.00	-84.00
1	0.5	55570	0.23	26.21	-85.28
2	1.0	55570	0.40	26.62	-84.78
3	2.0	55570	0.31	26.37	-85.09
4	5.0	55570	0.16	26.02	-85.51
5	10.0	55570	0.29	26.30	-85.11
6	20.0	55570	0.39	26.45	-84.98
7	30.0	55570	0.38	26.37	-85.09
8	40.0	55570	0.02	25.63	-85.69
9	50.0	55570	-0.27	24.99	-86.32
10	75.0	55570	-0.35	24.80	-86.28
11	100.0	55570	-0.35	24.74	-86.26
12	125.0	55570	-0.77	23.86	-87.23
13	150.0	55570	-1.03	23.35	-87.61
14	175.0	55570	-0.60	24.22	-85.96
15	200.0	55570	0.02	25.46	-84.29
16	250.0	55570	-0.24	25.27	-83.05
17	300.0	55570	-0.77	24.29	-83.24
18	350.0	55570	0.19	26.02	-80.95
19	400.0	55570	0.80	27.61	-77.93
20	450.0	55570	1.49	29.45	-75.54
21	500.0	55570	1.97	30.92	-73.05
22	Aux 1				
23	Aux 2				
24	Aux 3				

Close

Figure 12. Quadratic Calibration Listing

● Example of Quadratic Calibration

The main advantage of a quadratic calibration fit is better conformance at low power, and it should therefore be performed at three relatively low power levels, say 0, -30 and -60 dBm. An example of such a calibration at 50 MHz is shown in Figure 13. The departure from linearity is small, and the curvature of the fit correctly models the reduced slope at lower powers, but does so over the entire span rather than mainly at the low power end. Nevertheless, the resulting reading errors were all below 0.5 dB from +10 to -60 dBm, and below 1 dB from +13 to -70 dBm.
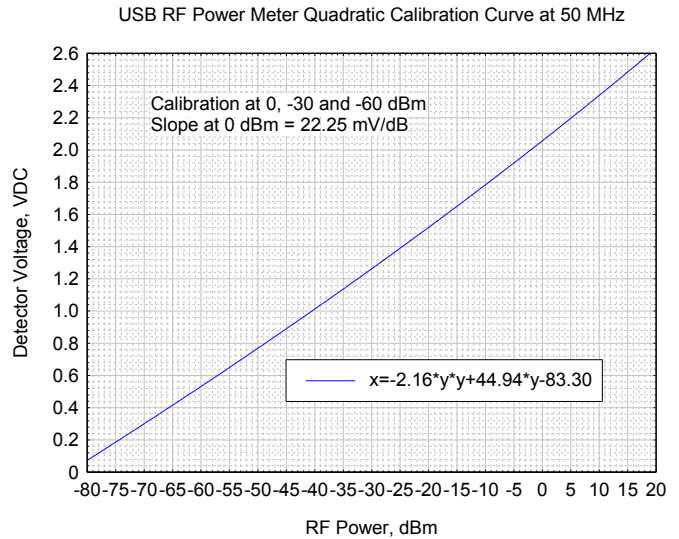
USB RF Power Meter Quadratic Calibration Curve at 50 MHz

Calibration at 0, -30 and -60 dBm
Slope at 0 dBm = 22.25 mV/dB

x=-2.16*y*y+44.94*y-83.30

Figure 13. Quadratic Calibration Curve

● Errors

Most of the RFS power meter errors are associated with either the RF detector or its input termination. The basic characteristics of the logarithmic RF detector are shown in Figures 14 and 15 from the AD8307 data sheet [1]. The data sheet claims less than ±1 dB error to 100 MHz over an 88 dB range, degrading only slightly to 500 MHz. It shows a ±1 dB error for ±5% change of the 5V supply voltage, and negligible TC down to -60 dBm input.
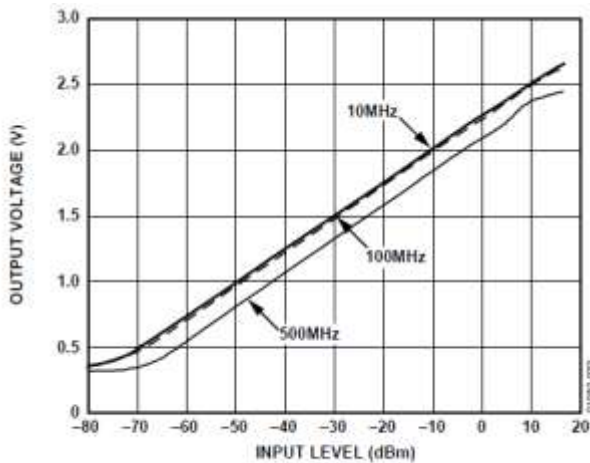
Figure 33. Log Response at 10 MHz, 100 MHz, and 500 MHz
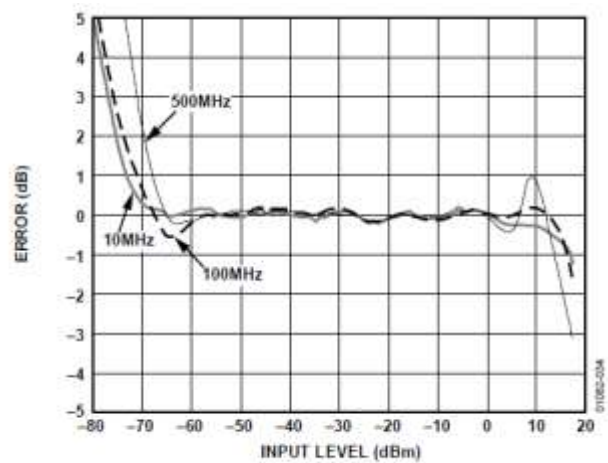
Figure 14. Log Response Plot

Figure 34. Logarithmic Law Conformance at 10 MHz, 100 MHz, and 500 MHz

Figure 15. Log Compliance Plot

The actual AD8307 voltage readings are displayed during calibration measurements, and these are quite accurate in the exact ADC reference voltage is measured and manually entered into the unit.

The AD8307 response is quite linear versus applied RF power over most of its range, and a single set of slope and intercept values seems adequate to characterize the device at a given frequency. The loss of response at the low end can be compensated for with a quadratic fit, while the compression at high power is best handled by using an input attenuator.

Assuming an accurate calibration source, the most significant error for the USB RF power meter reading is nonconformity with the log-linear response characteristic, which varies with both the applied power level and frequency, and is worst at high power. Thus the judicious use of an accurate fixed attenuator is recommended above +10 dBm. Input impedance mismatch is probably the next most significant error, but it mitigated somewhat by the calibration process. An attenuator also improves the input return loss, and the calibration can be performed that way for measuring relatively high power, perhaps using one of the auxiliary calibration sets. In general, calibration should be performed near the expected power and frequency, and sufficient averaging should be used during both calibration and measurement. In that case, the absolute power reading error should not exceed ±1 dB, and relative readings should be even better. My evaluations have shown errors well below that near the calibration frequency and power level, limited mainly by the calibration instrumentation itself.

● **Input Return Loss**

The input return loss (S_{11}) [21] of the breadboard USB RF power meter from 1 to 500 MHz is shown in Figure 16. It varies from 37 dB at 1 MHz to only about 12 dB at 500 MHz. The final design with an SOIC AD8307 package and lower input shunt capacitance was better, particularly when inductive compensation was used (see below). Examination of the equivalent parallel input resistance and capacitance indicates that the most important stray reactance is the capacitance in parallel with the termination resistors, which was reducible by removal of ground plane under the resistors. The effect of the an imperfect power meter input match is, to some extent, corrected for by the calibration process, but it nevertheless makes the power meter reading dependent on the input cable length at high frequencies.
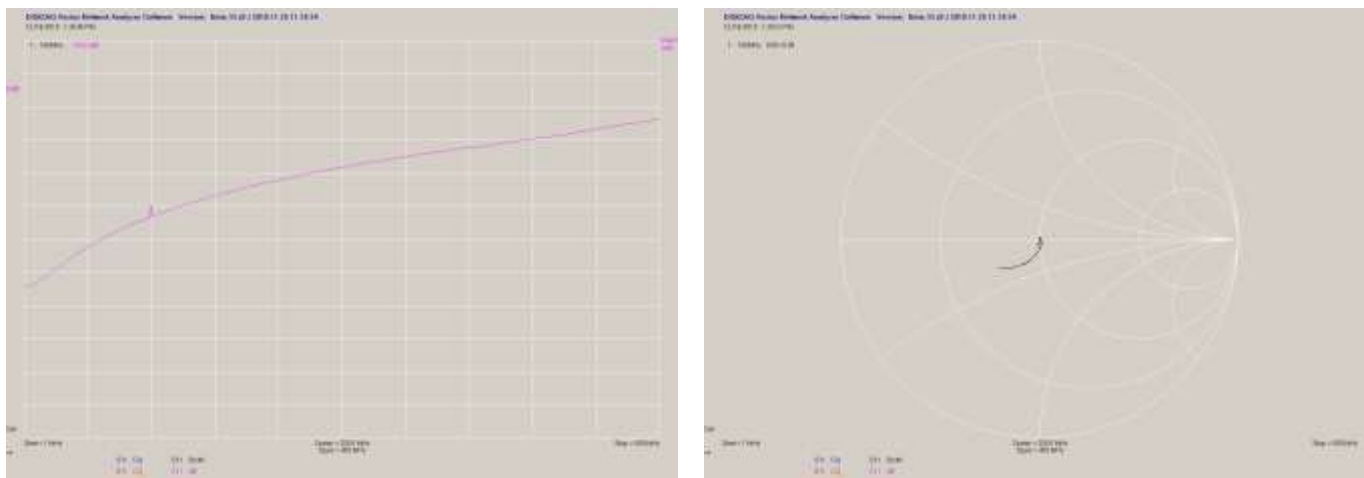

Figure 16. Input Reflection Coefficient (S_{11})

A Qucs [22] simulation of the input impedance of the USB RF power meter is shown in Figure 17. The input is terminated by four 210 ohm resistors in parallel with a small inductance in series with them and a small shunt capacitance between the input and ground. The AD8307 detector is modeled by the parallel combination of a 1.1 kΩ resistor and a 1.4 pF capacitor as shown on its data sheet. The most critical factor is the additional shunt capacitance (C1) which is minimized by eliminating the ground plane under R1-R4 and is estimated as 0.8 pF (subsequently measured as 0.7 pF). Inductance L1 is not only physically exists but also serves as a compensating circuit element, and the 6.5 nH value (larger than the layout causes) provides the best return loss (about 24 dB minimum) for the values shown. Fortunately, it is easy to add a small amount of inductance in series with the terminating resistors.
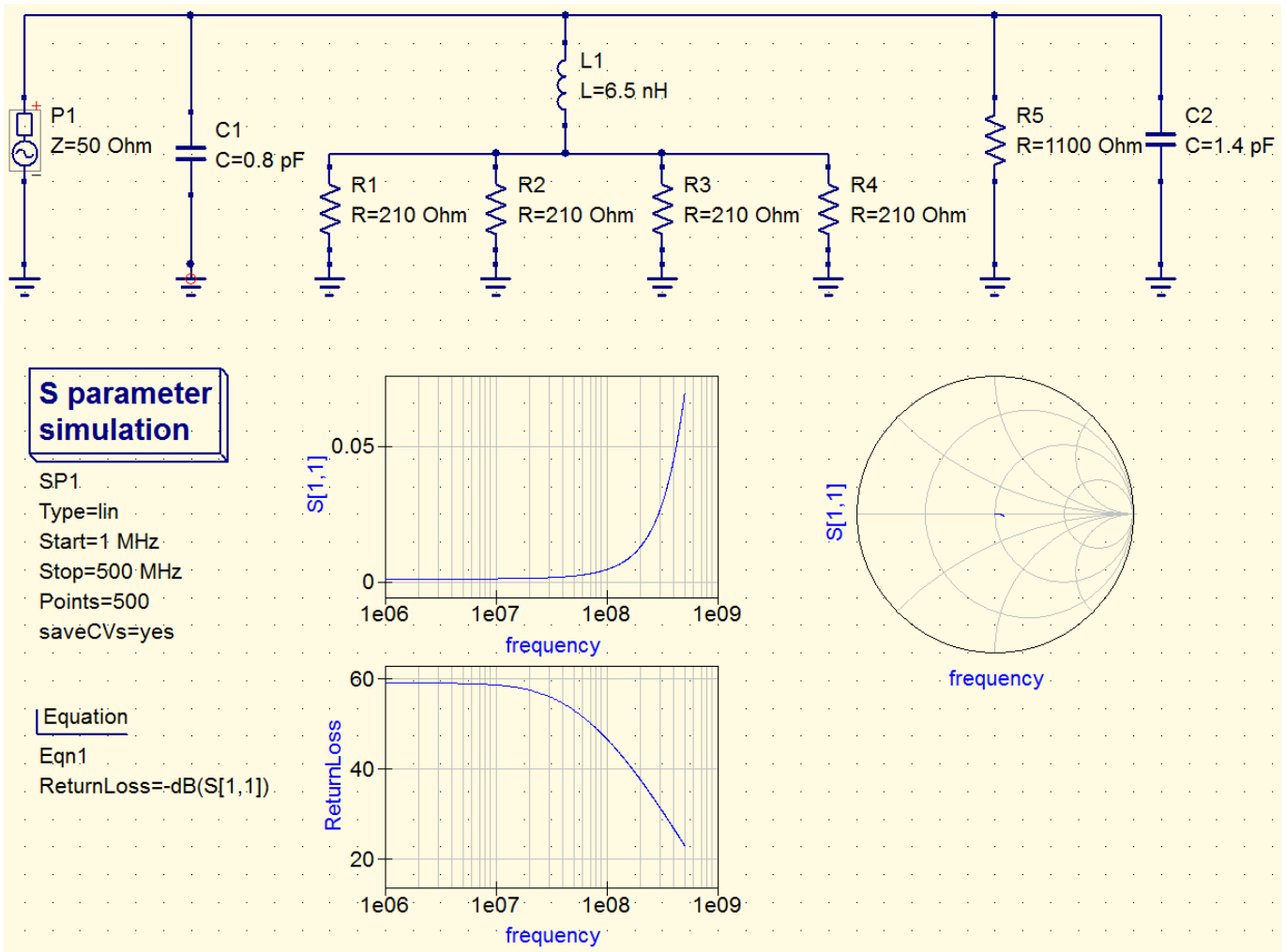
Figure 17. Qucs Simulation of Input Impedance

For this device, an input reflection coefficient (S_{11}) not exceeding 0.1, corresponding to a return loss of 20 dB and a mismatch loss of 0.04 dB is a reasonable requirement.

The first production version of the USB detector section was assembled outside the Pomona box to a BNC flange connector with the components facing away from the connector as shown in Figure 18. Applying inductive compensation to this circuit resulted in the expected return loss improvement. Adding a 0.3" x 0.1" AWG #26 bent hairpin inductor between C10 and R13 gave an excellent 32 dB minimum return loss at 500 MHz as shown for S/N 001 in Figure 19. The actual USB RF power meter is assembled with the components facing the connector and the board ground plane serving as a shield. Ferrite beads were placed on the detector power and output leads as seen in the photograph.
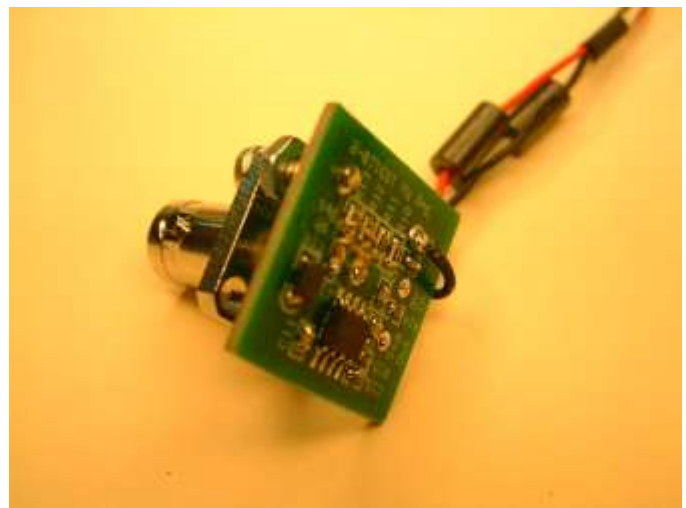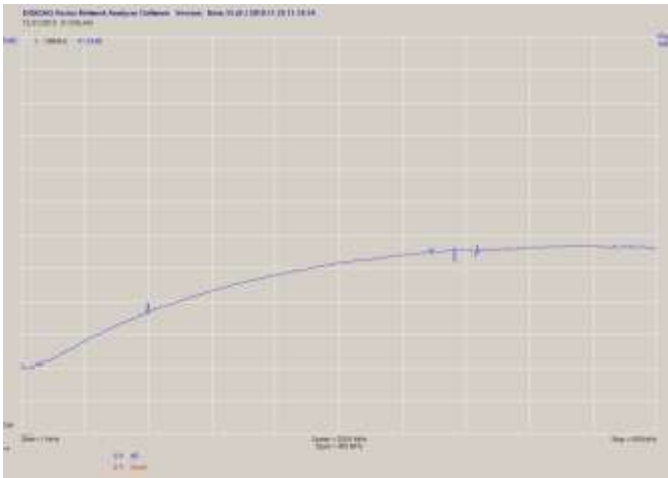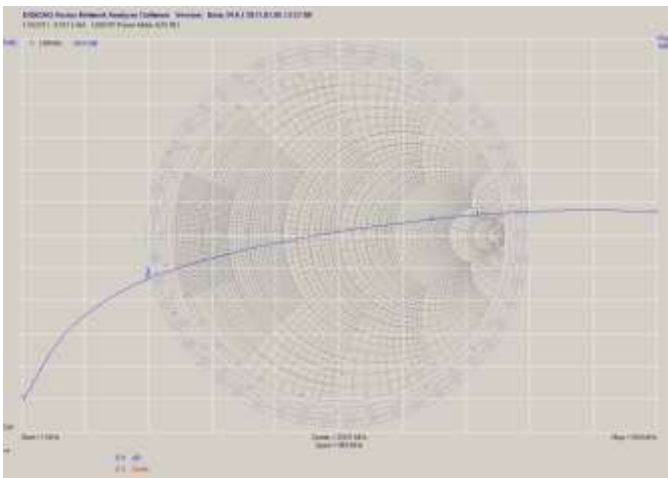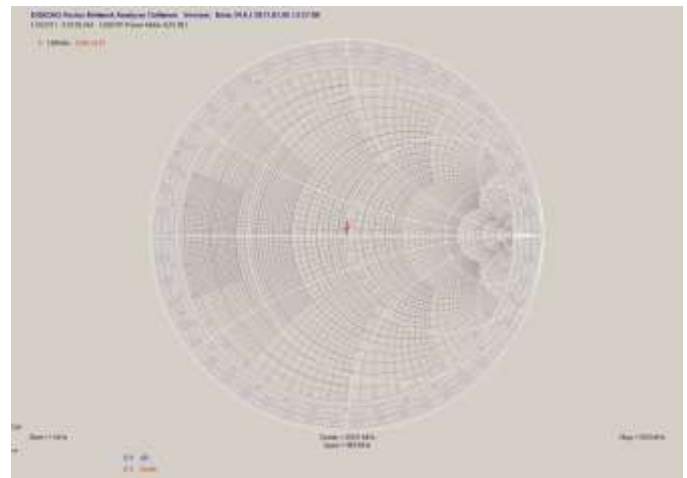

Figure 18. Detector Section Test Configuration

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S/N 001 Return Loss

S/N 001 S_{11}

S/N 003 Return Loss

S/N 003 S_{11}

Figure 19. Compensated Return Loss

The first unit of the final design (S/N 003) also had good return loss (≥ 27 dB). That design uses SMD ferrite beads and bypass capacitors on the interface board, simplifying the wiring while also providing good suppression of stray RF pickup.

● **Communications Interface**

The USB RF power meter is generally interfaced as a virtual PC COM port using a driver for the FTDI FT232 device. Its firmware is set up for the default RS-232 serial communications parameters of 9600 baud, 8 data bits, 1 stop bit, no parity and no flow control. Under Windows 7, one may use Start/Devices & Printers to look for a device called USB RF Power Meter, and Start/Control Panel/System/Device Manager/Ports will show the USB Serial Port COM number, which may be changed using Port Settings/Advanced/COM Port Number.

● Commands

The USB RF power meter firmware implements a set of 19 commands that can be used to directly communicant with the unit via a terminal program such as TeraTerm [23]. These commands are shown in the following table.

```
/*************************************************************************/
/*                                                                       */
/*    USB RF Power Meter Commands (upper or lower case)                  */
/*                                                                       */
/*    Code   Type    Description     # Hex Chars     Format & Remarks    */
/*     A     Output  Get ADC reading    4  10-bits: 0-1023 dec = 000-3FF hex */
/*     E     Input   Store cal slope    4  XX.XX mV/dB DP implied in middle  */
/*     F     Input   Store ADC ref volt 4  Not in UI                     */
/*     I     Input   Enter cal index    2  0-20 dec = 00-14 hex          */
/*     C     Output  Confirm index      2  See I                         */
/*     J     Output  Get cal MJD        4  Offset by 50000               */
/*     M     Input   Store cal MJD      4  see J                         */
/*     N     Output  Get unit S/N       4  0001-9999 dec = 0001-270F hex */
/*     O     Output  Get cal slope      4  see E                         */
/*     P     Output  Get cal intercept  4  XX.XX dB neg DP implied in middle */
/*     Q     Output  Get quadratic cal  4  XXXX dBm/V² x1000 (signed)    */
/*     R     Output  Get ADC ref volt   4  XXXX mV                       */
/*     S     Input   Store unit S/N     4  Not in UI                     */
/*     T     Input   Store cal intercept 4 See P                         */
/*     U     Input   Store quadratic cal 4 See Q                         */
/*     V     Output  Get firmware rev   4  XX.XX DP implied in middle    */
/*     W     Input   Store firmware rev 4  see V                         */
/*     X     Input   Reset PIC          -  Not in UI                     */
/*     ?     Output  Show commands      -  Not in UI                     */
/*                                                                       */
/*    Notes:                                                             */
/*    1. PIC reset sends "USB RF Power Meter" message                    */
/*    2. Nominal slope 25 mV/dB = 2500 dec = 09C4 hex                    */
/*    3. Nominal intercept -84 dBm = 8400 dec = 20D0 hex                 */
/*    4. Nominal ADC ref volt = 3300 mV = 0CE4 hex                       */
/*    5. Unprogrammed EEPROM = FFFF = MJD code for blank entry           */
/*    6. FFFF quadratic coeff = code for linear fit                      */
/*    7. Quadratic fit 1/B coeff in mV/dB stored as slope               */
/*    8. Quadratic fit C coeff in dBm stored as intercept               */
/*    9. Quadratic coefficient A in dB/mV² x1e9 for EEPROM              */
/*                                                                       */
/*************************************************************************/
```

● Windows Software

The main screen, shown in Figure 20, controls and displays the USB RF power meter measurements. Absolute readings in dBm, μW, mW, μV, mV or V or a relative reading in dB can be made upon command or continuously with a settable averaging factor and with an optional offset for external attenuation or another purpose. Those readings can be written to a data file with a selectable format at an adjustable rate. There are command buttons for single or continuous readings, to copy the results to the Windows clipboard, to open the calibration and settings screens, to obtain help, or to close the program.

The linear calibration screen, shown in Figure 21, supports calibration of the unit at a selected frequency, using measurements at two power levels to determine a linear fit to its log-linear response. The resulting ADC voltage readings and calibration parameters are shown. There are command buttons to apply the calibration results, to open the listing and settings screens, to obtain help, or to close the calibration screen.

The quadratic calibration screen is similar except for its third calibration point, as shown in Figure 22. The three quadratic coefficients are shown, as well as the equivalent linear coefficients at 0 dBm.
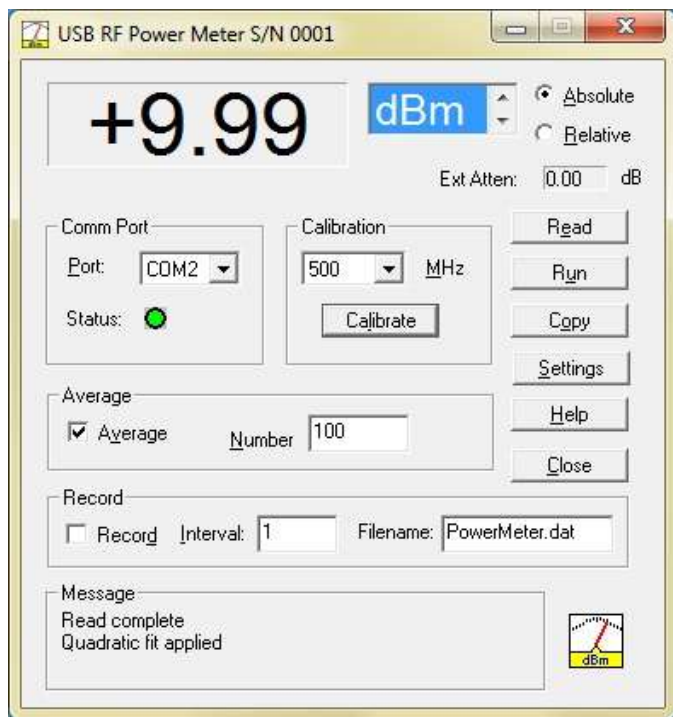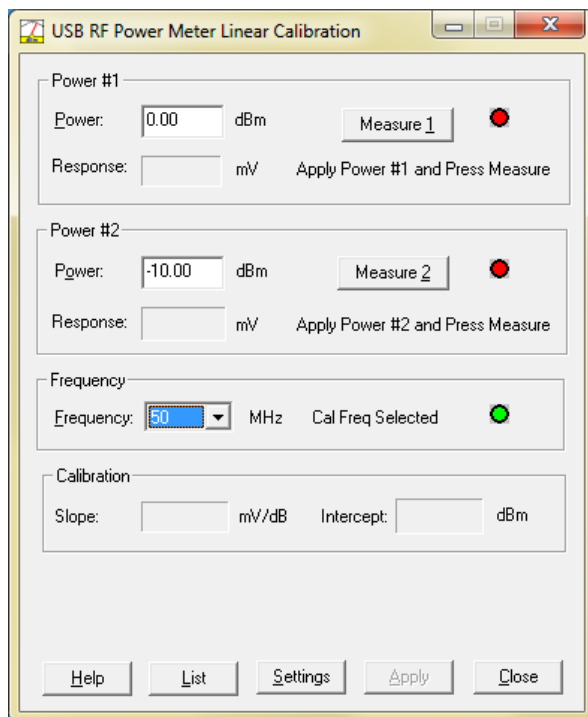

Figure 20. Main Screen   Figure 21. Linear Calibration Screen

The listing screens, shown previously in Figures 11 and 12, display lists of all the calibration sets for no calibration, at 21 predetermined and 3 auxiliary frequencies for either linear or quadratic calibrations. The corresponding EEPROM index, frequency, and calibration date, and calibration parameters are shown. The date format is the modified Julian date (MJD).

The settings screen, shown in Figure 23, displays and controls for several miscellaneous instrument settings. The device reference voltage and firmware revision are shown as read-only values. The format of the copy and record functions can be selected to include a heading, the RF power value and units, and the MJD, date and time. The number of measurements averaged for a calibration can be set, and one of them can be cleared at a selected frequency. The value of an external attenuation or other power reading offset can be entered.
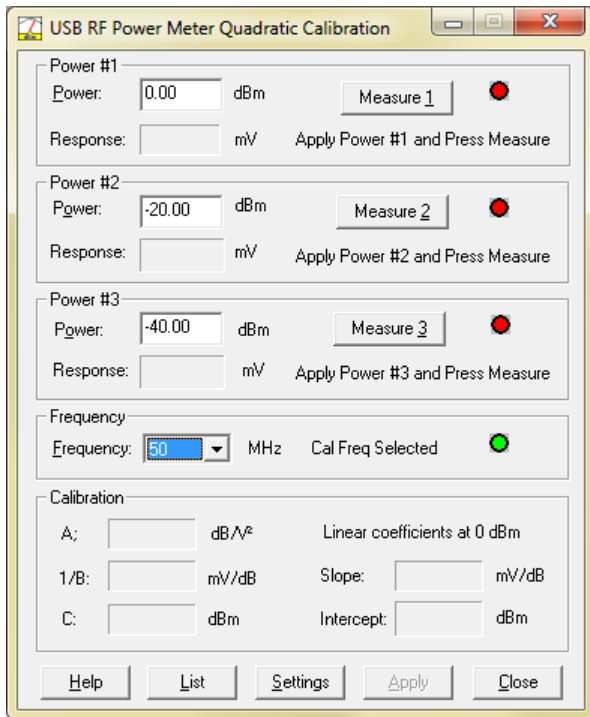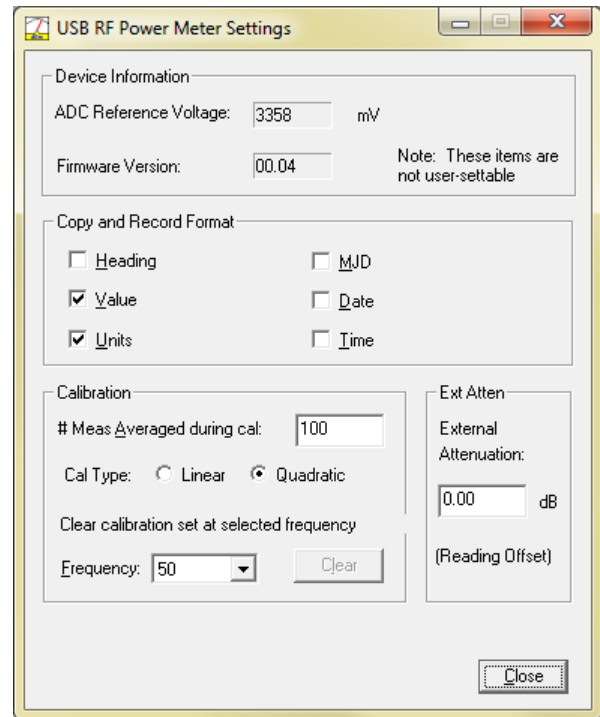
Figure 22. Quadratic Calibration Screen

Figure 23. Settings Screen

● **Measurement Rate**

The USB RF power meter makes about 38 readings per minute (τ=1.6 s) when they are averaged by a factor of 100, a rate of 63 measurements per second. Without averaging, the measurement rate is limited by a 0.25 second software delay to about 3.4 measurements per second (τ=0.29 s) for display visibility. The full measurement rate can be used by setting the averaging factor to 1. An additional decimation factor can be performed when recording data to set a longer collection interval.

● **Measurement Noise**

The unaveraged USB RF power meter measurement noise shows obvious quantization, has a white power spectral density and no outliers, as shown in Figure 24 for a 12-minute run of some 2500 points. Averaging by a factor of 100 reduces the noise by an order-of-magnitude to σ=0.033 dBm, as shown in Figure 25.
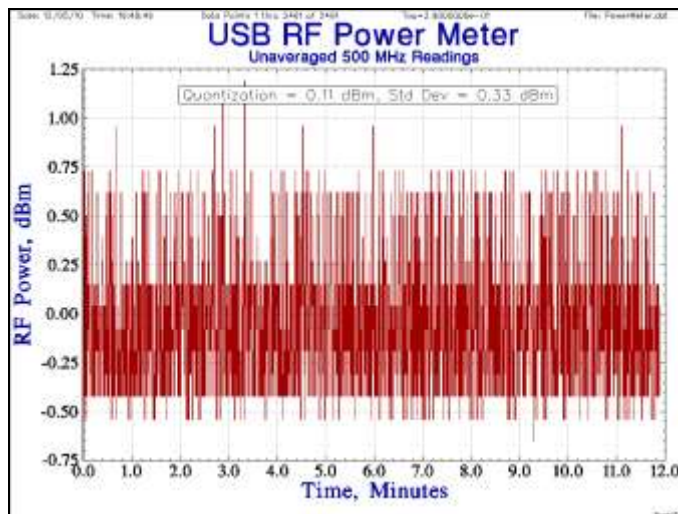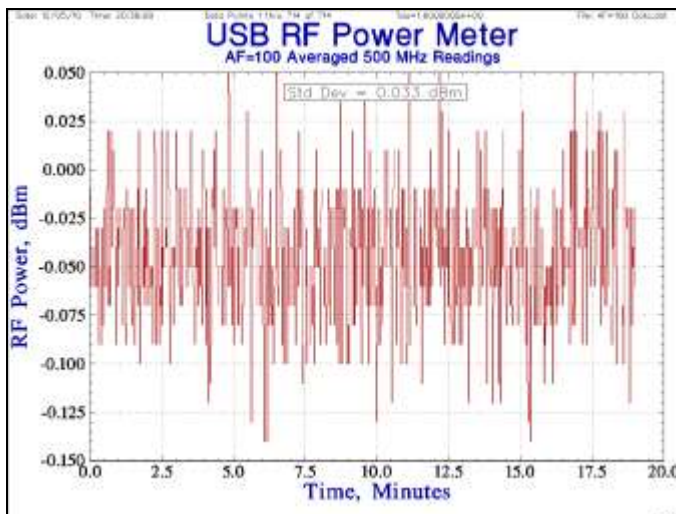
Figure 24. Unaveraged Data

Figure 25. Averaged Data

● Options

One useful option would be to provide dual detectors for use with a 4-port directional coupler to make scalar return loss and VSWR measurements, using another PIC ADC channel. Different firmware and software would be needed. That concept could easily be extended for up to eight channels. Other options would be to use the spare ADC channels to read the supply voltage and/or a temperature sensor.

● Applications

An RF power meter is an indispensible instrument for working with RF circuits, measuring the output of a source, the gain of an amplifier, the attenuation of a network or forward and reflected power with a directional coupler. For example, this RF power meter, along with a suitable source, it makes the evaluation of a step attenuator very easy.

While the USB RF power meter is no substitute for an instrument like the HP 436A for precision measurements, it can nevertheless serve as a low-cost substitute in many less demanding applications where 1 dB accuracy is sufficient. The unit can be especially useful in portable applications, and when data recording is needed.

● References

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