An Antenna Impedance Meter for the High Frequency Bands

When SWR isn't enough — here's a tool that you can build.

Bob Clunn, W5BIG

An SWR meter is a very useful instrument and in many situations provides all the information needed to check an antenna. However, an *impedance* meter provides a much more detailed picture of the antenna parameters. There are several such instruments on the market with prices in the range to appeal to hams.[1] These typically have broadband inputs and use diode detectors. The broadband input is subject to incorrect reading due to strong signals, such as broadcast radio stations, even when the frequencies of these signals are a long way from the test frequency. The diode detectors are subject to nonlinearity error at low signal levels, so their dynamic range may be limited.

Design Goal

My goal was to design an instrument for accurately measuring impedance, with magnitude and phase, so that all the desired parameters of an antenna can be determined and displayed in a graphical format. The resulting antenna impedance meter (AIM430) measures RF voltage and current and uses these values to calculate complex impedance and other parameters of interest. The AIM430 provides a detailed look at the antenna system. Formulas in the design books become more meaningful when you can quickly see how the real and imaginary parts of the impedance vary with frequency.

The AIM430 continuously covers the frequency range of 500 kHz to 32 MHz and operates in conjunction with a PC, which allows easy control through a graphical user interface. It can also be battery powered and connected to a laptop computer for completely portable operation.

Basic Operation

The AIM430 uses two frequency sources that are heterodyned to produce a low frequency signal in the audio range that can be easily amplified, filtered and analyzed. The required frequencies are generated by two AD9851 direct digital synthesizer (DDS) integrated circuits made by Analog Devices. One DDS operates at the specified test frequency and the other is programmed to operate 1 kHz above it. These are both driven by a crystal-controlled oscillator running at 20 MHz. The DDS chips internally multiply this clock by a factor of six, so the effective clock rate seen by the DDS is 120 MHz. In general, the DDS can be used to produce an output up to about one-third of its clock frequency.[2] A block diagram of the AIM430 is shown in Figure 1.

The output of each DDS is followed by a low pass filter with a cutoff frequency of 45 MHz. These filters remove the spurious high frequency components that appear in the output. The DDS generates many frequency components in addition to the one that is desired. For example, if the DDS is programmed for 32 MHz, there is a strong signal at the clock frequency minus 32 MHz, in this case 120 – 32 or 88 MHz. Therefore, to get good attenuation at 88 MHz and beyond, the DDS low pass filter cutoff is set at 45 MHz. The filter attenuation is greater than 60 dB above 88 MHz.

After the DDS output is filtered, it is used directly to provide the stimulus signal for the impedance measurement. There is no buffer amplifier. This eliminates the harmonic distortion of an amplifier and keeps the output signal amplitude low to reduce the interference to nearby radio receivers. The maximum output power is less than 50 μW.

The output amplitude of the DDS goes down slightly as the frequency goes up. The variation over the entire operating range of the analyzer is only about 3 dB. This is no problem since we are using the *ratio* of two RF signals to calculate impedance and the amplitude of the stimulus cancels out in this ratio.

To calculate impedance, we need two values, voltage and current. Both the magnitude and the phase are measured. These two parameters are sensed using 1% resistors. (There are no transformers in the AIM430.) The voltage across one resistor is proportional to the voltage being applied to the circuit under test and the voltage across another resistor is proportional to the current flowing into the circuit connected to the analyzer's test port. The ratio of these two voltages corresponds to the impedance we want to measure. Figure 2 shows the voltage and current waveforms.

In Figure 3 there are two mixers, one for

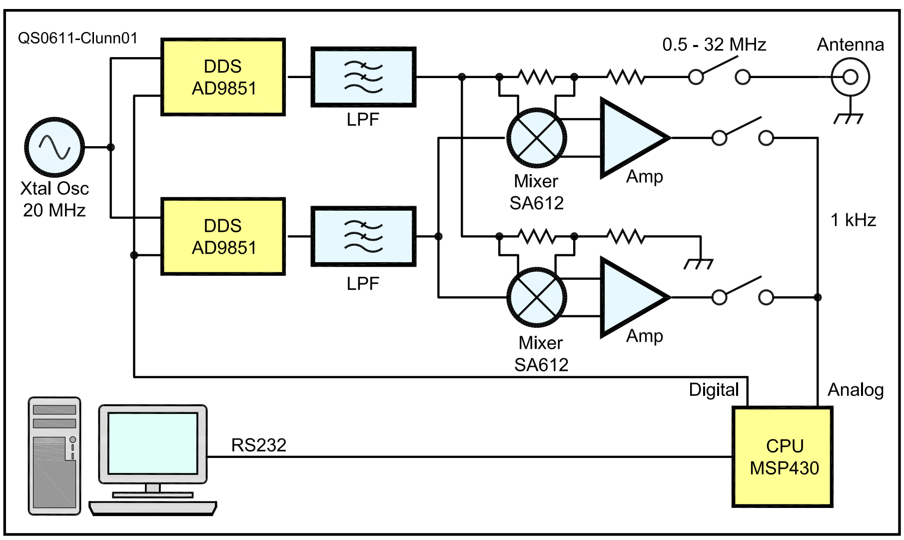


Figure 1 — Block diagram of AIM430 antenna analyzer.

[1]Notes appear on page 32.

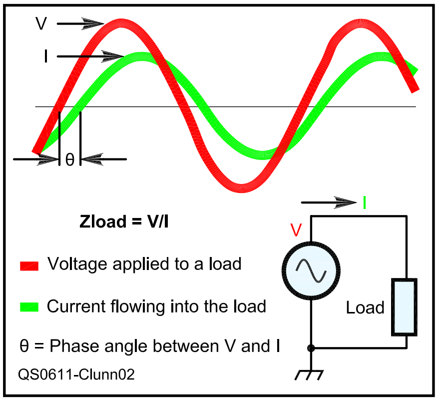


Figure 2 — Voltage and current waveforms with complex load.

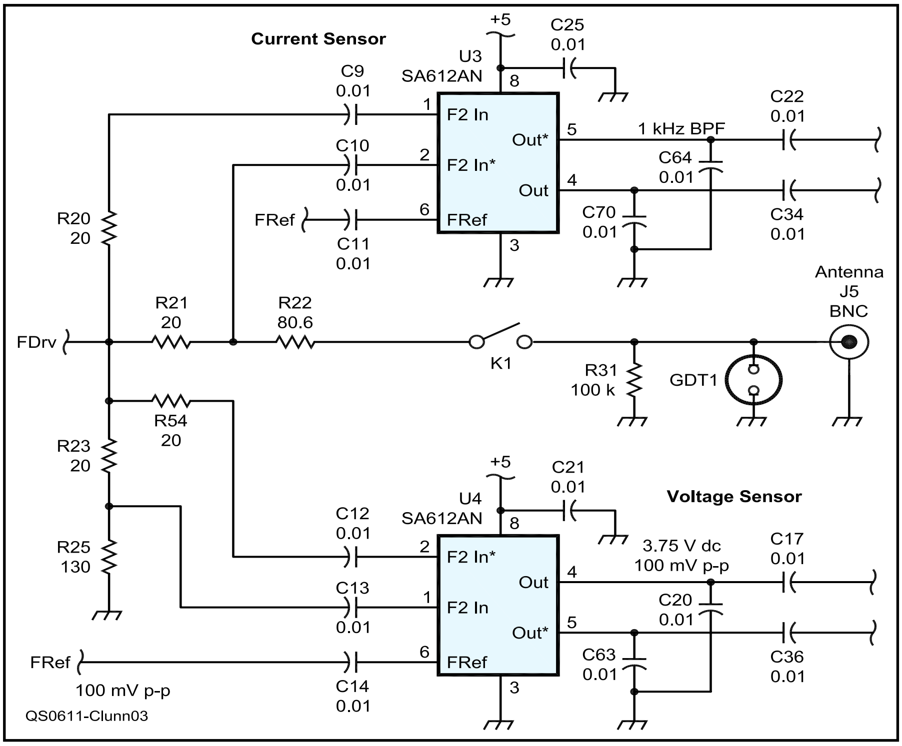


Figure 3 — Schematic of the voltage and current sensing circuits. Two mixers are used to convert the load current and load voltage to the audio range (typically 1 kHz).

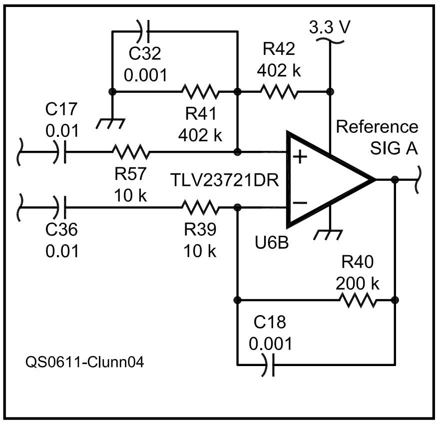


Figure 4 — One of the two 1 kHz differential amplifiers and band-pass filters.

sensing the current flowing into the load and the other for sensing the voltage applied to the load. FDRV is the programmed test signal from one of the DDSs. This is the stimulus signal for the load under test. FREF is the output of the other DDS, which is 1 kHz higher in frequency than FDRV. This second DDS is the local oscillator. The SA612 has differential inputs, which make it very handy to directly measure the voltage across a current sensing resistor. Therefore, we don't have to use transformer coupling.

The output impedance of the SA612 is about 1500 Ω. A 0.01 µF capacitor to ground filters out the high frequency component (the sum of the input and local oscillator), leaving the 1 kHz difference signal. The differential outputs of the mixers are connected to op-amps through dc blocking capacitors. These capacitors also provide attenuation at low frequencies.

Figure 3 shows the input protection circuit of the AIM430. An isolation relay is open except when a measurement is in progress. A gas discharge tube (GDT) protects the input against high voltage due to static charge on the antenna.

One of the op amp circuits is shown in Figure 4. There are two poles of high frequency attenuation including the R-C filter at the output of the mixer. A third pole is provided by a sample-hold circuit later in the analog signal processing chain. The frequency response of the signal path peaks at 1 kHz and is 60 dB down at 100 kHz. The op-amps provide filtering and also convert the differential signal to a single ended signal for input to the analog to digital converter (ADC). Since the desired signal is always 1 kHz, we do not have to worry about variations in the amplitude and phase response of the low pass filters.

Identical mixer and amplifier circuits are used for both the voltage and current sensing paths. Any small differences in the gain and phase shift of these two paths are taken care of by the calibration process, which will be discussed later. After the RF signals are converted to the audio range, it is much easier to measure their amplitude and phase. This is done by digitizing the two signals with a 12-bit ADC that is contained in the Texas Instruments MSP430F149 microprocessor. This microprocessor runs at 7 MHz and the ADC samples are precisely timed by its internal clock. Both the current and the voltage channels are sampled with 16 samples per cycle.

The raw data is sent to a PC through the RS232 serial port (an RS232/USB converter can also be used). The PC calculates the impedance and all the other desired parameters. The PC then graphically displays a detailed view of the parameters as the frequency range is scanned.

The software has been used with *Windows 95, 98, 2000* and *XP*. There is no definite speed requirement, although faster is better because the program is computationally intensive. I've run it successfully on a 300 MHz laptop using *Windows 95*. The program doesn't require an installation procedure; just click on the *.exe* file and it runs. It can be copied to a hard drive or run directly from a floppy or a CD.

Data Analysis

The two sets of digital data from the voltage and current sensors are analyzed using the discrete Fourier transform. This produces the amplitude and phase of the 1 kHz fundamental signal and cancels out any dc component due to offsets in the operational amplifiers. The magnitude of the load impedance is the voltage amplitude divided by the current amplitude. The phase angle of the impedance is the difference in the phase angles of the voltage and current. Knowing these two parameters, we can calculate the equivalent resistance and reactance of the load impedance:

R = Resistance = Impedance_Magnitude × cosine(phase_angle)

X = Reactance = Impedance_Magnitude × sine(phase_angle)

The external load resistance is found by subtracting the internal 100.6 Ω series resistance (R21 + R22 shown in Figure 3) from the calculated resistance. The equivalent series circuit is $Z = R + jX$, where j is the square root of –1. The equivalent parallel circuit is also calculated and displayed in the data window as the cursor moves along the frequency axis.

Resistance is always a positive number. Reactance can be positive or negative. Positive reactance is associated with inductance and negative reactance with capacitance. The true sign of the phase angle is determined by the data processing routine, so capacitive reactance and inductive reactance can be distinguished without ambiguity. As can be seen from the scan pictures, the phase changes rapidly as it passes through zero. Critical points in the plot, such as maximum or minimum impedances, can be located more accurately on the frequency axis using phase rather than by looking only at the impedance magnitude.

Standing Wave Ratio

SWR is probably the antenna's most interesting parameter. This is calculated by first determining a parameter called *reflection coefficient*. When a signal travels down a transmission line with a characteristic impedance of Z_0 and arrives at the antenna with a *different* impedance, some of the signal is reflected back toward the transmitter. This reflection occurs even if the transmission line is of the highest quality and the antenna is a perfect radiator. The reflection coefficient is the fraction of the voltage that is reflected at the antenna back toward the transmitter. (Its magnitude is also equal to the square root of the ratio of reflected power to incident power.) If there is no reflection (i.e., the reflection coefficient is zero) then all the power from the transmitter is absorbed by the antenna, which is usually the desired case. If the transmission line is open at the antenna (perhaps due to a broken wire), all the power arriving at the break point is reflected back toward the transmitter, none is radiated, so the reflection coefficient has its maximum value of unity. If the transmission line is open, the reflection coefficient is plus one; if the line is shorted, the reflection coefficient is minus one.

$$\text{Reflection\_coefficient} = \rho = (Z_L - Z_0) / (Z_L + Z_0)$$

where

Z_L = Impedance of the load

Z_0 = Impedance of the transmission line.

Z_L is a complex number; therefore, ρ is, in general, a complex number with a magnitude between 0 and 1 and a phase angle in the range ±90°.

Since the reactive component of Z_0 is usually very small, it is often ignored and Z_0 is considered to be a real number, such as "50 Ω" or "75 Ω." The value of Z_0 can be entered from the program's main menu, so the SWR can be calculated for any value of transmission line impedance.

For the SWR calculation let U equal the *magnitude* of ρ.

U will be in the range of 0 to 1.

SWR = (1+U) / (1–U)

Note the SWR only depends on the magnitude of ρ, so it is *not* a complex number. If ρ is zero (no reflection), the SWR is 1.0:1. Since a term 1–U appears in the denominator, the SWR can be very large when the transmission line is badly matched to the antenna and the magnitude of the reflection coefficient, U, is almost equal to one.

Applications

The analyzer's test conditions are specified by entries on the PC. These include scan start/stop frequencies, frequency increment between data points and display scale factors. There is also a provision to enter the nominal transmission line impedance so the SWR can be calculated for any value. After the scan is complete, the mouse can be used to move a cursor along the frequency scale to display the numeric values of several parameters including SWR, impedance magnitude and phase, equivalent series circuit and equivalent parallel circuit.

The full-scale ranges for measurements are:

- SWR up to 100:1
- Impedance magnitude 1 Ω to 10 kΩ.
- Phase angle –90 to +90°.
- Frequency scan 500 kHz to 32 MHz.

Figure 5 shows the scan of a piece of RG-58 coax that is open at the far end. The coax is 28 feet long. The frequencies at which the phase angle crosses the axis are called "resonant frequencies" and are listed across the top of the graph. In this case, the first frequency corresponds to the ¼ λ of the coax. The second value is the ½ λ frequency. Because of loss in the cable, the maximum impedance at the ½ λ frequency (11.681 MHz) is only about 1200 Ω at the input end of the coax, not infinity. At the frequency corresponding to a 1 λ, 23.467 MHz, the impedance is about 800 Ω because of increased loss at the higher frequency. The 1 λ and ½ λ frequencies are not exactly in a 2:1 ratio because the velocity of propagation varies slightly with frequency.

Notice the way in which the phase angle (violet trace) changes rapidly at 5.765 and 17.532 MHz even though the magnitude of the impedance is changing slowly. Finding the phase angle zero crossing makes the location of the ¼ λ frequencies more accurate than relying on the magnitude of the impedance. The cursor is the light colored vertical line at 11.697 MHz and the data displayed

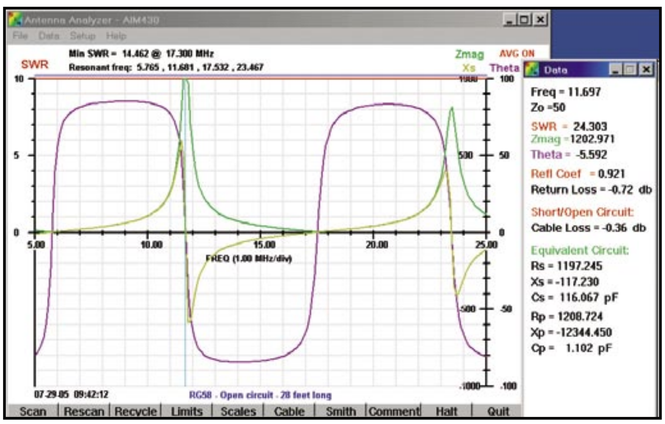


Figure 5 — Scan of 28 foot unterminated coax.

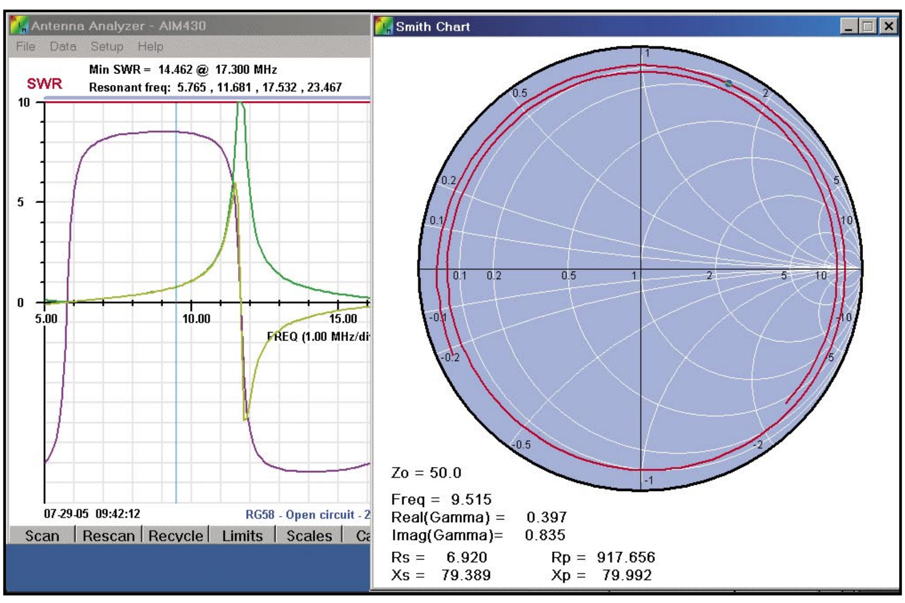


Figure 6 — Smith chart of 28 foot unterminated coax.

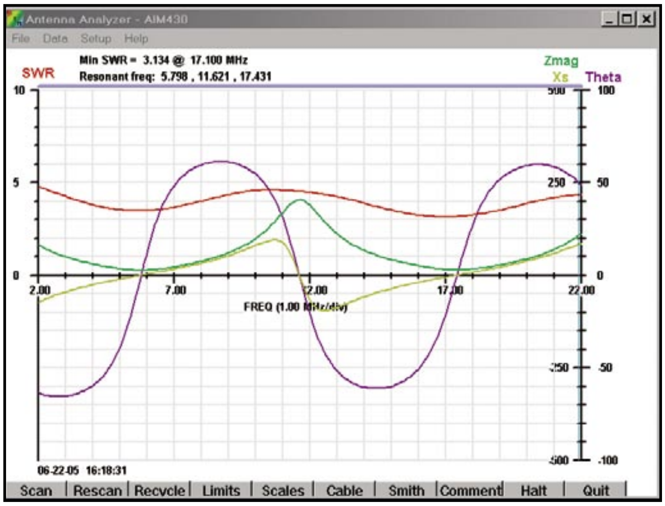


Figure 7 — Scan of 28 feet of RG-58 coax with a 243 Ω resistor termination.

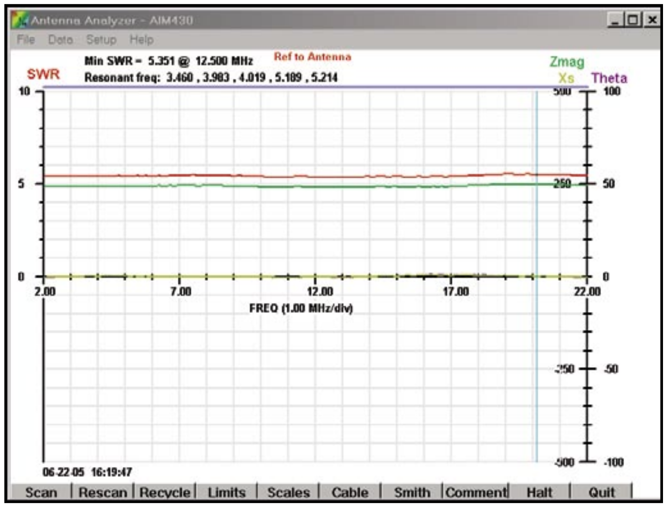


Figure 8 — Scan of Figure 7 configuration referred to antenna terminals.

in the window on the right side of Figure 5 corresponds to this frequency. R_s and X_s are the series circuit values. R_p and X_p are the parallel circuit values.

Figure 6 shows a Smith chart of the data from the scan in Figure 5. The small dot at about the 1 o'clock position is a marker that moves along the Smith chart as the cursor moves along the frequency axis. In this picture the cursor is at 9.515 MHz. The equivalent series and parallel circuit values are shown on the Smith chart along with the real and imaginary parts of the reflection coefficient. The trace spirals inward because the cable loss increases with frequency.

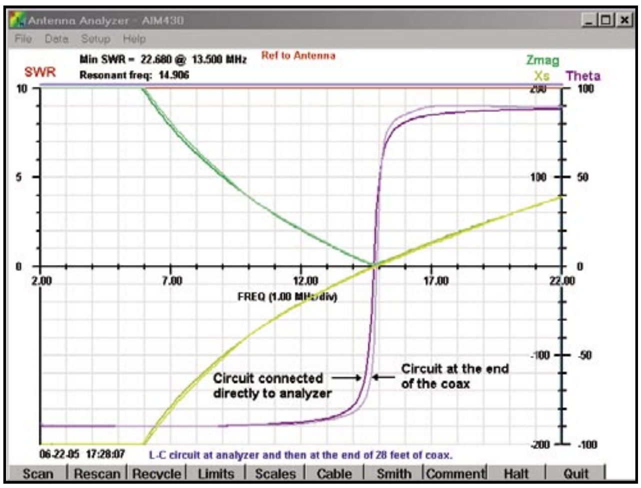
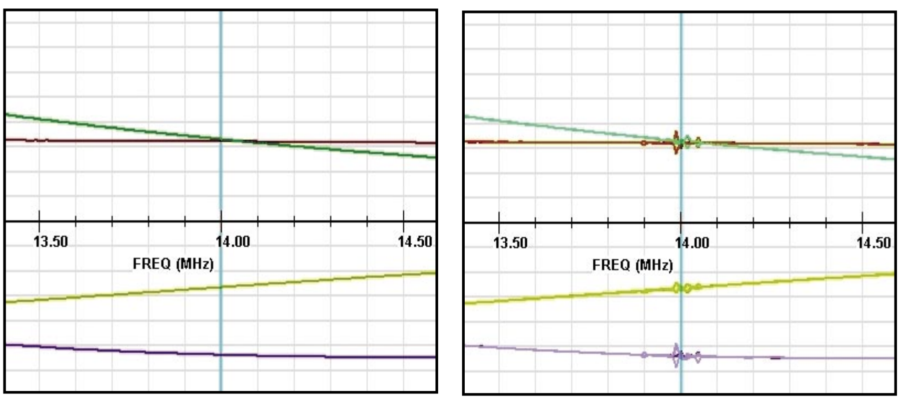


Figure 9 — Two scans of a series L–C tuned circuit termination. The first is with the circuit connected directly to the AIM430, the second is referenced to the end of the coax. In the ideal case, they would be identical.



(A) (B)

Figure 10 — Scans with and without interfering signal. At A, a scan without interference. The SWR reading (red trace) is 3:1 in this example. At B, a scan with a CW interference level of +63 dB over S-9 injected directly into the input.

Reference Transformation

Sometimes it is desirable to know the impedance directly at the antenna terminals. After a calibration phase during which the properties (length and loss) of the cable are determined at each measurement frequency, measurements made at the transmitter end of the line can be transformed to the antenna terminals. This is done in real time during the scan and the displayed data is very close to what would be measured if the analyzer were actually mounted at the antenna.

The calibration is done by disconnecting the far end of the transmission line from the antenna and then scanning the cable input impedance with two different resistive terminations. One terminating resistor is typically in the range of 20 to 100 Ω and the other can be in the range of 1 kΩ to 2 kΩ. The resistor values are not critical, as long as they are accurately measured with a digital ohmmeter. When the transmission line calibration is performed, the exact resistor values are entered in the program via dialog boxes. The terminating resistors can be low power film devices since they don't have to handle the transmitter power. After the cable calibration is finished, the data are saved to disk so they can be recalled anytime later.

Using the Impedance Transformation Feature

Figure 7 shows a conventional scan with the 243 Ω resistor at the end of 28 feet of RG-58 coax. The green trace is the magnitude of the measured impedance. As expected, the value varies over a wide range as a function of frequency. At the ½ λ frequency, 11.621 MHz, the indicated impedance is close to 243 Ω because the same impedance is seen at both ends of a half-wave line.

Now we click SETUP and REF TO ANTENNA. The legend REF TO ANTENNA is

Figure 11 — The enclosure is 5×5×2 inches, which leaves room inside for an optional battery pack. The dc current required is about 150 mA while taking a measurement and 30 mA if idle. After 10 minutes of inactivity, the dc power is turned off automatically. Two LEDs on the front panel indicate POWER ON (green) and TEST IN PROGRESS (red).

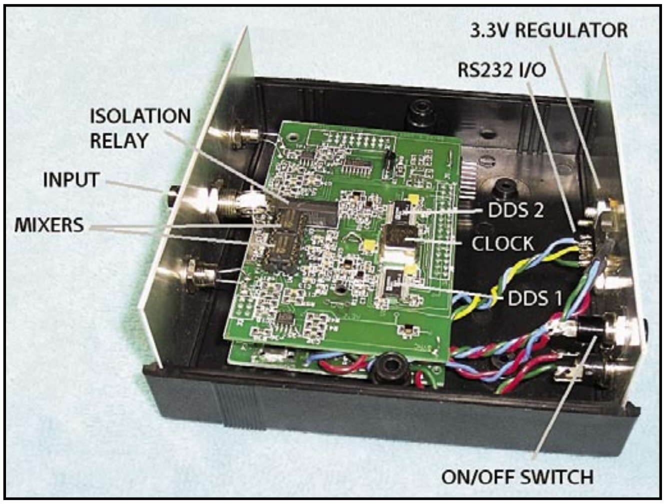


Figure 12 — There are two PC boards sandwiched together with 0.1×0.1 inch connectors. The top board contains all the RF circuitry and the bottom board has the microprocessor and electronic power switch. The 3.3 V regulator is mounted on the rear panel that acts as a heat sink.

displayed in red at the top of the graph while this feature is enabled. The resistor (243 Ω) and the cable are the same as used in the previous graph. The Z_{mag} plot (shown in green) is relatively flat across the frequency range. The measured resistance now varies only from 243 to 248 Ω, a range of 2%. The phase angle and the reactive component are nearly zero.

Figure 9 shows that the transformation also works quite well with a complex load circuit. A series L-C tuned circuit was used for the load. For the first scan, it was connected directly to the BNC connector on the AIM430. Then it was rescanned with the load at the end of 28 feet of coax. The impedance and reactance curves almost coincide; it's hard to see the difference between them on the graph. There is only a small difference in the two phase-angle traces shown in violet.

Interference Rejection

The band pass circuits in the AIM430 help to reject interfering signals that are more than about 100 kHz from the desired test frequency. Figure 10 shows the result with and without an interfering signal that has an amplitude of +63 dB over S-9. The disturbance of the reading is confined to an interval of about ±100 kHz.

Additional Applications

In addition to measuring antennas, the AIM430 can be used to measure discrete components, such as resistors, capacitors and inductors. It is particularly interesting to see how the component value varies as a function of frequency. Inductors with metal cores are often very frequency sensitive. It can also be used for adjusting tuned circuits, such as traps, and for measuring the parameters of quartz crystals and other resonator devices.

The output signal from the analyzer can be used as a test signal for checking receivers. The output into a 50 Ω load is about 35 mV_{rms}. The amplitude is not precisely calibrated but the variation over any of the ham bands is less than 0.5 dB. The frequency can be set in 1 Hz increments and it can be calibrated against WWV.

Calibration

The AIM430 is calibrated by measuring the residual capacitance and inductance in its output circuit. The phase shift and amplitude differences in the voltage and current amplifiers are also measured. This calibration data is then used to compensate each reading. Stray capacitance and inductance associated with an external test fixture, if used, are also taken into account by this procedure.

Calibration is performed by using a short circuit and an open circuit. First, a short circuit is connected to the analyzer and several measurements are taken. Then the short is removed and the open circuit properties are measured. This data is saved in a file that is automatically loaded each time the program is run. The whole calibration process takes only a few seconds. Since the analyzer does not have any internal adjustments (no pots or trim caps), the calibration is very stable. It only needs to be done when the external test fixture or cable adapter is changed.

Construction

The microprocessor is initially programmed through a 14-pin JTAG interface. Subsequently, the program can be updated through the standard RS-232 interface.

Conclusions

The operation of an affordable vector impedance meter for measuring antennas in the high frequency range has been presented. Using state-of-the-art components for signal generation and analysis, the AIM430 provides a high level of accuracy and wide dynamic range for complex impedance measurements. The unit is also quite useful for measuring discrete components and tuned circuits.

Acknowledgments

I would like to thank Dave Russell, W2DMR, Danny Richardson, K6MHE, and Paul Collins, ZL3PTP, for evaluating the AIM and providing suggestions that greatly enhanced the program. Thanks also to Bill Cantwell, WB5SLX, and Forest Cummings, W5LQU, for their proofreading and encouragement.

Notes

[1]J. Hallas, W1ZR, "Product Review — A Look at Some High-End Antenna Analyzers," *QST*, May 2005, pp 65-69.

[2]Direct digital synthesizers, theory of operation — **www.analog.com/library/analogDialogue/archives/38-08/dds.pdf**.

[3]AIM430 User Manual and demonstration program — **w5big.home.comcast.net/antenna_analyzer.htm**.

[4]Data sheet for AD9851 DDS — **w5big.home.comcast.net/AD9851.pdf**.

[5]Data sheet for SA612 mixer — **w5big.home.comcast.net/SA612.pdf**.

[6]Data sheet for MSP430F149 microprocessor — **focus.ti.com/docs/prod/folders/print/msp430f149.html**.

[7]Schematic and printed circuit board design software — **www.expresspcb.com**.

Bob Clunn, W5BIG, received his Novice license in 1956 while in junior high and his general license soon after. During high school he was very active on 40 and 20 meter CW. During this time he made the decision to study electrical engineering in college. Bob received his BS degree in electrical engineering from Rice University in 1965 and his MS from Southern Methodist University in 1969. He was employed at Texas Instruments in Dallas from 1963 until 1991. His work there involved the design of computer controlled test equipment for transistors and integrated circuits. From 1991 to the present he has been working as a consultant for several companies in the fields of electronic circuit design and machine vision.

In 2002, Bob renewed his interest in ham radio and obtained his Amateur Extra class license. Soon afterward he got interested in equipment to evaluate antennas and began the design of this antenna analyzer. He can be reached at 509 Carleton Dr, Richardson, TX 75081 or at **w5big@comcast.net**.