

# DSP-Based Vector Network Analyzer for 10 Hz to 40 kHz

*This impedance measuring system, based on the Teensy Arduino microprocessor, also measures amplitude and phase in transmission mode. Control is by built-in touch screen along with serial control through a USB cable.*

Network analyzers at RF frequencies have become popular with amateur experimenters. In one form, the “antenna analyzer” is available commercially and often can measure both resistive and reactive components of an impedance. In its more sophisticated form, measurements can also be made of transmission circuits, such as filters. Examples of the latter are the N2PK<sup>1</sup> and DG8SAQ<sup>2</sup> Vector Network Analyzers (VNA). My experience with the N2PK design included many fine measurements, but sometimes the lower frequency limit of about 50 kHz left a need. Note that the DG8SAQ design operates down to about 1 kHz.

Several interesting approaches to these measurements have been published. The project from George Steber, WB9LVI,<sup>3</sup> measures impedances in the audio range with a minimal amount of hardware along with a PC sound input. The huge advantage of this is hardware simplicity, but it does not provide for a wide range of frequencies nor transmission measurements. Jacques Audet, VE2AZX's Low-Frequency Adapter<sup>4</sup> is very flexible, but requires an RF VNA.

I became curious about making a parallel design to the RF VNA using DSP. The goal was a VNA that would cover from perhaps 10 Hz to a frequency that would join up with the N2PK VNA coverage. I hoped that most of the complexity could be hidden in software and in doing so, the cost could remain low. When fellow experimenter, Johannes Forrer, KC7WW, steered me towards the Teensy Arduino DSP-capable product<sup>5</sup>, I was on my way.

The original idea was to make this Audio Vector Network Analyzer (AVNA) a USB serial driven box without a front control panel. But the availability of the 320x240 color touch screen at low cost<sup>6</sup> changed the approach. The final AVNA has serial control as well as a touch-screen fully-independent alternative. This is very convenient for component identification and measurements, in particular. The stand-alone capability includes transmission as well as swept measurements, there is no need to use the complete PC control.

The result is a little box, costing around US\$100, that can do conventional VNA functions and also serves as an LCR meter for resistors from a fraction of an ohm up to a few megohms, capacitors from a picofarad up to thousands of microfarad, and inductors from a few nanohenry up to thousands of henry.

To make this project available to as many experimenters as possible, high quality double-sided printed circuit boards have been made available, in multiples of 3, through OSH Park<sup>7</sup>. The software is open-source<sup>8</sup>, as is the development system<sup>9</sup> and the processor/CODEC library software<sup>10</sup>.

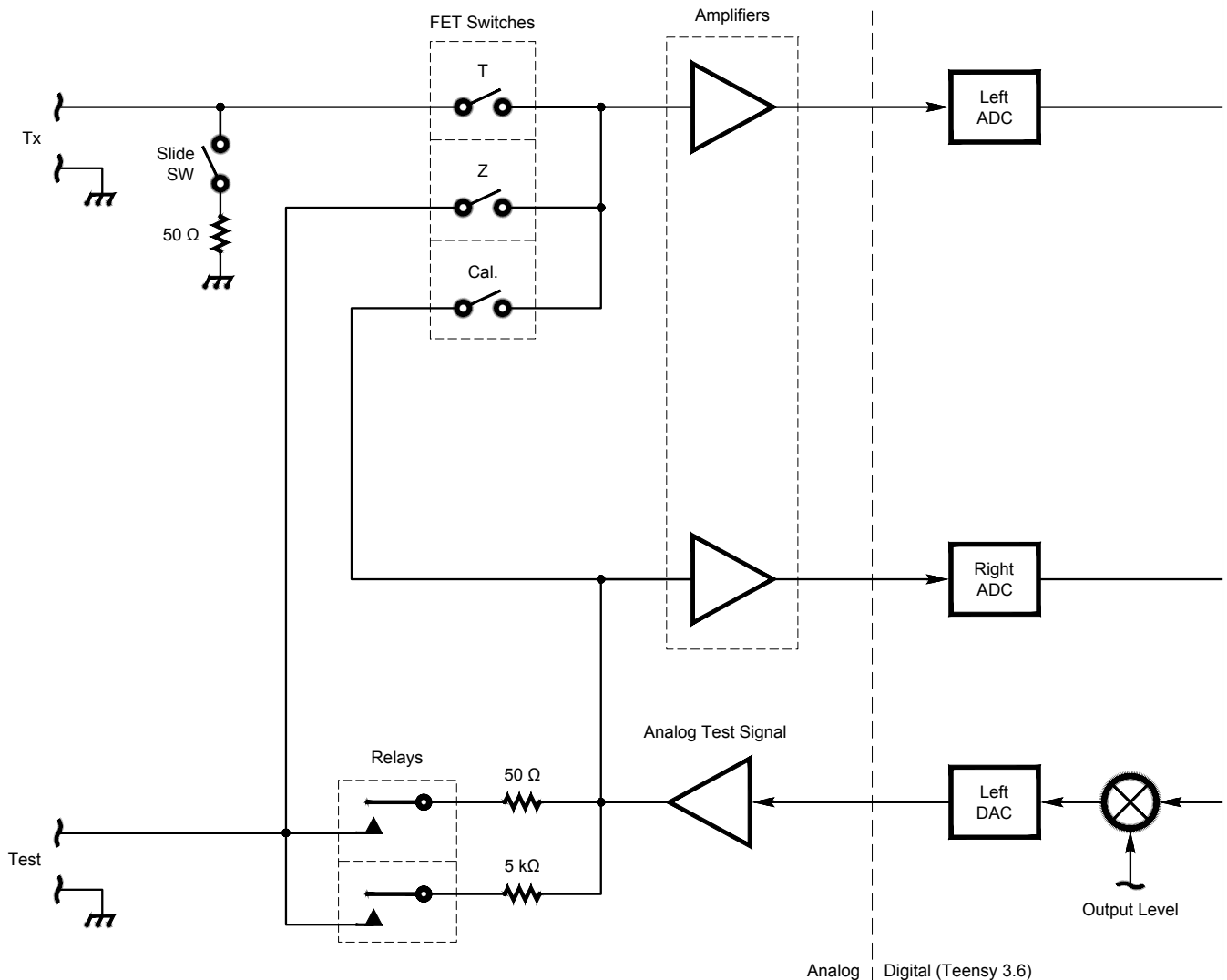
## Overall Operation

The block diagram of Figure 1 shows how a combination of hardware and software produces a conventional VNA. The process starts with a sine wave generator implemented as direct numerical calculation in DSP software. This signal can be at any

frequency from 10 to 40,000 Hz and is sent to a Digital-to-Analog converter (DAC) that drives an amplifier producing a very low output impedance. Relays are used to connect a precision resistor of either 50 or 5 k $\Omega$  to the impedance measurement point. This resistor is used as a reference for measuring impedances, and also serves as a known source resistance for transmission measurements. If desired for transmission measurements, the low output impedance point can also be accessed directly.

Both impedance and transmission measurements involve knowing the amplitude and phase of the sine wave voltage at the low-impedance output. This is the reference signal, and it is always available via the right channel Analog-to-Digital Converter (ADC). The left channel measurement is taken across the unknown impedance for impedance measurements, or at the output of the device being tested for transmission measurements. Differential Op-amps ahead of the ADC allow careful control of their megohm input impedance. This allows software correction of this quantity when measuring impedance.

Inside the DSP, the two outputs of the ADCs are each applied to a pair of mixers that are multipliers. Each pair of multipliers has a locally generated sine and cosine wave for producing in-phase,  $I$ , and quadrature,  $Q$ , measurements. This process is completely analogous to direct-conversion receivers. Implemented in DSP, the isolation between either of the inputs and the output is close to perfect. The output signal does still include second harmonics of the inputs, that are



**Figure 1 — Block diagram shows a sine wave signal source that comes from the DSP via the left DAC. One of the two receiving channels always measures this signal level via the right ADC and is the reference channel. The left ADC measurement channel is switched between three functions, Calibrate, Impedance, and Transmission. Two different reference resistors can be selected by relays to provide either 50 or 5,000 Ω test level.**

important and will be discussed below.

Next, the *I* and *Q* signals for the reference and measurement channels are averaged over at least a tenth of a second to reduce noise and increase the range of signal levels over which accurate measurements can be made. In the DSP, the averaged *I* and *Q* are converted to amplitude and phase by calculating

$$\text{amplitude} = \sqrt{I^2 + Q^2} ;$$

$$\text{phase} = \arctan(Q/I)$$

Error corrections applied at this point correct for gain and phase differences in the measurement and reference amplifiers, as well as for the input impedance of the measurement amplifier. Finally, for impedance measurements, the resistance

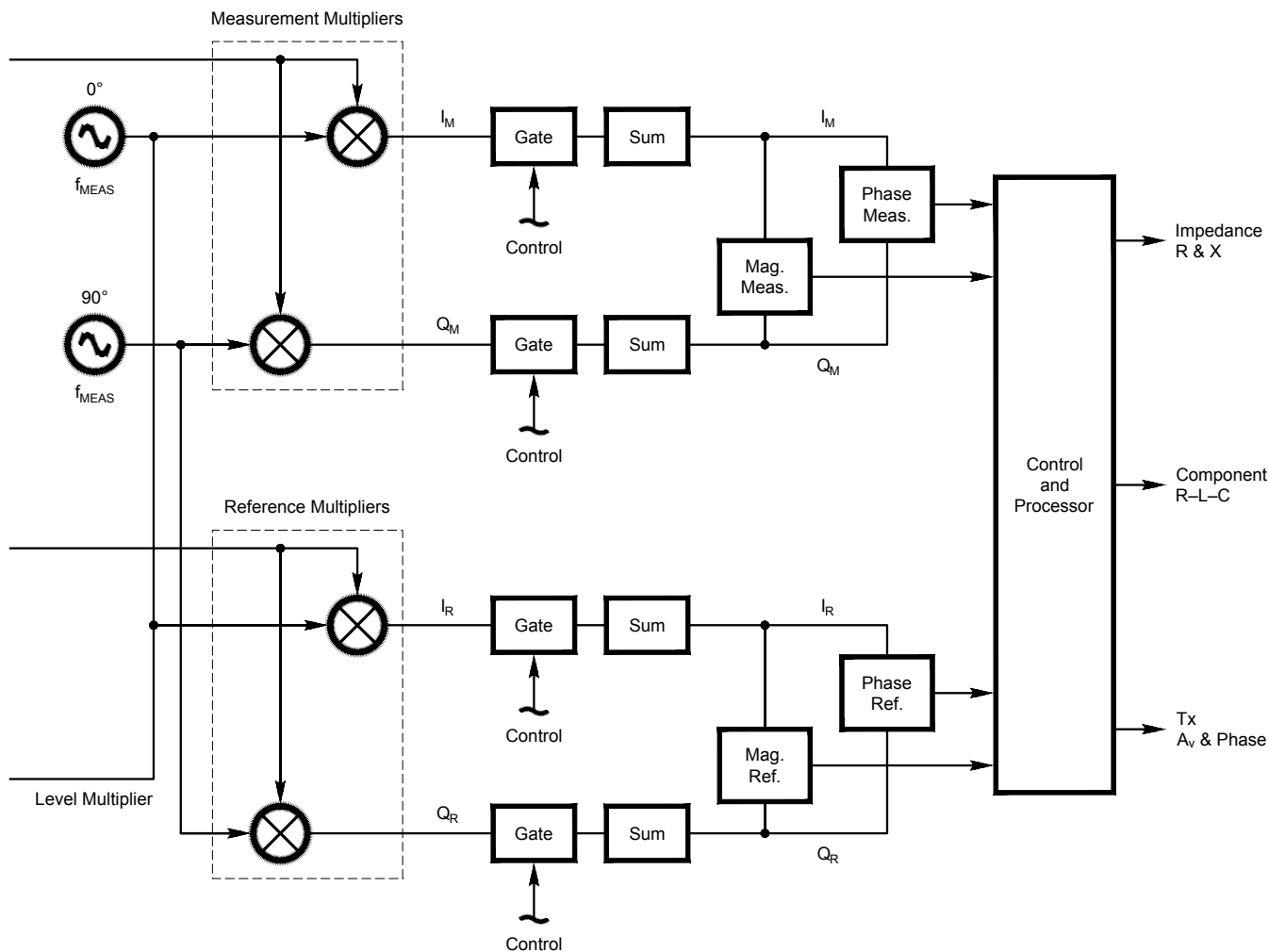
and reactance of the unknown component is found from the voltage amplitudes at the top of the reference resistor and across the unknown impedance, along with the relative phase shift. For transmission measurements the gain or loss comes directly from the measurement of the input and output.

The basic structure of this VNA is parallel to that of RF tools such as the N2PK VNA. Sine waves are computed in the DSP rather than by lookup tables in a DDS. Multipliers are mathematical operations in DSP rather than MC1496 Gilbert cell devices. One area that is a bit different is the impedance measurement method. The most common device for the RF frequencies is a bridge, comprised of three precision resistors and a transformer to keep grounds isolated. This

can be implemented at low frequencies as well, but the accuracy and simplicity of measurements using a single reference resistor favor this latter method. To some extent, this method also has a parallel. The N2PK project has an *I-V* accessory board available<sup>11</sup> that extends this single reference method to RF, using a pair of high turns-ratio transformers.

### Hardware

The schematic diagram of the AVNA hardware PC board, Figure 2, shows the processor board, U3. This is not an IC, but rather the Teensy 3.6 version of an Arduino. Not shown is the PJRC Audio Adapter ADC/DAC board that plugs directly into Teensy



board<sup>12</sup> and connects to the AVNA board via P1. The Teensy board is a member of the Arduino family. Its software allows most of the Arduino IDE and library programs to be applied. To the user it behaves like an Arduino. However, the processor and memory capabilities are much greater than a board such as the Arduino UNO<sup>13</sup>. The Teensy 3.6 uses an ARM Cortex-M4 processor with a basic instruction rate of 180 MHz, an internal 32-bit floating-point processor, and a considerable instruction set just for DSP, see the sidebar “DSP Code in Teensy Arduino”. Part of the Teensy board is a USB serial interface that allows full control of the AVNA from most computing devices such as PCs and Laptops.

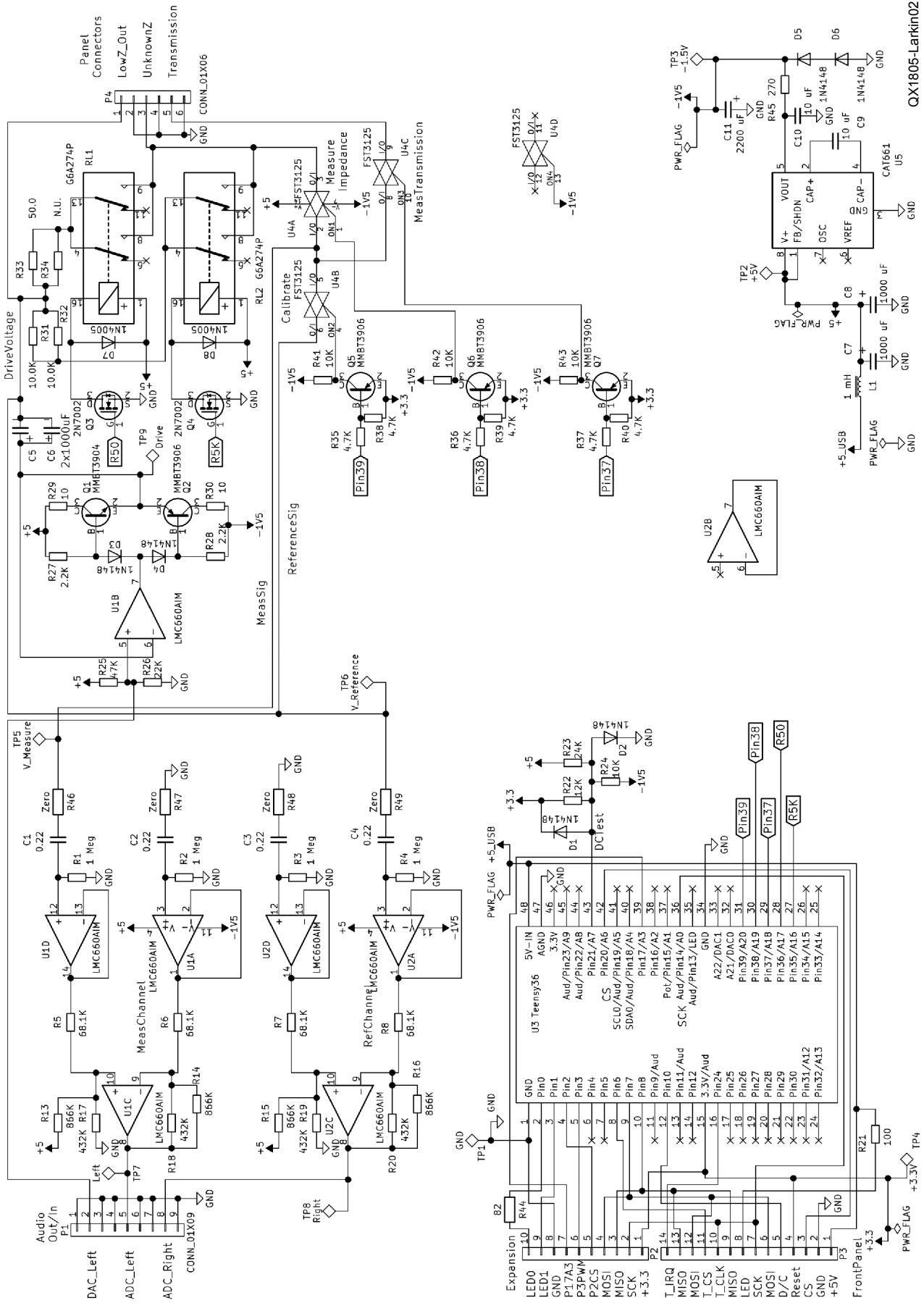
Not shown on the schematic is the front

panel device which is a 320x240-pixel color LCD with touch-screen capability. This plugs into P3 on the AVNA board, either directly or with an extension cable. This display provides a stand-alone capability for the AVNA.

The amplifier comprising U1B op-amp and the transistors Q1 and Q2 has no voltage gain but, because of heavy negative feedback, provides both power drive and a low output impedance. One of a pair of relays, RL1 and RL2, connects the Unknown Z output connector to the drive voltage. These relays were chosen because their gold contacts help to ensure a reliable output impedance. The impedance setting resistors, R31, R32 and R33, R34, are parallel combinations that can be used in several ways to provide

accurate 50 and 5 k $\Omega$  values. As shown, a single 50  $\Omega$  0.05% resistor and a pair of 10 k $\Omega$  0.05% resistors are used. These high precision resistors are used for their low 10 ppm temperature coefficients. Errors in the resistor values can be calibrated out in the software. Any other combination of parallel resistors can be used, depending on what you have available.

Three FET switches, parts of U4, choose the input path for the measurement channel. The calibrate switch, U4B, connects the reference and measurement channel inputs together. With both relays open, this provides an accurate measurement of the differences in gain and phase between the two channels. These differences are small, but end up distinguishing between rough measurements



QX1805-Larkin02

**Figure 2 — Schematic diagram of the AVNA PC board.**The relays are small signal with gold-plated contacts, Omron G6A-274P-ST40-US-DC5 (DigiKey Z2931-ND)]. Resistors R31 and R32 are 0.05% 10 kΩ with 10 ppm/°C temperature coefficients (Mouser 594-UXB02070F1002AR1). R33 is 50 Ω (Mouser 71-PTF5650R000AYR6).

and those of a precision instrument. Because of the relays, this calibration can be done with components connected to the measurement connector. Switches, U4A and U4C, connect the measurement channel for either impedance or transmission measurements.

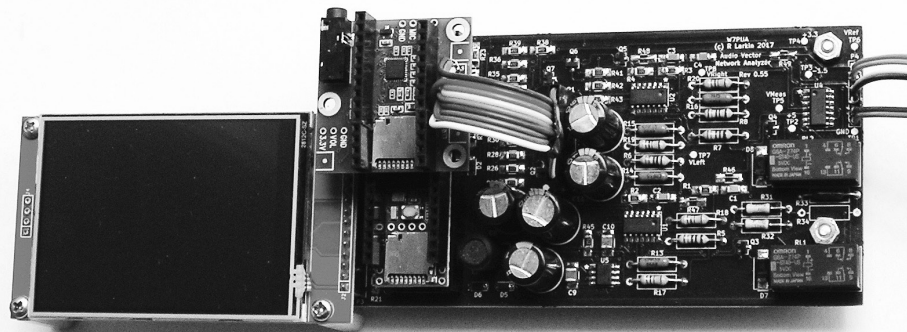
The reference and measurement channels have identical amplifiers driving the pair of ADCs. The voltage gain of about 3.7 allows the drive voltage to be delivered from the linear region of the output amplifier. This gain can sometimes increase the dynamic range of transmission measurements. The amplifiers should be matched so that the two sides of the differential amplifier should be the same. To this end, I purchased a surplus of resistors in values for R5 to R8, R13 to R16, and R17 to R20, and selected a matched sets of four. The exact values are not important. I used leaded 50 ppm temperature coefficient resistors. The 0 Ω resistors at the amplifier inputs, R46 to R49, are not required for the AVNA, but allow for future experimentation.

The AVNA is supplied by the 5 V dc on the USB cable going to the Teensy board. Current consumption is about 200 mA, allowing operation from any USB power source, including rechargeable battery types. The -1.5 V supply is needed to increase the voltage swing of the DAC output amplifier, and is produced by the CAT661 switched-capacitor voltage inverter, U5. The 3.3 V supply is on the Teensy board. The three supply voltages, 5, 3.3 and -1.5 V, are monitored by the Teensy using a single analog voltage input generated by resistors R22 to R24.

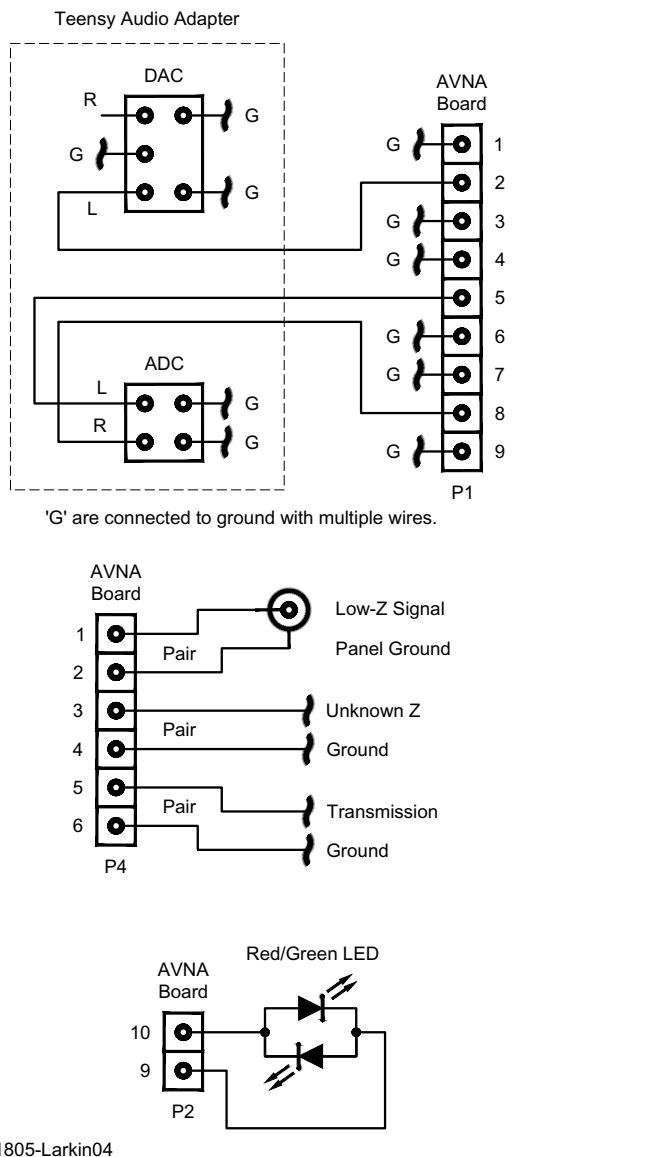
The Teensy 3.6 board has a large number of inputs and outputs supported by peripheral controllers for a wide variety of devices. Many of these pins are unused in the AVNA and could be used to expand the functions of this project. Likewise, the project uses just a small part of the available memory for programs and data.

**Overall Assembly**

Most of the assembly is done by merely plugging the Teensy board into the AVNA board and plugging the Teensy Audio Adapter into the Teensy board. Orientation of the connectors is important, see Figure 3. The LCD+Touch-Pad board likewise will operate



**Figure 3 — The Teensy 3.6 processor and the touch-screen LCD boards are plugged into the AVNA printed circuit board. The Teensy Audio Adapter is on top of the Teensy 3.6. All precision resistors are leaded types.**



**Figure 4 — This diagram shows the interconnection that requires wiring, rather than plugging boards together. All connections except for the LED carry audio signals and use multiple ground leads to minimize ground loops and capacitive coupling. The “Unknown Z” and “Transmission” terminals keep the ground isolated from the panel for the same reason. The LED is red/green bi-color, and the connector can be reversed if green is not the normal color.**

by plugging it directly into the AVNA board at P3. If this is done, the LCD ends up physically lower than the Audio Adapter. With a bit of extra effort, a step can be put into the top of the enclosing box, giving full access to the LCD. I did this for the wooden box shown in Figures 7 and 12. Alternatively, an extension cable can be placed on the touch-screen, allowing a simpler package.

Figure 4 shows the wiring that is external to the PC boards. My construction used banana plug terminals for the Impedance and Transmission panel connections, but these could be coaxial connectors. The “Low-Z” output from the drive voltage is for specialized transmission measurements, and not normally used. For convenience I brought this to a BNC connector. Not shown in this figure are the interconnections between the Teensy 3.6 board and the other parts. These can be seen on the Figure 2 schematic for the AVNA board.

The AVNA starts up as soon as power is applied to the USB connector on the Teensy board. This USB connector can carry serial data, or for stand-alone operation, it can merely supply power from any standard USB power source. The connector is a USB Micro-B style. The schematic shows P2, listed as an expansion connector. This has no particular function at present, but does make available an I2S serial interface, as well as analog and general purpose digital pins.

### DSP Functions

All measurements are made using the two analog inputs, labeled as *Reference* and *Measurement* channels. The digital outputs from the ADC are 16-bit signed words. ADC noise covers several of these bits,

not all of which is random. The coherent portions of the ADC noise can be avoided by careful choice of sampling frequencies. For this reason, both 44.1 kHz and 100 kHz sampling rates are used, as automatically set in the software. The 100 kHz sampling rate allows measurement frequencies up to about 40 kHz. This is high enough to have adjoining ranges with the N2PK VNA. The lower end of measurement frequencies is set at 10 Hz by the coupling capacitors that are on the Teensy Audio Adapter. These could probably be changed, and along with a few other modifications, to allow operation below 10 Hz.

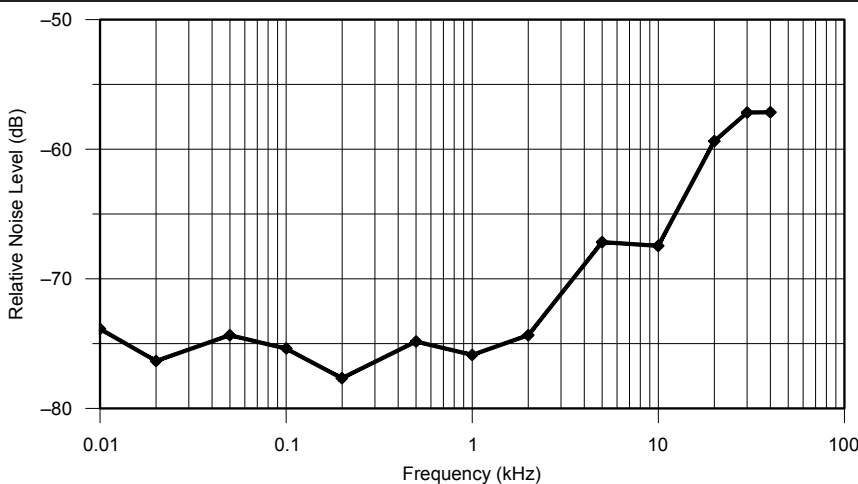
Referring back to the block diagram, the digital outputs of the ADC are applied to multipliers. A bit of trigonometry shows

us most of what we need to understand the operation. The internally generated sine wave at frequency  $f$  Hz is  $\sin(2\pi ft)$ , where  $t$  is time in seconds. This waveform is centered around zero volts and has maximum excursions of  $\pm 1$ . Our reference or measurement signals are exactly the same frequency, but with amplitude  $A$  and phase shift  $p$ ,

$$A \sin(2\pi ft + p)$$

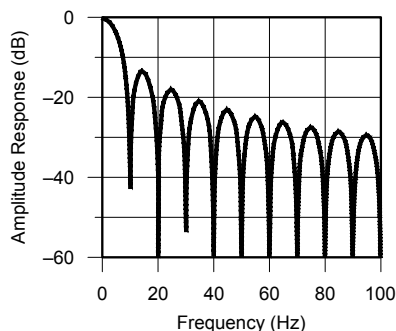
Applying trigonometric identities to the product of our sine waves, we find the multiplier output voltage is of the form,

$$e_{os} = \frac{A}{2} \cos(p) - \frac{A}{2} \cos(2\pi 2ft)$$



QX1805-Larkin06

Figure 6 — Response of a transmission measurement with no connection to the input, except for the 50  $\Omega$  termination. The floor is 75 dB below full input up to 2 kHz, then rises with increasing frequency. The rise is due to capacitive leakage in the “Calibrate” FET switch.



QX1805-Larkin05

Figure 5 — Frequency response is averaged for a tenth of a second. The position of the nulls can be set exactly by controlling the length of the averaged sample period. The nulls for this tenth second average occur at 10 Hz intervals at and above 10 Hz. This eliminates the second harmonic output from the multipliers.



Figure 7 — The AVNA shows the measurement of a 20 nF capacitor at 2,000 Hz.

which shows that the output of the multiplier has no component at the fundamental frequency  $f$ . The first term is an output at dc, which is the desired value. The second term is at the second harmonic  $2f$ , which we don't want. Because of the low frequency involved, we do the low-pass filtering to eliminate the second harmonic by averaging the multiplier output over a very specific period of time. If averaging period is an integer multiple of the second harmonic period, the harmonic component will always cancel out completely, independent of the phase of the harmonic signal. The AVNA uses 64-bit double-precision floating point for this averaging to prevent loss of resolution. The averaging time period must be at least a full cycle at 20 Hz, or 50 ms. The current implementation uses averaging times of around 0.1 second, or two periods at 20 Hz. The exact averaging time depends on the measurement frequency. Depending on the frequency of operation, a slight adjustment of the measurement frequency may be needed to account for the inflexible 44,100 or 100,000 Hz. sample rate.

This averaging process can be viewed as a finite impulse response (FIR) low-pass filter. The FIR coefficients are all the same value and the number of FIR taps is that required to span an integer number of second harmonic cycles. The frequency response of this low-pass design is of the general form,

$$\frac{\sin(kf)}{f}$$

and a careful choice of  $k$  can place nulls at the second harmonic frequency. The integer second harmonic approach described above is one easy way to choose a proper  $k$ . The frequency response of the averaging is shown in Figure 5 for the 0.1 second averaging time suitable for use at 5 or 10 Hz.

The in-phase and quadrature components  $I$  and  $Q$  can be handled computationally as complex numbers,  $I + jQ$ , where  $j$  is the square root of  $-1$ . The Arduino system, through its underlying C++ language, easily handles calculations with complex numbers without separating the real and imaginary parts. Examination of the program shows that this is used extensively.

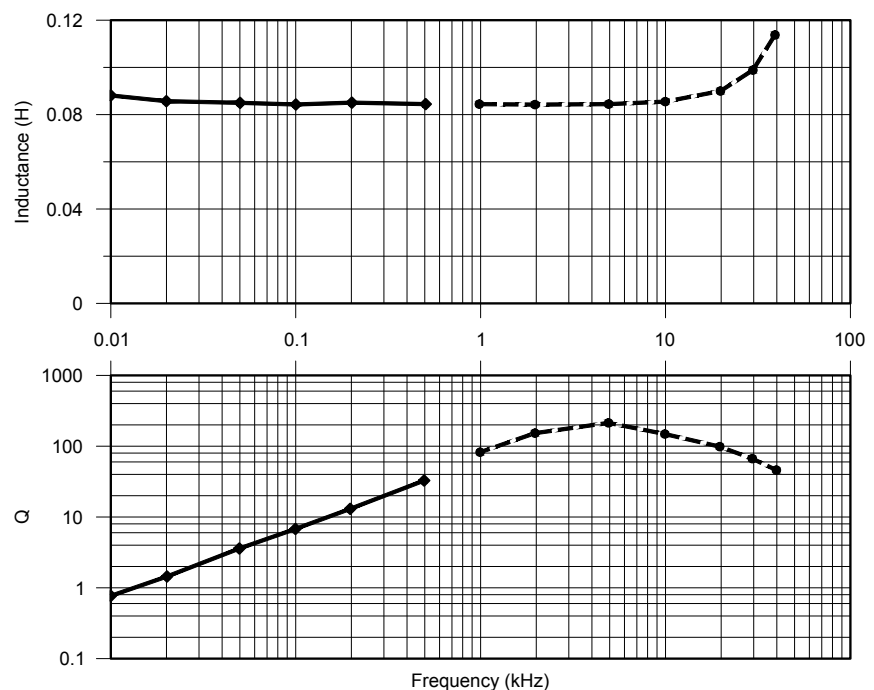
Getting back to finding the measured impedance, the complex voltages from the measurement and reference channels are corrected for small amplitude and phase errors. Next the measured impedance complex value  $Z_m = R + jX$ , is found from the voltages by

$$Z_m = R \frac{V_m}{V_r - V_m}$$

That is, the complex voltage across

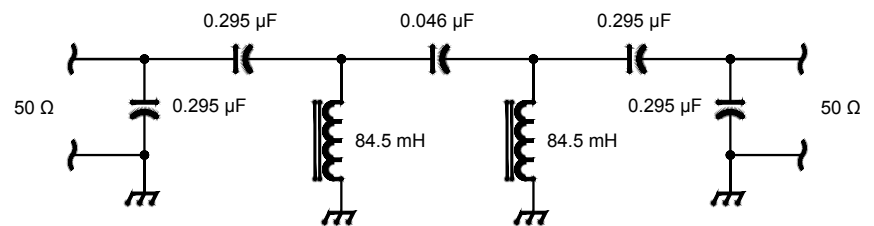
the reference resistor is proportional to the complex current flowing through it. The unknown impedance is then the complex voltage across the unknown, divided by the current. This is the total impedance across the measurement point and includes the components at the input to the amplifier. The input circuitry needs to be de-embedded mathematically. The input components,  $R1$ ,  $C1$ , the input stray capacity, lead inductance and lead resistance are all compensated for. These values remain relatively fixed with a particular measurement configuration, so the AVNA needs no procedure for automatically calibrating these values. If needed, they can be changed by commands from a PC.

The DSP functions described here are all part of the Arduino sketch using the Teensy audio library. This hides away many of the bookkeeping details of grouping ADC input samples into blocks and having the data blocks handled in the proper order. The necessary data hooks are all available to interface with conventional Arduino C++ functions. In addition, the hardware floating-point operations are all available to the sketch. In some places, it is useful to have full double-precision calculations. For this, slower software routines are all available. The Arduino development environment remains conventional for all of this. It has proven to be a convenient and powerful set of tools.



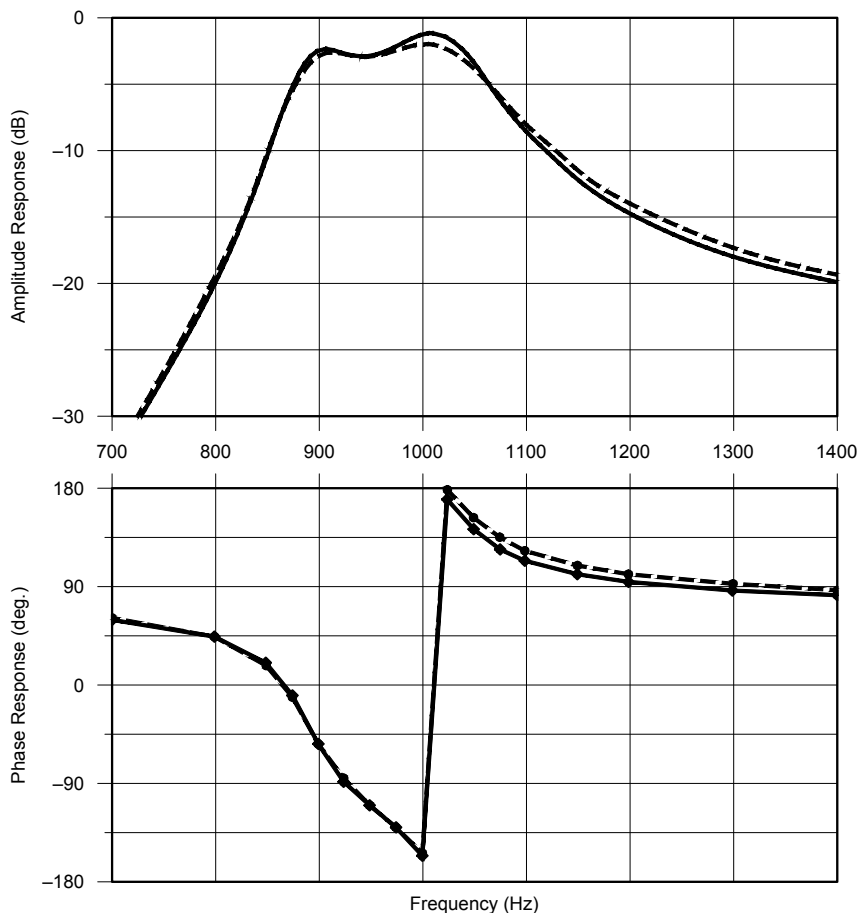
QX1805-Larkin08

Figure 8 — Measurements of the inductance and Q of an 88 mH inductor below 1,000 Hz were made with a 50 Ω reference resistor, while the higher frequency measurement used the 5 kΩ reference. The rise in apparent inductance above 10 kHz is attributed to the shunt capacitance of the inductor.



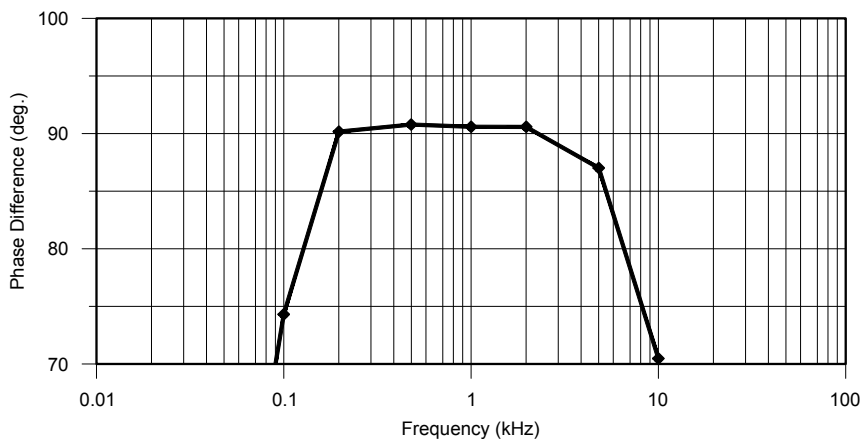
QX1805-Larkin09

Figure 9 — Schematic of a double-tuned filter test piece designed around available components.



QX1805-Larkin10

**Figure 10** — The amplitude and phase response for the 2-inductor filter of Figure 9. The dashed line shows the computer-predicted response, based on the measured inductor impedance. The solid line shows the AVNA measured response of the completed filter.



QX1805-Larkin11

**Figure 11** — The transmission function was used to measure the response of a Mini-R2 phasing receiver. Separate measurements were made of the phase-shift of the two receiver channels, and the difference is shown here.

## Control of the AVNA

A large part of the Teensy program is devoted to control functions. This is done twice since control from the touch-screen and from a PC via the serial connection are usually different in detail. For direct display, the emphasis is on convenience of making measurements. This limits the options somewhat, as does the size of the display. The serial control is intended to work with a program in a PC and thus flexibility is important.

With touch-screen control, a measured impedance can be displayed in a number of ways:

- Series resistance and reactance ( $R$  and  $X$ )
- Series inductance or capacitance, and  $Q$
- Parallel resistance and reactance
- Parallel inductance or capacitance, and  $Q$ .

The best choice depends on the component being measured and the application. There are always six annotated buttons at the bottom of the display to control functions.

For transmission measurements the touch-screen display shows gain both as a voltage ratio and in dB, along with the phase shift in degrees.

In addition to measuring components at a single predetermined frequency, a 13-frequency broad-band sweep is always available. This covers 10 Hz to 40 kHz in 1-2-5 steps, see points in Figure 8. There is sufficient touch-screen space for 7 results, which can be scrolled to cover any of the 13 frequencies. This same sweep is also available for transmission measurements.

Available only from touch-screen is a “What?” function that does two impedance sweeps with 50 and 5 k $\Omega$  references. An estimate of the measurement quality is made by the observed impedance magnitude. For the best quality measurement the component value, such as “ $L = 2.5$  mH  $Q = 8.6$ ”, is displayed. In addition, a rough quality estimate is given in terms of excellent, good, poor and no value. For many purposes, this gives a quick evaluation of components with minimal setup.

The control from a PC uses about 25 commands. A typical command is “FREQ 1251” that sets the generator and detectors to 1251 Hz.

## Impedance Measurement Accuracy

Standard components to measure against are a perfect way to check for accuracy. Ideally one should have a bag full of 0.1%  $R$ ,  $L$  and  $C$  components. For most of us, this is not the case, especially for  $L$  and  $C$  parts where the best tolerances available at experimenter prices are about 2% for  $L$  and 1% for  $C$ . At mid-range component values,



the precision of this AVNA is better than the accuracy of these available comparison  $L$  and  $C$  values. This leads to a conclusion that impedance measurements done with this instrument are probably better than the available reference parts. This instrument topology fundamentally references reactance measurement back to a single resistor. Resistors with 0.1% or 0.05% tolerance are readily available, and also many people have access to a high accuracy Digital Voltmeter-Ohmmeter. The AVNA part list has the 50.0 and 5,000.0  $\Omega$  resistors known to within 0.05%.

A first check of the final board was to measure resistance. I used the rule: measure impedances over the level of 500  $\Omega$  with the 5 k $\Omega$  reference and those below with the 50  $\Omega$  reference. The Table 1 results were obtained at 1,000 Hz.

The best accuracy is for values near the reference resistors. Accuracy analysis of the measurement circuit predicts that. The larger errors for measuring values are around a megohm, and may come from not having the proper compensating value in software for the R1 input resistor.

Moving to the next best known

component, the capacitor, we obtained the results in Table 2, at frequencies where the reactance was in the same order of 500  $\Omega$ . These capacitor measurements show the general range of errors around the central impedance ranges. The last measurement included subtracting the 1.3 pF that was showing with no component attached.

One area where it is useful to explore inductance measurements is for small coils at 40 kHz. Here we have inductors that have Q-meter and RF network analyzer measurements. For example, 18 turns of #26 squeezed together on a T37-6 toroid shows 1.61  $\mu\text{H}$  at 7.9 MHz on a Boonton Radio 260-A Q-meter, and 1.59  $\mu\text{H}$  at 40 kHz with an N2PK VNA. At 40 kHz this inductor measured 1.65  $\mu\text{H}$  using the AVNA.

One final accuracy test example is a 0.47  $\mu\text{F}$ , 1% capacitor in series with a 5,000  $\Omega$ , 0.05% resistor. At 500 Hz, this measures 0.4769  $\mu\text{F}$  in series with a 4998  $\Omega$  resistor, in good agreement with the separate measurements.

### Transmission Accuracy

The calibration for transmission measurements involves two steps. First, the measurement and reference channels are made to track by comparing their response with the inputs tied together by the “Calibrate” switch U4B. Next, the transmission path is normalized for external components by doing transmission measurements with a through-path in place. Amplitude and phase values are stored for later forming of ratios and subtractions.

As a quick check on transmission, a re-measurement was done with the through-path still in place. This typically shows amplitudes between 0.9999 and 1.0001 and phase errors around 0.02°, which is the noise in the system.

A simple  $RC$  circuit, consisting of a series resistor followed by a capacitor to ground, was used to test the transmission path. An external 5,000  $\Omega$ , 0.05% resistor was in series with the internal 50  $\Omega$  source resistor. A 0.02  $\mu\text{F}$ , 1% capacitor was connected across the high- $Z$  measurement port. The response of this circuit can be easily calculated to allow a comparison with the measured values. The most telling measurement is probably the phase shift around the 45° phase shift point of 1576 Hz (for exact component values). The calculated and measured phase shifts differed by 0.14° at 1,000 and 2,000 Hz, and could be fully matched by changing the calculated capacitor to 0.019905  $\mu\text{F}$ . The capacitor value difference is about 0.5%, which seemed reasonable.

A limiting factor for transmission measurements is the noise floor and transmission feed-through. These cause an



Figure 12 — The AVNA screen shows the result of using the “What?” function to determine the best measurement of a Pi inductor marked as 50  $\mu\text{H}$ , using the 50  $\Omega$  and 5 k $\Omega$  reference resistors. The quality grade is shown on the right edge, with “E” meaning excellent, and “P” for poor. The value of this inductor allows it to have excellent quality with 50  $\Omega$  and at 40 kHz. Other quality grades are “G” for good and “O” for don’t use.

Table 1

Measured resistor	AVNA value	Difference	Difference
10.000 $\pm$ 0.005 $\Omega$	9.975 $\Omega$	-0.025 $\Omega$	-0.250%
50.000 $\pm$ 0.025 $\Omega$	50.018 $\Omega$	+0.018 $\Omega$	+0.036%
100.00 $\pm$ 0.05 $\Omega$	99.90 $\Omega$	-0.10 $\Omega$	-0.100%
5,000.00 $\pm$ 0.25 $\Omega$	4998.7 $\Omega$	-1.3 $\Omega$	-0.026%
20,000.0 $\pm$ 10 $\Omega$	19918 $\Omega$	-82 $\Omega$	-0.410%
100.0 k $\pm$ 50 $\Omega$	99330 $\Omega$	-670 $\Omega$	-0.670%
1.00 M $\pm$ 500 $\Omega$	973,000 $\Omega$	-27,000 $\Omega$	-2.70%

Table 2

Ref R $\Omega$	Frequency	Capacitor	Measured	Difference	Difference
5 k $\Omega$	500 Hz	0.470 $\pm$ 0.0047 $\mu\text{F}$	0.4715 $\mu\text{F}$	+0.0015 $\mu\text{F}$	+0.32%
50 $\Omega$	500 Hz	0.470 $\pm$ 0.0047 $\mu\text{F}$	0.4684 $\mu\text{F}$	-0.0016 $\mu\text{F}$	-0.34%
5 k $\Omega$	200 Hz	0.940 $\pm$ 0.0094 $\mu\text{F}$	0.9442 $\mu\text{F}$	+0.0042 $\mu\text{F}$	+0.45%
50 $\Omega$	200 Hz	0.940 $\pm$ 0.0094 $\mu\text{F}$	0.9265 $\mu\text{F}$	-0.0135 $\mu\text{F}$	-1.44%
50 $\Omega$	2,000 Hz	0.01 $\pm$ 0.0001 $\mu\text{F}$	0.00993 $\mu\text{F}$	-0.00007 $\mu\text{F}$	-0.70%
5 k $\Omega$	2,000 Hz	0.01 $\pm$ 0.0001 $\mu\text{F}$	0.00999 $\mu\text{F}$	-0.00001 $\mu\text{F}$	-0.10%
5 k $\Omega$	40,000 Hz	100.0 $\pm$ 1.0 pF	99.5 pF	-0.5 pF	-0.50%

apparent output when no input is applied. Figure 6 is a swept plot with the input shunted by 50 Ω. Noise limits the dynamic range to about 75 dB up to about 2,000 Hz. At higher frequencies, signal leakage is seen, and at 40 kHz, about 55 dB of range is available.

If the input is left without a shunt resistor, the leakage through the capacitance of the “Calibrate” switch is the limiting factor at 200 Hz and above. At 20 to 40 kHz, this signal is within 20 dB of a direct connection. A more elaborate switch arrangement would avoid this problem. However, for most transmission applications the measurement port will be either driven by a low impedance, or can be terminated by 50 Ω, removing the issue.

In summary, the ADCs on the audio adapter board are extremely linear. The DSP-based *I-Q* mixers and the associated sine and cosine generators are very accurate. This results in amplitude and phase measurements that do not limit the impedance or transmission measurements, except when the levels are 60 or 70 dB down, which is low enough to make noise a factor. For impedance measurements, this puts the limitations on the analog circuitry. Here uncertainty of the reference

resistors is limiting for the middle range of resistance and reactance values, perhaps for 1 to 100 kΩ. Outside this range noise and ADC resolution become issues, but still allow useful measurements from about 0.1 Ω to 1.0 MΩ. Transmission measurements, for most applications, are limited only by the noise floor.

### Applications

The real fun of a project like this is performing measurements. Here are the steps to make these measurements in 1-2-3 fashion.

- 1 — Apply the 5 V, and a greeting screen appears.
- 2 — Touch “Set Ref R” and select “5K”. Touch “Back”.
- 3 — Touch “Single Freq” a frequency selection screen appears.
- 4 — Touch “Freq Up” until “Freq = 2,000 Hz” appears.
- 5 — Connect the component to the terminals, in our case a 0.02 μF capacitor.
- 6 — Touch “Meas Z” causing an automatic calibration and measurement.
- 7 — The screen of Figure 7 shows a series measurement of 20.01 nF (0.02001 μF) with a *Q* of 1845.9.

---

## Series and Parallel Components

The AVNA displays impedances in two forms, a series resistance and reactance, as well as a parallel resistance and reactance. The reactance can represent either an inductance or a capacitance. Any impedance can be represented as either a series or as a parallel combination. Measured externally, they are indistinguishable.

For some purposes, it is easiest to think of the inductor and resistor in series. Actually, resistance is distributed through the inductor, so neither model is precise physically. A contrasting example is a resistor that has a parallel capacitance. For this case, the series resistance and capacitance is valid, but not generally as useful as the parallel model.

What may be surprising at first glance is that the component values depend on whether they are considered in series or parallel. By example, suppose we have an inductor at a frequency where the series reactance  $X_s$  is 100 Ω. Furthermore, let the *Q* be 5 so that the series resistance  $R_s$  is 100/5 or 20 Ω. In complex arithmetic, the series connection for the impedance *Z* is:

$$Z = 20 + j100.$$

For the parallel model, we first need to find the admittance that is the inverse of the impedance. In our example, the admittance *Y* is:

$$Y = 1/Z = 1 / (20 + j100)$$

After some manipulation we find:

$$Y = (20/10400) - j(100/10400).$$

From this form we can get the parallel component conductance and susceptance that we are looking for by inverting real part of *Y*, the conductance, to get the equivalent parallel resistance:

$$R_p = 10400/20 = 520 \Omega,$$

and taking the imaginary part of  $1/(-j(100/10400))$ , the susceptance, to get the equivalent parallel reactance:

$$X_p = 10400/(100) = 104 \Omega.$$

The series resistance was 20 Ω, and the parallel resistance is 520 Ω. [Notice that  $Q = X_s/R_s = R_p/X_p = 5$  remains invariant.— *Ed.*] Perhaps surprising is that the apparent inductive reactance has changed from 100 to 104 Ω. As noted, this shift in apparent inductance diminishes as the *Q* increases. The AVNA displays these values using this same arithmetic.

There is more data on the screen. It shows a series resistance of 2.155 Ω, and also component values that are marked “Par” for parallel. This means that at 2,000 Hz, the effect of a 7.342 MΩ resistor in parallel with our capacitor is indistinguishable from the series 2.155 Ω value. Both answers are correct. For lower *Q* capacitors (or inductors) the capacity value will be different for the parallel model than it is for the series model, see the sidebar, “Series and Parallel Components”. The number of digits of resolution should not be used as an indicator of accuracy. However, there are instances where the extra resolution is useful for observing differences of components.

Let’s design an *LC* audio filter using an old inductor component as a basis. The 88 mH toroidal inductors were used in huge quantities by telephone companies. Ray Cannon, W7GLF, gave me a few for this design. Step 1: characterize the inductor. Impedance measurements were made with the 50 and 5 kΩ reference resistors. At the frequency extremes, which are also the impedance extremes, the measured results differed. In the central region from around 100 to 5,000 Hz, the results were very similar. The final data was selected by using the 50 Ω reference for impedances below about 500 Ω (up to 500 Hz) and the 5 kΩ reference data for the higher impedance levels (above 500 Hz). Figure 8 shows the measured inductance and *Q*. The inductance for lower frequencies was about 84.5 mH. The rising inductance at the higher frequencies is a normal result of the inductance approaching its parallel resonant point. The *Q* has a distinct peak around 5,000 Hz, as is normal. In the audio range, the *Q* is lower, but adequate for filter design.

A top coupled filter<sup>14</sup> was designed as shown in Figure 9. This design includes small alterations to use available capacitors that were measured with the AVNA. The *ARRL Radio Designer* program was used to predict the network behavior. Instead of describing the toroids by a single inductance and *Q*, the 88 mH toroid was entered as a table of measured impedances, converted to reflection coefficients.

The filter was built up with free-form construction and tested between 50 Ω terminations using the AVNA “Transmission” function. Figure 10 shows both the predicted and measured insertion loss and insertion phase. The exact response is not the feature to look for, but rather the differences between the predicted and measured values. This is one validation of the full AVNA accuracy, as it is built on the ability to measure both the component impedances and the transmission amplitude and phase. The curves show very tight agreement below 950 Hz and adequate agreement above that frequency. The largest

discrepancy is the predicted loss (dashed) at 1,000 Hz, 0.75 dB less than that measured (solid). Speculation is that errors in inductor  $Q$  measurement may be a factor here, as high- $Q$  values can be difficult to measure.

Another application is the measurement of the active phase shift network for a direct conversion receiver. In addition to use as a

design aid, this could have value in troubleshooting an  $I$ - $Q$  receiver or transmitter. The circuit tested was a mini-R2 receiver<sup>15</sup> designed by Richard Campbell, KK7B. The portion of the circuitry is from the mixer output, where audio first appears through the filtering and active phase shift networks. The circuit operates with two cascaded all-

pass networks arranged so that the difference between the two paths is close to 90° throughout the voice audio band.

For a simple experiment, the  $I$  and  $Q$  channels were measure in the transmission mode, doing a sweep over the standard 13 frequencies between 10 Hz and 40 kHz. The 13 frequencies are not enough to show all

## DSP Code in the Teensy Arduino

A collection of DSP-specific instructions are built into the ARM Cortex-M4 processor used in the Teensy 3.6. Accessing these can be tedious as many details involved. PJRC, with help from users, has produced an Arduino Audio software library that hides everything not normally used. This is all open software, and can be altered if needed.

Along with the library, there is a drag-and-drop graphical design tool to control the structure of the DSP processing. A simplified version of the measurement channel for the AVNA, as produced by the design tool, is in Figure 13.

The names are assigned automatically, and need translation into AVNA terms. For instance, “waveform 1” is the sine wave generator and “waveform 2” is the sine wave generator shifted 90° (a cosine wave). The “queue” blocks transfer data from the time critical DSP processing to the conventional processing. The *i2s1* output is the DAC.

Part of this same design tool is a code generator that created the code in Table A. The names, such as *AudioInput2S* (the ADC converter), are C++ objects that are part of the library. Names such as “*audioInput*” are instances of these objects, and as can be seen, there can be many instances for any object. The “*AudioConnection*” objects appear as connecting lines in the design tool. They do much more than a simple line would suggest. They control the order that computations will occur, thus they make sure that delays are provided as needed. In addition, for efficiency reasons, all of this DSP is done in blocks, typically 128 long. This requires memory arrays to store data at various points, and this storage is allocated automatically.

In practice, very few lines of the Arduino sketch (program) are used for DSP. A 1,000 Hz sine wave generator is created by the code in Table B. It will compute sine waves at the chosen sample rate until changed. Follow on steps, such as the multipliers, require no instructions once they have their instances declared.

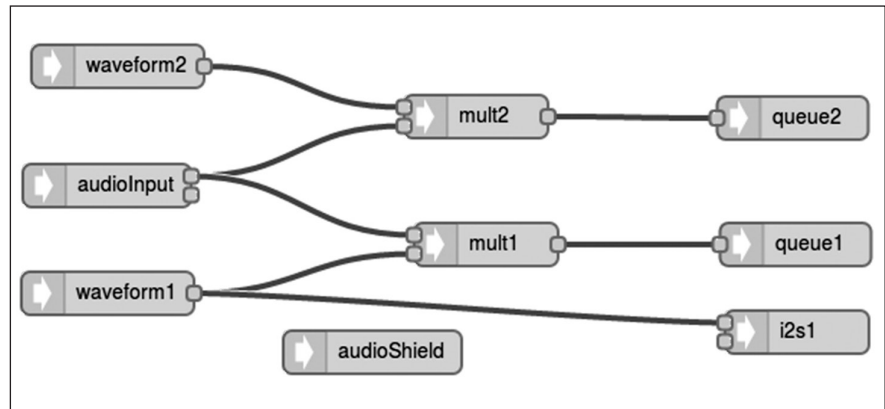


Figure 13 — The graphical DSP description produced by the PJRC design tool.

Table A. DSP Code for describing the block diagram of Figure 13.

```
// GUItool: begin automatically generated code
AudioInput2S          audioInput;           //xy=76.5,247
AudioSynthWaveform   waveform1;           //xy=77,322
AudioSynthWaveform   waveform2;           //xy=84,164
AudioEffectMultiply   mult2;               //xy=333,199
AudioEffectMultiply   mult1;               //xy=340,288
AudioRecordQueue     queue2;               //xy=553,200
AudioRecordQueue     queue1;               //xy=555,288
AudioOutput2S        i2s1;                 //xy=556,349
AudioConnection      patchCord1(audioInput, 0, mult2, 1);
AudioConnection      patchCord2(audioInput, 0, mult1, 0);
AudioConnection      patchCord3(waveform1, 0, mult1, 1);
AudioConnection      patchCord4(waveform1, 0, i2s1, 0);
AudioConnection      patchCord5(waveform2, 0, mult2, 0);
AudioConnection      patchCord6(mult2, queue2);
AudioConnection      patchCord7(mult1, queue1);
AudioControlSGTL5,000 audioShield; //xy=261,363
// GUItool: end automatically generated code
```

Table B. for generating a 1000 Hz sine wave.

```
waveform1.begin(WAVEFORM_SINE);
waveform1.frequency(1,000.0);
waveform1.amplitude(1.0);
waveform1.phase(0.0);
```

Table C. for finding RMS amplitude.

```
amplitudeMeas = sqrt(aveIm * aveIm + aveQm * aveQm);
```

Non-standard computations, such as finding the amplitude of each channels is done by operating on the integer data from *queue1* and *queue2*. This can be operated on as integers, floating point variables, or double precision floating point, as required.

For instance the amplitude is found from the averages of  $I$  and  $Q$  by the code line in Table C, where in this case all variables are double precision. As can be seen, the DSP code writing has been made very accessible.

the subtle detail but it is quite adequate for trouble-shooting. 500, 1,000 and 2,000 Hz are well inside the design phase-shift region and 200 Hz is close to the region. The measurement needed to allow for the 40 dB gain of the amplifier that precedes the phase shift networks. A 50  $\Omega$  attenuator was placed at the two parallel connected mixer outputs in the Mini-R2. The mixers had no LO connection and so as far as affecting the 10 mV level signals, they didn't exist.

Before connecting the signal source to the attenuator, the AVNA was set to transmission measurements using the 50  $\Omega$  source resistor. This was done over the serial control line so that the output data could be retrieved directly to the PC. Data plotting was done with a *Gnumeric* spread sheet program. Calibration was also under PC control, which is simple since the 13 frequencies are calibrated as a group. Following calibration, swept transmission measurements were made for both channels of the receiver and taken from the serial terminal in the PC.

Omitting the various steps to process the data in the spread sheet, the difference in the phase shifts of the *I* and *Q* channels was calculated by taking the difference in the phase measurements. Figure 11 shows the results. The three in-band frequencies are within 0.7° of the ideal 90°, constituting a vote of confidence for both the receiver and the AVNA! Not shown is the ratio of amplitude measurements for *I* and *Q*, but all three in-band frequencies had ratios within 0.1 dB. Most of this is correctable with the trimmer pot leaving an uncorrected ratio of only 0.03 dB.

Under PC control, the AVNA can measure at any number of frequencies, not just the stored 13. For circuits such as these phase shift networks it could be useful to place 50 or more data points in the 200 to 5,000 Hz range. When using serial control, there is also provision for uncorrected measurements, meaning that all calibration can be done in the PC control program. This is convenient as it allows all calibration

to be done first, and then any number of measurements later, the same as is done in the AVNA for the simple sweep.

Finally, the "What?" function is shown in Figure 12 with a 50  $\mu$ H inductor measuring 49.24  $\mu$ H.

### Summary and Acknowledgment

This project provides high accuracy impedance and transmission measurements throughout the audio frequency range. It can be used either as a standalone measurement instrument or under PC control as a controllable measuring head. The analog portion of the project is on a home-built printed circuit board. The Teensy 3.6 board, audio CODEC adapter, and Touch Display can all be purchased assembled.

For impedance measurements, the approximate range for highest accuracy is impedance levels from 5 to 50 k $\Omega$ . With a frequency range of 10 to 40,000 Hz, this covers resistors from 5 to 50 k $\Omega$ , inductors from 20  $\mu$ H to 800 H, and capacitors from 80 pF to 3,000  $\mu$ F.

Measurements of a tenth to ten times these values are reliable and of good quality. Beyond that point, some measurements are still quite useful. In particular, capacitors less than 8 pF can be measured at 40 kHz by observing the residual capacity with no component attached, and subtracting that value. Transmission measurements of gain and loss cover a 50 to 70 dB dynamic range, and include both amplitude and phase.

Major credit goes to Paul Stoffregen at PJRC and the many contributors to the Teensy family of boards and software. In addition, this project benefited from hardware, ideas and reviews by Russ Carpenter, AA7QU; Johan Forrer, KC7WW; Jimmy Oldaker, W7CQ; Larry Liljequist, W7SZ; Ray Cannon, W7GLF; and Mike Reed, KD7TS.

*Bob Larkin, W7PUA, has been active in Amateur Radio since he was first licensed in 1951 as WN7PUA. He received a BSEE from the University of Washington and an MSEE from New York University. He is retired from a career in electronic circuit and system design along with work in analog and digital signal processing. He continues an interest in Amateur Radio applications in these areas, as well as boat building and sailing.*

### Notes

- <sup>1</sup>Information on the N2PK 50 kHz to 60 MHz VNA, [n2pk.com/#TP1](http://n2pk.com/#TP1).
- <sup>2</sup>T. C. Baier, DG8SAQ, "A Low Budget Vector Network Analyzer for AF to UHF," *QEX* Mar./Apr. 2007, pp. 46-54; and, "A Small, Simple, USB-Powered Vector Network Analyzer Covering 1 kHz to 1.3 GHz," *QEX* Jan./Feb. 2009, pp. 32-36.
- <sup>3</sup>G. R. Steber, WB9LVI, "A Low Cost Automatic Impedance Bridge," *QST* Oct. 2005, pp. 36-39; and, "LMS Impedance Bridge," *QEX*, Sep./Oct. 2005, pp. 41-47.
- <sup>4</sup>J. Audet, VE2AZX, "A Low Frequency Adapter for your Vector Network Analyzer," *QEX* Jan./Feb. 2015, pp. 10-16.
- <sup>5</sup>See <https://www.pjrc.com/store/teensy36.html>.
- <sup>6</sup>See [https://www.pjrc.com/store/display\\_ili9341\\_touch.html](https://www.pjrc.com/store/display_ili9341_touch.html).
- <sup>7</sup>PCB is available in KiCad format. Boards can be ordered in multiples of 3 from OSH Park company, [https://www.oshpark.com/shared\\_projects/BjMLw9B9](https://www.oshpark.com/shared_projects/BjMLw9B9).
- <sup>8</sup>All project hardware and software files are open source and available from [www.arrrl.org/qexfiles](http://www.arrrl.org/qexfiles). For additional information see [www.janbob.com/electron/AVNA1/AVNA1.htm](http://www.janbob.com/electron/AVNA1/AVNA1.htm).
- <sup>9</sup>See <https://www.arduino.cc/en/Main/Software> for Arduino Integrated Development Environment (IDE) that can be extended to handle the Teensy boards.
- <sup>10</sup>See <https://www.pjrc.com/teensy/teensy-duino.html> for extensions to use with the Arduino IDE.
- <sup>11</sup>See [n2pk.com/VNA/RFIV\\_Single\\_%20Detector\\_Switch\\_%20and\\_%20Sensors\\_V1c.pdf](http://n2pk.com/VNA/RFIV_Single_%20Detector_Switch_%20and_%20Sensors_V1c.pdf).
- <sup>12</sup>See [https://www.pjrc.com/store/teensy3\\_audio.html](https://www.pjrc.com/store/teensy3_audio.html).
- <sup>13</sup>See <https://www.arduino.cc/en/main/arduinoBoardUno>.
- <sup>14</sup>Designing double-tuned LC filters, Section 3.3 in W. Hayward, W7ZOI, R. Campbell, KK7B and R. Larkin, W7PUA, *Experimental Methods in RF Design*, ARRL publication No. 9239, available from your local ARRL dealer or from the ARRL Bookstore. Telephone toll free in the US: 888-277-5289 or call 860-594-0355, fax 860-594-0303; [www.arrrl.org/shop](http://www.arrrl.org/shop); [pub-sales@arrrl.org](mailto:pub-sales@arrrl.org).
- <sup>15</sup>The Mini-R2 receiver by KK7B, Section 9.9, *Experimental Methods in RF Design*, op. cit.