QEX

November/December 2021

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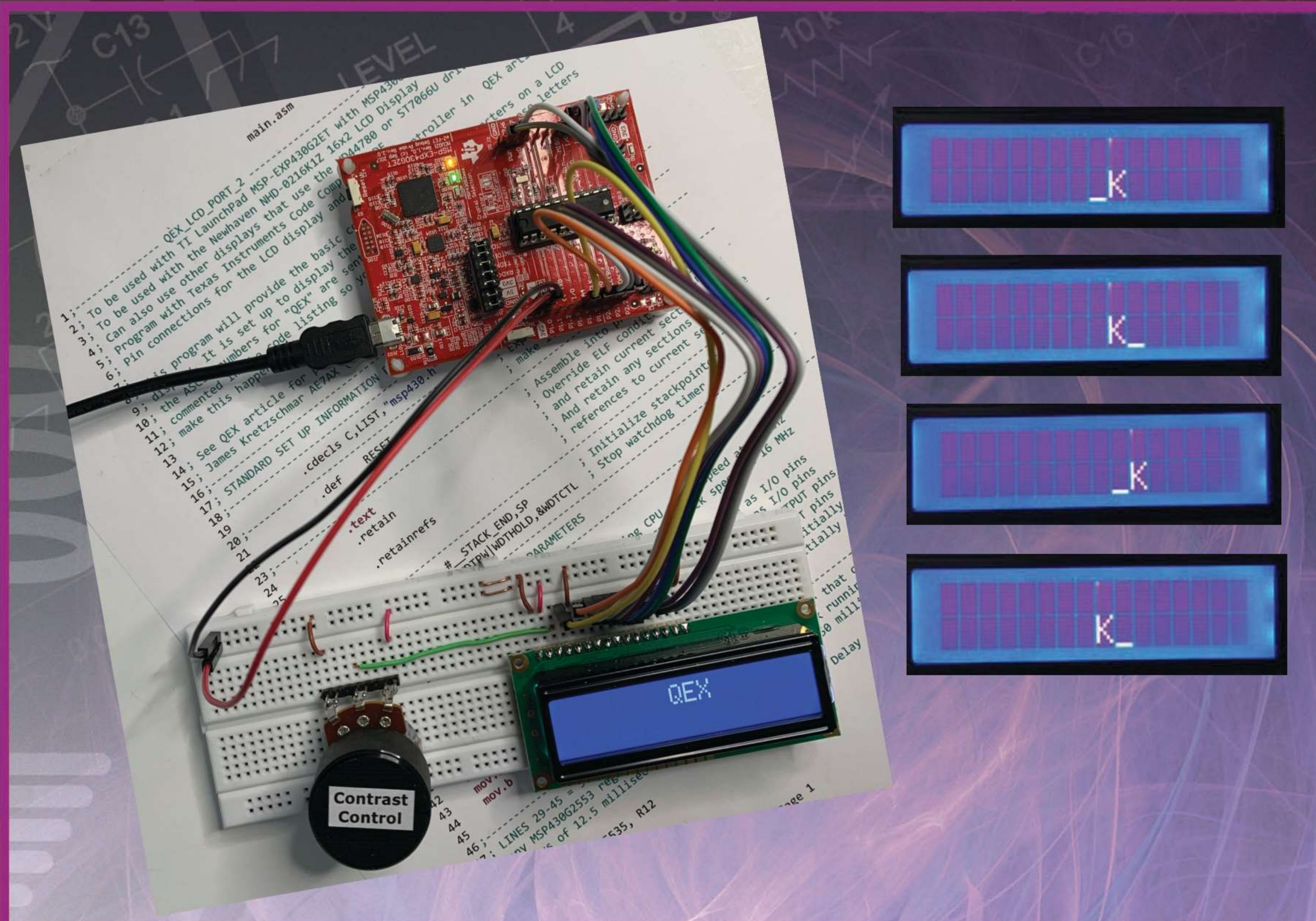
A Forum for Communications Experimenters

Issue No. 329



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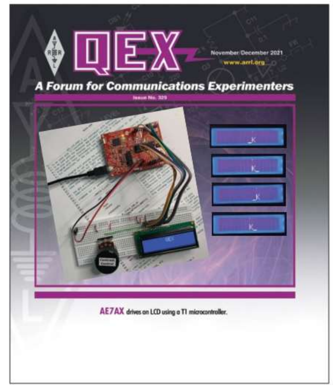
About the Cover

James Kretzschmar, AE7AX, describes how to display data on a liquid crystal display (LCD). A Texas Instruments MSP430G2553 microcontroller controls the Newhaven NHD-0216H1Z LCD 16 by 2 LCD with the your custom programming. AE7AX discusses five commands in detail: (1) clear the display, (2) display control, (3) display shift, (4) entry mode, and (5) setting of the character position DDRAM address. One example program sets up the LCD to display the letters "QEX". Another example program provides a practical application using one of the analog-to-digital (ADC) channels on the MSP430G2553 microcontroller to sample a position sensor and display the digital number on the LCD.



In This Issue

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The purpose of *QEX* is to:

1) provide a medium for the exchange of ideas and information among Amateur Radio experimenters,

2) document advanced technical work in the Amateur Radio field, and

3) support efforts to advance the state of the Amateur Radio art.

All correspondence concerning *QEX* should be addressed to the American Radio Relay League, 225 Main St., Newington, CT 06111 USA. Envelopes containing manuscripts and letters for publication in *QEX* should be marked Editor, *QEX*.

Both theoretical and practical technical articles are welcomed. Manuscripts should be submitted in word-processor format, if possible. We can redraw any figures as long as their content is clear. Photos should be glossy, color or black-and-white prints of at least the size they are to appear in *QEX* or high-resolution digital images (300 dots per inch or higher at the printed size). Further information for authors can be found on the Web at **www.arrl.org/qex/** or by e-mail to **qex@arrl.org**.

Kazimierz "Kai" Siwiak, KE4PT

Perspectives

Like a Science Fiction Movie – a Year On

It has been more than a year since we quoted actor Robert De Niro, "*Kind of like a science fiction movie, but it's real*." After more than two years we still awaken to an eerily different world, one where things are still in a fog, still unsettled and still unnatural. Words like *social distancing*, *masks*, *lock-down* and *stay-at-home* are now solidly locked into our vocabulary, joined now with *Zoom*, *jab* and *vaccination*. These words and phrases speak to the promise of ending the pandemic. We have all the necessary tools, if only we would follow the science.

Ham club meetings are still held online or over ham FM repeaters. By their very nature, ham radio *operations* are distancing events, and have been for more than a century. As such they remain "pandemic proof." Slowly the camaraderie of face-to-face interaction is returning. It's also a good time for our members to catch up on and enjoy the mental stimulation of *QEX* and other ARRL publications. Stay safe!

In This Issue

- James Kretzschmar, AE7AX, controls a 16x2 LCD display with a TI microcontroller.
- Andrew Anderson, WQ1S/VK3CV, uses the 30 THz band as a communications medium.
- George Steber, WB9LVI, describes his SSB receiver based on the Silicon Labs Si4732-A10 IC.
- Tom Alldread, VA7TA, describes a tweezers probe for measuring SMD components.
- Eric Nichols, KL7AJ, in his Essay Series, describes maximum power transfer.
- Larry Lamano, WAØQZY, builds a pulse generator for making TDR measurements.

Writing for *QEX*

Please continue to send in full-length *QEX* articles, or share a **Technical Note** of several hundred words in length plus a figure or two. *QEX* is edited by Kazimierz "Kai" Siwiak, KE4PT, (**ksiwiak@arrl.org**) and is published bimonthly. *QEX* is a forum for the free exchange of ideas among communications experimenters. All members can access digital editions of all four ARRL magazines: *QST*, *On the Air, QEX*, and *NCJ* as a member benefit. The *QEX* printed edition is available at an annual subscription rate (6 issues per year) for members and non-members, see **www.arrl.org/qex**.

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Very kindest regards,
Kazimierz "Kai" Siwiak, KE4PT
QEX Editor

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Controlling a 16x2 LCD with the Texas Instruments MSP430G2553 Microcontroller

Display your data with your own custom programmed LCD.

Many projects sense or analyze data that needs to be displayed (**Figure 1**). LCDs are very common and inexpensive, however, incorporating the display into a project can be difficult. For example, a project may have particular data, as in the schematic of **Figure 2**, to display at a particular line location (**Figure 3**), however, finding software to drive the LCD exactly for what is needed may be impossible. With a thorough understanding of how the LCD must be driven, it is possible to write your own software, and use an inexpensive microcontroller (MCU) to interface with the LCD.

This article describes how to interface a Texas Instruments MSP430G2553 microcontroller with the 16x2 Newhaven NHD-0216H1Z LCD. The TI MSP-EXP430G2ET Launchpad has the 20-pin PDIP MSP430G2553 microcontroller already installed on the board and is available for approximately $12.00 from several sources. Programming the MSP430G2553 microcontroller is accomplished with the Texas Instruments Integrated Development Environment (IDE) Code Composer Studio platform which is available for free on the Texas Instruments website **www.ti.com**. The 16x2 NHD-0216H1Z LCD is available on the Newhaven website **www.newhavendisplay.com** for approximately $12.00.

The 16x2 LCD receives data in parallel format (some LCDs receive data in serial format), and built into the LCD is the

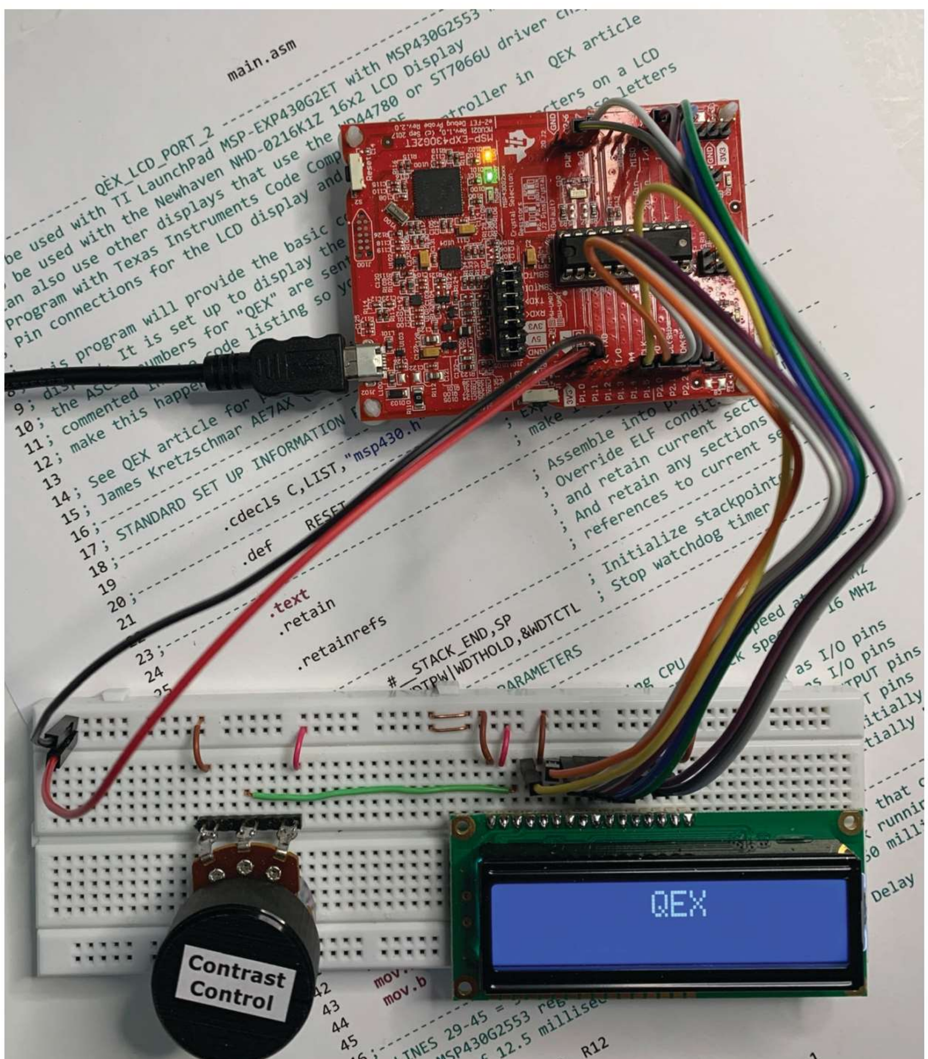


Figure 1 — TI MSP430G2553 and LCD.

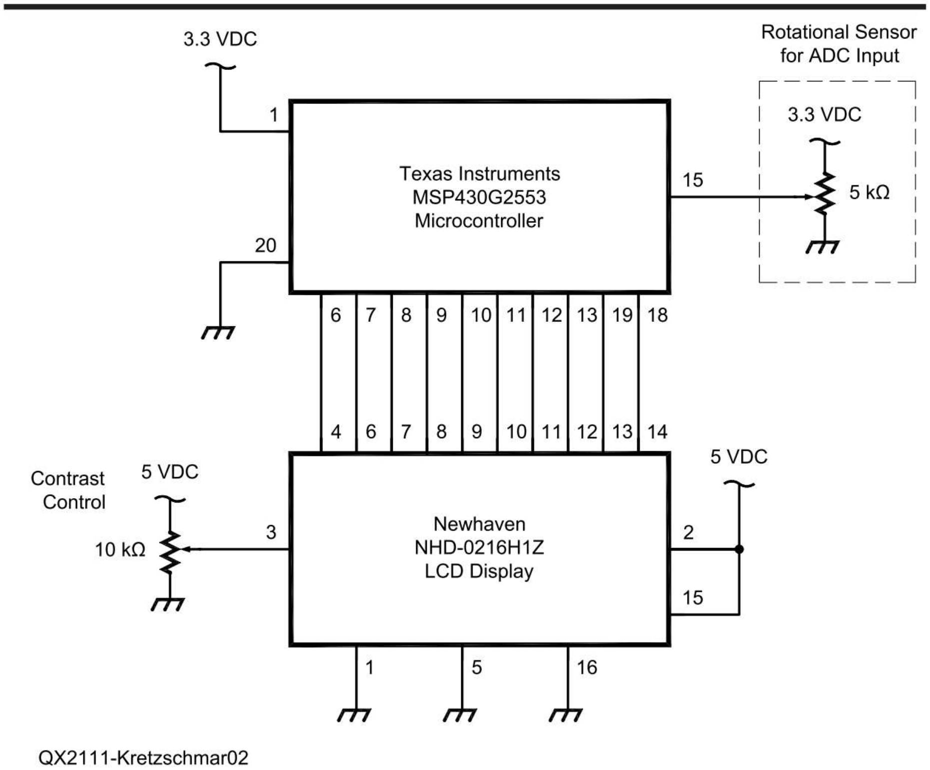


Figure 2 — LCD and microcontroller connections for the sensor used with Example Program #2.

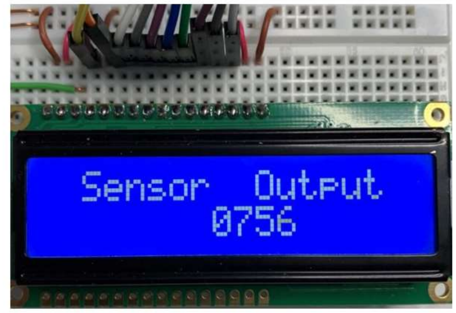


Figure 3 — LCD displaying sensor data.

Table 1 – Connections between LCD and MSP430G2553 MCU and contrast potentiometer.

LCD Pin Description	*LCD Pins*	*Connection*	*MSP430G2553 and Potentiometer Pins*
Ground	Pin #1	**CONNECT**	Pin #20 (Ground)
+5.0 V (from Launchpad)	Pin #2	**CONNECT**	Available on Launchpad
Contrast Control	Pin #3	**Potentiometer**	Middle terminal
R/S Register Select	Pin #4	**CONNECT**	Pin #6 (P1.4)
R/W Read - Write	Pin #5	**CONNECT**	Ground
Enable	Pin #6	**CONNECT**	Pin #7 (P1.5)
Data-0	Pin #7	**CONNECT**	Pin #8 (P2.0)
Data-1	Pin #8	**CONNECT**	Pin #9 (P2.1)
Data-2	Pin #9	**CONNECT**	Pin #10 (P2.2)
Data-3	Pin #10	**CONNECT**	Pin #11 (P2.3)
Data-4	Pin #11	**CONNECT**	Pin #12 (P2.4)
Data-5	Pin #12	**CONNECT**	Pin #13 (P2.5)
Data-6	Pin #13	**CONNECT**	Pin #19 (P2.6)
Data-7	Pin #14	**CONNECT**	Pin #18 (P2.7)
Backlight (+5.0 V)	Pin #15	**CONNECT**	Available on Launchpad
Backlight (Ground)	Pin #16	**CONNECT**	Ground

Table 2 – LCD Initialization steps.

Step#	*Step detail*	*Comments*
1	Power Applied to LCD	
2	Delay more than 40 ms	(example program code gives it 50 ms)
3	Special Function Command is sent	#00110000b (Hex Number #0x30)
4	Delay more than 4.1 ms	(example program code gives it 5 ms)
5	Special Function Command sent again	#00110000b
6	Delay more than 37 µs	(example program code gives it 100 µs)
7	Special Function Command sent again	#00110000b
8	Delay more than 37 µs	(example program code gives it 100 µs)

ST1066 driver chip, which accepts data in 8-bit or 4-bit packages. When learning the operation and how to control a LCD, the 8-bit mode is easier to understand, set up, and program and will be the mode discussed. The disadvantage of using the 8-bit mode is that it uses more pins on the microcontroller that could otherwise be used for another purpose.

Accompanying this article are two example programs that are available in **www.arrl.org/QEXfiles** web page. Both programs are written in assembly code and heavily commented so that the reader can understand the flow of the programming. The first example program displays the letters 'QEX' and the second example program displays the reading from a rotational sensor. Also available in **QEXfiles** is a guide for navigating around the Texas Instruments Code Composer Studio IDE.

Connections Between the LCD and MSP430G2553

The MSP430G2553 microcontroller has 16 pins that can be used as input/output pins, 8 pins on Port 1, and 8 pins on Port 2. Because we want to use the analog-to-digital module on the microcontroller for a demonstration of showing how data can be displayed, and the fact that many pins on the microcontroller are multiplexed (can be selected for other uses), selecting the 8 pins on Port 2 to transfer information into the LCD worked out the best. Notice in **Figure 4** that the 16-pin header pin connector could have been placed in one of two locations. **Table 1** lists the connections between the LCD and MSP430G2553 MCU.

Communicating with the NHD-0216K1Z

The NHD-0216K1Z LCD uses the ST7066U driver chip to control the device. It receives commands and data similarly to the HD44780 driver chip which was used in older model LCDs. The information presented in Table 2 is referenced from the ST7066U and HD44780 datasheets, both are available on the Newhaven website.

Before any COMMAND or DATA information can be sent, the LCD must go through a one time wake-up sequence, which involves sending a Special Function Command several times with appropriate delays as shown in **Table 2**.

In the example program code on the **QEXfiles** web page, the delays are loop routines based upon the microcontroller CPU clock set at 16 MHz. Instruction cycle time calculations and a microcontroller test program that generated calibration waveforms and viewable on an oscilloscope, were used to achieve the proper timing of the delay routines.

The LCD needs specific instructions delivered to it to make it function. Pin #4 of the LCD is the Register Select (R/S) pin. Placing a "0" (0 V) on Pin #4 tells the LCD to get ready because the next information you will receive will be a COMMAND telling it what to do (i.e. Clear Screen, Return to Home, etc.). Placing a "1" (+3.3 V) on Pin #4 tells the LCD to get ready because the next information you will receive will be DATA in the form of an ASCII number. Regardless of whether COMMAND information or DATA information is sent to the LCD the following steps must happen.

Steps for Command or Data entry into the LCD.

1. – LCD Pin #4 (Register Select) either brought "HIGH" or "LOW".
2. – Pin #6 (Enable) is brought "HIGH" (+3.3 V placed on Pin #6) for a minimum of 100 µs before a Command or Data is sent.
3. – Information (COMMAND or DATA) is sent to the LCD.
4. – Pin #6 (Enable) is brought "LOW" (0 V placed on Pin #6) for a minimum of 100 µs before program continues.

Sending a Command to the LCD

Commands can be sent to the LCD setting up such parameters as where on the display characters will appear, or which direction the next character will be displayed (i. e., left or right). For example, if you are displaying a word then the next character would appear on the right, however, if you were running a counter, then the next character may need to appear on the left as the count increases. Each setup command is followed by a 100 µs delay, however, the "Clear Display" command is followed with a 5 ms delay. This longer delay is needed because it takes longer to clear the DDRAM memory spaces.

Table 3 — List of Commands for the LCD. The * bits are ignored (make them a "0"in the program code); an option must be selected for the X bits .

Command	*Base Code*	*What Happens*
Clear Display	00000001b	Display is cleared
Cursor Home	0000001*b	Cursor goes home (00)
Entry Mode	000001XXb	How characters displayed
Display Control	00001XXXb	On/Off, Cursor, Blink
Cursor Display Shift	000100**b	Cursor Shift control
8-Bit or 4-Bit Setup	001XXX**b	8-Bit/4-Bit, 1 or 2 lines
CGRAM Setup	01XXXXXXb	Character Generator
Sets DDRAM Address	1XXXXXXXb	Sets DDRAM Address

Table 3 lists the command "base" code (the bit position for where a "1" is present). Five of the commands allow you to select options (where an "X" appears in the binary number). When options are selected, a "0" or a "1" is placed in the bit position, and added to the "base" number, this new number specifies a particular option.

For simplicity, only 5 commands will be discussed in detail: (1) Clear Display, (2) Display Control, (3) Display Shift, (4) Entry Mode, and (5) Setting of the Character Position Address (DDRAM address). The 3 remaining commands involve advanced display options and special character generation, and these options can be investigated if needed.

The 5 commands will be discussed in the following order: (1) Selection of 8-bit / 2 line mode, (2) Clear Display, (3) Setting of the DDRAM address where you want characters to be displayed, (4) Display Control, and (5) Display Shift (left or right). Each command will be detailed with pictures showing how the LCD responds.

Selection of 8 or 4-bit 1 or 2 line mode.

COMMAND: Selecting 8-Bit/4-Bit mode, 1 or 2 Lines (001XXX**b)

BIT-0 – Ignored (make = 0).

BIT-1 – Ignored (make = 0).

BIT-2 = 0 – Font of characters is 5x7 Dots (always select this option).

BIT-2 = 1 – Font of characters is 5x10 Dots (not common).

BIT-3 = 0 – Information displayed on 1 line.

BIT-3 = 1 – Information displayed on 2 lines (always select this option).

BIT-4 = 0 – Commands and Data sent in 4-bit format.

BIT-4 = 1 – Commands and Data sent in 8-bit format.

#00111000b selects 8-bit mode 2 line mode for entry of information. Inspect the example code listings to see how the binary number for this command is sent to the LCD. There is nothing displayed (**Figure 5**), but the LCD is set up for 8-bit / 2-line entry of information.

Figure 4 — Connections on the LCD.

Figure 5 — Selection of 8-bit / 2-line mode.

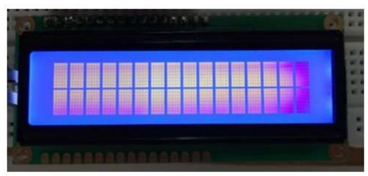


Figure 6 — Clear the display.

Clear Display

COMMAND: Clear Display (00000001b), clears display and places cursor at home position, the upper left position in **Figure 6**, DDRAM address 00). After this command a 5 ms or longer delay is needed.

Setting where you want the characters displayed

COMMAND: Sets DDRAM Address (1XXXXXXXb).

This instruction sets the position on the 16x2 LCD where the first character will be displayed. Arriving at the correct number to enter can be confusing, however, follow the example below. There are 32

(A)

(B)

Figure 7(A), 7(B) — Setting where you want the characters displayed.

possible DDRAM addresses (defined by a unique number for each location), see **Figure 7A**. To select a particular location, add the unique number to the base number (#10000000b) as shown in the DDRAM Addresses (Decimal Notation,) in **Table 4**:

For example, the letter "K" placed in DDRAM address 73:

[#10000000b = 128 (base number)] + [#01001001b = 73]

[128 + 73] = 201 Conversion to Binary = #11001001b, thus #**1**1001001b places "K" in DDRAM address 73, see **Figure 7B**.

Display Control

COMMAND: Display Control (0000**1**XXXb)

BIT-0 = 0 – Cursor Blinking OFF.

BIT-0 = 1 – Cursor Blinking ON.

BIT-1 = 0 – Cursor OFF.

BIT-1 = 1 – Cursor ON.

BIT-2 = 0 – Display OFF.

BIT-2 = 1 – Display ON.

#0000**1**000b Display OFF, Cursor OFF, Cursor Blinking OFF (**Figure 8A**).

#0000**1**100b Display ON, Cursor OFF, Cursor Blinking OFF (**Figure 8B**).

#0000**1**110b Display ON, Cursor ON, Cursor Blinking OFF (**Figure 8C**).

#0000**1**111b Display ON, Cursor ON, Cursor Blinking ON (**Figure 8D**).

Display Shift (Left or Right)

COMMAND: Display Shift/Cursor Move (Right or Left) (00000**1**XXb).

BIT-0 = 0 – Display shift OFF.

BIT-0 = 1 – Display shift ON.

BIT-1 = 0 – Cursor moves one space to the left (for next character).

BIT-1 = 1 – Cursor moves one space to the right (for next character).

#00000**1**00b Display Shift OFF / Cursor to the left (**Figure 9A**). (The K stays in DDRAM 73 while the next characters go in on the left).

#00000**1**10b Display Shift OFF / Cursor to the right (**Figure 9B**). (The K stays in DDRAM 73 while the next characters go in on the right)

Table 4

00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15
64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79

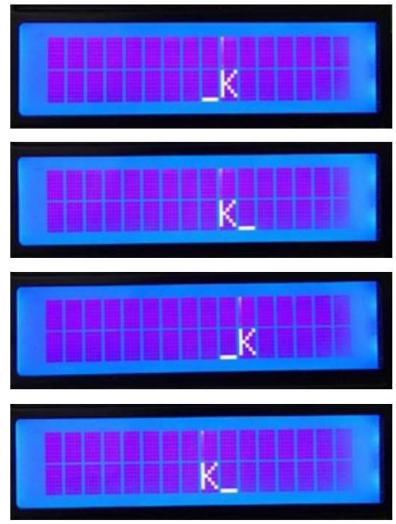
(A)

(B)

(C)

(D)

Figure 8 (A), 8(B), 8(C), 8(D) — Display control.



(A)

(B)

(C)

(D)

Figure 9 (A), 9(B), 9(C), 9(D) — Display shift (left or right).

#00000**1**01b Display Shift ON / Cursor to the left (**Figure 9C**). The Cursor stays in DDRAM 73 and stays on the left while the K moves.

#00000**1**11b Display Shift ON / Cursor to the right (**Figure 9D**). The Cursor stays in DDRAM 73 and stays on the right while the K moves).

Sending Data To The LCD

Sending data to the LCD follows the same format as sending a command to the device. The only difference is that a "1" (+3.3 V) is placed on the R/S (Register Select) line (pin #4 of the LCD) to send data, whereas a "0" (0 V) is placed on the R/S line to send a command. Regardless of whether COMMAND information or DATA information is sent to the LCD the following steps must happen.

Steps for Command or Data Entry into the LCD

1. LCD Pin #4 (Register Select) either brought HIGH or LOW.
2. Pin #6 (Enable) is brought "HIGH" (+3.3 V placed on Pin #6) for a minimum of 100 µs before a Command or Data is sent.
3. Information (COMMAND or DATA) is sent to the LCD.
4. Pin #6 (Enable) is brought "LOW" (0 V placed on Pin #6) for minimum of 100 µs before program continues.

Two Example Programs

Two example programs are available at **www.arrl.org/QEXfiles** and are heavily commented so the reader can understand what is happening as the programs are executed. The MSP430G2553 microcontroller was programmed with the Texas Instruments IDE Code Composer Studio.

Program #1

"QEX_LCD_PORT_2" sets up the Newhaven NHD-0216H1Z LCD to print the letters "QEX" starting at character position #7 on the LCD . To gain experience in working with the LCD print an ASCII table and practice entering different characters.

Program #2

"ADC_LCD_OUTPUT" provides a practical application that may be useful as a basis for a project. Using one of the analog-to-digital (ADC) channels (there are 8 channels available) on the MSP430G2553 microcontroller, a 5 kΩ potentiometer is used as a position sensor (roughly 270° of rotation). As the potentiometer is rotated a small voltage is outputted (somewhere between 0 and 3.3 V), and this voltage is then represented as a digital number (somewhere between 0 and1023). This program displays the digital number on the LCD.

Analog-to-digital converters allow analog signals such as sound, temperature, or RF signal strength to interface with digital systems. With analog information represented as a digital number the information can then be evaluated and manipulated / processed as needed. Sensors sample analog signals and provide a small voltage that is then converted to a digital number. The ADC_LCD_OUTPUT program demonstrates how this number can then be displayed on the LCD screen, and this program can be adapted for any type of sensor. The ADC available in the MSP430G2553 microcontroller is a 10-bit ADC, which means that when an analog voltage is converted to a digital number the digital number will be somewhere between 0 and 1023. When working with binary numbers the maximum a 10-bit number can be is 1023.

Conclusion

For those amateurs who are technically inclined and willing to try something new, the Texas Instruments MSP-EXP430G2ET Launchpad development platform with the MSP430G2553 microcontroller on the board, and an inexpensive LCD would be a great addition to a project that needs to output information. In the process one can learn a great deal about assembly programming with a microcontroller that could be very useful in future projects.

A supplemental guide is available on **www.arrl.org/QEXfiles**.

James Kretzschmar, AE7AX, was first licensed in 1972 as a Novice and now holds an Amateur Extra class license. He retired from the US Air Force in 2004 after a 25 year career as a general dentist. He currently works part time as a Temporary Lecturer at the University of Wyoming, and has designed and written the lab portions of the Microcontroller and Electric Circuit Analysis courses for the Department of Electrical and Computer Engineering. James is an ARRL and IEEE member, and enjoys all aspects of electronics, homebrew projects, and 40 meter CW operating, bicycling and kayaking.

Errata

In Dan Koellen, AI6XG, *"Telegram Your Commands," QEX* July/Aug. 2021, Figure 6 on page 33 contains an error. R2 should be connected to V_RPI, not Vtarget. Thanks toWilton Helm, WT6C, for spotting the error.

Andrew J. Anderson, VK3CV/WQ1S
1/18 Glenmore Crescent, Black Rock, Victoria 3193, Australia; **vk3cv_wq1s@yahoo.com**

Bridging the Terahertz Gap at 30 THz

Different techniques are needed to explore the 30 THz band as a communications medium.

The electromagnetic spectrum is vast — *from dc to daylight* is a commonly used term — but the spectrum extends beyond visible light to X-rays and gamma rays. In amateur radio we just call our section of the spectrum Radio Frequency (RF), which means somewhere between a few kilohertz and up to around 300 GHz or maybe a bit higher still. Above RF we usually consider the spectrum as optical, but there is a little utilized gap that has remained previously un-used in a communications sense: the Terahertz Gap. Amateurs are generally allowed to experiment above 300 GHz as there are no hard and fast regulations in many countries so there is a huge amount of spectrum to explore.

Background

As some of you know, especially those who have experimented on the higher millimeter wave bands, the gases in our atmosphere, including water vapor, have a dramatic effect on propagation losses in the high gigahertz range and it all gets dramatically worse as you go even higher in frequency. There are, however, atmospheric low loss windows that are best illustrated in **Figure 1**.

Starting at the left with 3 GHz (microwaves with a 100 mm wavelength), the atmospheric losses are reasonably low and generation and reception of RF signals is well understood. At these wavelengths it's relatively simple to implement practical transmitters and receivers with easily obtained electronic devices. **Figure 1** reports added atmospheric losses, those in addition to the usual inverse square law path losses associated with electromagnetic communications system. For users of LF, MF, HF, VHF and UHF bands, your spectrum of choice didn't even make it onto this spectrum graph.

Moving to the right along the spectrum in **Figure 1** we start to see large dips in relative transmission primarily due to absorption losses. The dashed line at the top of the graph separates the absorption losses from the scattering losses. The absorption losses exhibit narrow dips such as at 22 GHz, then 60 GHz, etc., and then many more until the losses become huge above 300 GHz. We're now in the Terahertz Gap — a term used to describe the spectrum between 1 and 10 THz or 1 and 30 THz depending on which reference you use. The Terahertz Gap terminology was coined for two reasons. First, it's difficult to

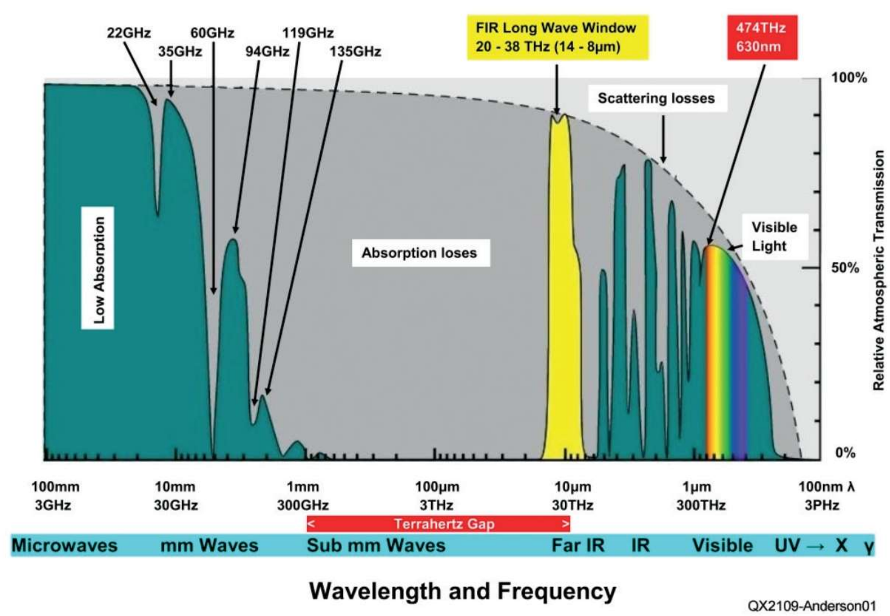


Figure 1 — Atmospheric losses.

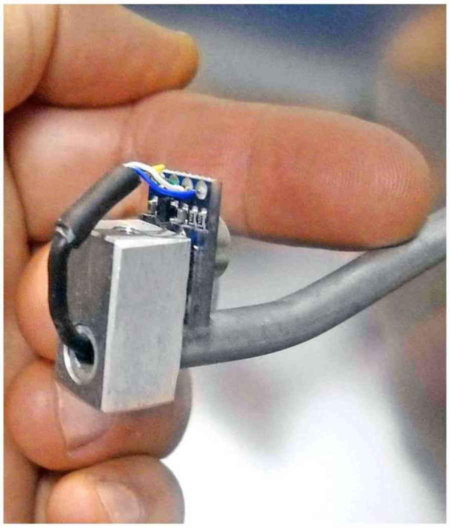


Figure 2 — The human hand used as a signal source.

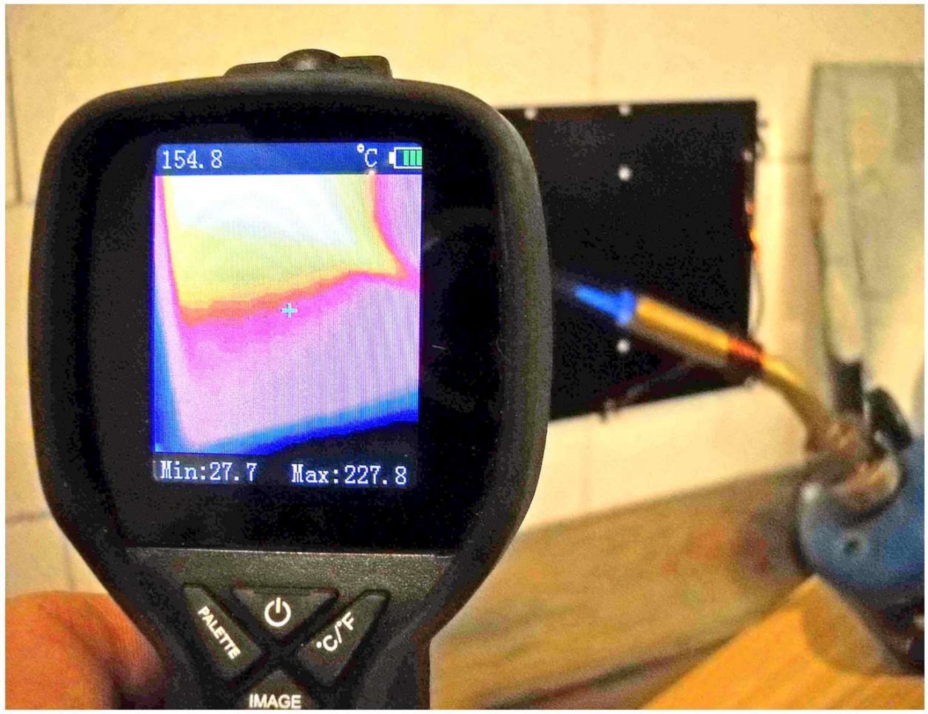


Figure 4 — A heated metal plate used as a signal source.

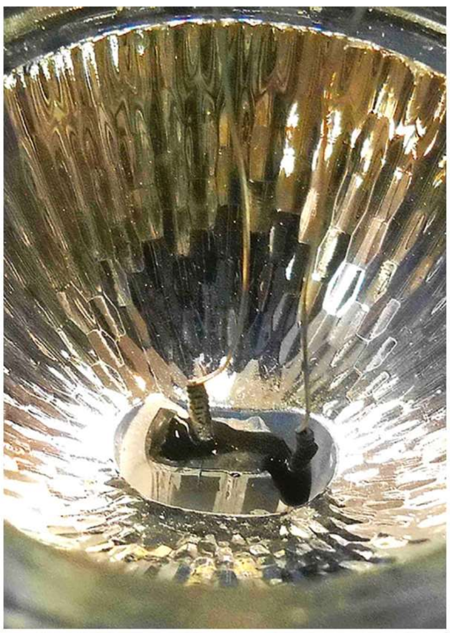


Figure 3 — An exposed filament from a 12 V down light.

use this area because the huge added atmospheric path losses makes the achievable propagation distances very small. Second, it's very difficult to obtain electronic devices that will generate and detect signals at these frequencies. At the very top end of the Terahertz Gap, between 20 and 38 THz (wavelengths between 8 to 14 μm), there is a low loss atmospheric window seen in **Figure 1**. This area is ripe for exploration and sits right at what classical science considers the *radio* and *optical* boundary. For the sake of simplicity, we'll term this region the 0.01 mm or 30 THz band.

We still need to figure out some way to generate and receive signals at 30 THz. As seen in **Figure 1**, the 30 THz band sits above the upper mm wave bands (>300 GHz), but well below the commonly used optical bands around 474 THz (630 nm, red light). Note also that **Figure 1** is an approximation of what happens to losses at a given altitude and relative humidity. The losses shown can deviate significantly in practice depending on the current atmospheric conditions and the barometric pressure.

In optical terms the 30 THz band sits right at the bottom of the far infrared range; the area is also called the long wave window. Energy in this band is perceived by our skin as heat and is relatively safe at the levels we are exposed to from natural sources such as the Sun. Our bodies also radiate this wavelength of energy as does any other physical matter that is above a temperature of absolute zero (–273 ºC). Thermal radiation we perceive as heat is actually electromagnetic radiation at around 30 THz. You've been experiencing 30 THz radiation your whole life and didn't even know it! You've also been generating 30 THz band signals. We don't even need any test equipment to generate or receive 30 THz test signals, as our bodies have them already built in. A warm hand makes a great low level signal generator and carefully bringing the same hand near a 30 THz transmitter will give an indication that the transmitter is radiating. Thermal radiation is the emission of electromagnetic waves from all matter that is at a temperature greater than absolute zero. Thermal energy is the kinetic energy of random movements of atoms and molecules in matter; and thermal radiation reflects the conversion of thermal energy into electromagnetic energy.

In physics, thermal radiation is often referred to as *Black Body Radiation*, which is a term first used during very early scientific experiments in this area, as it was thought that black bodies are near perfect radiators and absorbers of thermal radiation. In actuality the visual color of a body [This is not to be confused with the incandescent color glow.— *Ed*.] has no direct relationship with its thermal radiation characteristics, the thermal radiation efficiency is termed emissivity and is 1 for a perfect radiator, our own skin has quite high emissivity.

For those who are interested in details of thermal radiation, there are many references on the internet. Search on the terms 'black body radiation', or 'thermal radiation'. Pioneer scientists such as Planck, Stefan, Boltzmann, Wien, Stewart, Kirchhoff, and others contributed to the understanding and analysis of black body radiation.

All we need to understand about the physics is that the hotter the object, then the greater the amount of thermal radiation. Another important thing to know is that a

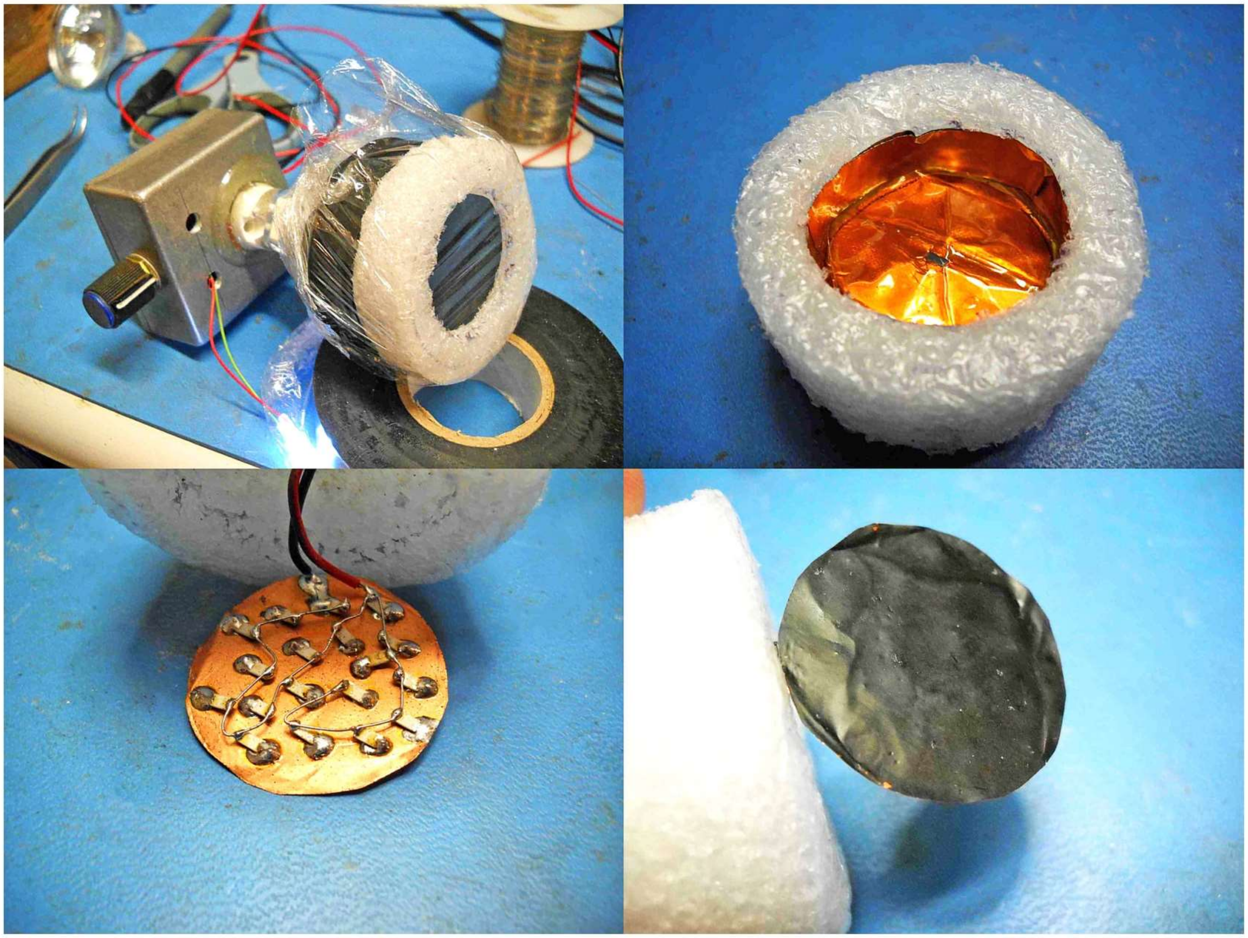


Figure 5 — Upper left: a resistor heated insulated plate assembly with a window. Assembly components are in the remaining images.

significant amount of the thermal energy radiated by a hot black body is located in the 30 THz band. Pioneering work in the understanding of thermal radiation led to part of the foundation of quantum mechanics.

Transmitting Equipment

So now onto some practical matters, the transmitter we're using is a black body source. I've experimented with several sources, such as my hand (**Figure 2**), an exposed filament from a low voltage downlight (**Figure 3**), a piece of aluminum (**Figure 4**) heated by a propane flame, a home-brew heated copper plate with insulation to minimize air cooling and a 30 THz clear transmission window using clear plastic cling wrap (**Figure 5**), the Sun and a heliograph modulator (**Figure 6**). Be careful, solar power density is 1 kW/m^2). The THz band signal from the black body source is then passed through some form of ON/OFF modulator to allow Morse code transmission

Figure 6 — Hand operated heliograph.

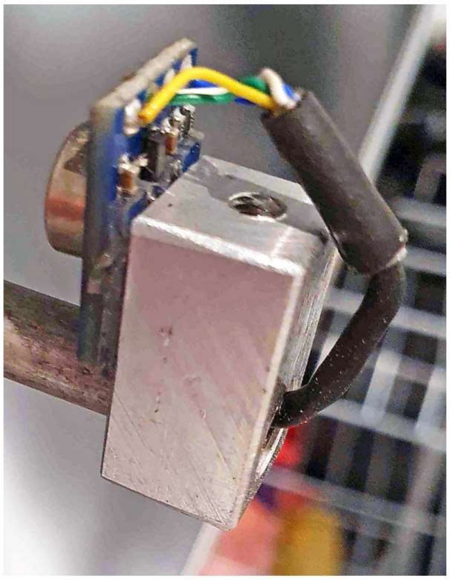


Figure 7— Melexis sensor mounting.

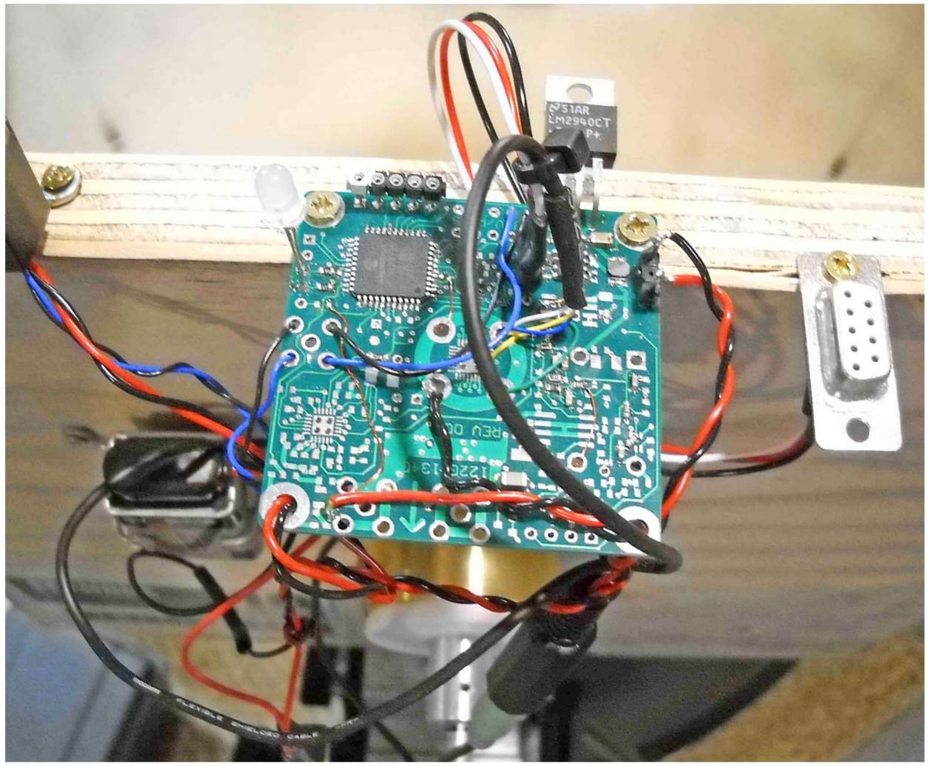


Figure 8 — A VK3CV 122 GHz transverter printed circuit board heavily modified for this project.

of information. The heliograph modulator used is simply a reflector that works at the frequency of interest. A normal glass mirror is not suitable since glass severely attenuates the THz signals. A polished aluminum plate works very nicely and is modulated using the "Armstrong" method (**Figure 6**).

To be blunt, the transmitting technology shares more similarities with a spark gap transmitter than to a modern solid state device. The transmitting spectrum is wide and the terahertz energy generated is non-coherent.

Receiving Equipment

The receiver is a bit more modern and sophisticated although it's principle of operation goes way back in history. The heart of the receiver is a thermopile sensor, MLX90614, made by Melexis **[1]**. The MLX90614 is intended for use as a non-contact thermometer. It works by measuring the heating from thermal radiation absorbed by the sensor element, which is a thermopile. A thermopile converts heat energy directly into electrical energy. The internal thermopile sensor has a band-pass filter window and is made of a material that responds to wavelengths between 8 and 14 μm (20 to 38 THz).

The receiver MLX90614 sensor is mounted at the focal point of a parabolic reflector (**Figure 7**). It is capable of differentiating temperature differences as small as 20 mK (0.02 °C) and has a built in compensation system to cancel out the device ambient temperature.

Figure 9 — Front view of the terahertz reflector system.

The main limitation of the sensor is its slow response time; it will only respond to changes in signal level at about 0.5 s intervals when operating at its best sensitivity. This means the Morse speed has to be kept very low at only a few words per minute.

The Melexis sensor has an I2C interface that is fed to a PIC processor with specially written code and a small amount of Digital Signal Processing (DSP) to take the stream of raw data readings from the sensor and provide some useful outputs to present to the operator.

The board used (**Figure 8**) is my heavily modified VK3CV 122 GHz transverter board **[2]** with an audio tone output for the demodulator, an analog RSSI meter, a serial RS232 port to output diagnostics, and a status LED. A switch is also fitted to select either demodulated audio or tone-based RSSI that is great for peaking the antenna. I would consider laying out a purpose designed board for the project if there is sufficient interest. The whole project is a work in progress and things are changing by the day.

I used a 600 mm diameter parabolic reflector (**Figure 9**) from Edmund Optics. On this band it has very questionable surface accuracy, but it does have significant gain in practice. All the parts of the system are mounted on a piece of plywood that is then attached to an adjustable tripod.

In November 2020, Karl Harbeck, VK3LN, and I made a two-way contact over a 60 m path and reported 5 by 5 signals each way. We believe this contact is the first ever in this band anywhere in the world. The result suggests we should be able to achieve much greater distances. We're already exploring more sensitive receiver technology using more advanced sensors. See the VK3CV_WQ1S YouTube channel **[3]** for a video made during testing.

Many thanks to Dr. Andrew Tirkel who gave valuable guidance during the development of the project and thanks again to Karl, VK3LN, for his assistance with field operations.

[Photos by the author.]

Andrew Anderson, VK3CV / WQ1S was first licensed in 1976 as a Novice in Australia (VK3NQU) at age 15. Andrew studied electronics at RMIT in Melbourne, Australia from 1979 to 1983. He soon achieved a limited Technical Class license, VK3YPD. He gradually became more interested in VHF, UHF and SHF bands using a mix of modified commercial and home brew equipment. In 1980 he consolidated his Novice and Limited call sign, later becoming VK3CV. Andrew has held many distance records in Australia from 144 MHz to beyond 134 GHz. In Australia he made the first 47 GHz contacts in 1995. His passion for experimenting was fuelled by his mentor and good friend, Les Jenkins,VK3ZBJ (SK). Les and Andrew hold the world distance record on the lost Australian 576 MHz band.

Andrew lived and worked near Boston MA, USA, and in 2009 obtained his US Amateur Extra class license, AB1LA, later changed to WQ1S. He is now semi-retired and spends more time in Australia. He enjoys experimenting on the millimeter and sub-millimeter bands, and machining his own mechanical hardware.

References

[1] **https://www.melexis.com/en/documents/documentation/datasheets/datasheet-mlx90614**

[2] A. J. Anderson, VK3CV/WQ1S, "A Simple 122 GHz Transverter," *QEX* May 2020, pp. 3-11.

[3] **https://www.youtube.com/channel/UCHpLCO3bMxpirBbKZ4x1A4g**.

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NanoSSB RX – An Ultra Low Cost SSB Multiband Receiver

Here is a microcomputer controlled SSB receiver constructed from an Arduino Nano module and a broadcast radio receiver chip.

The Silicon Labs Si4732-A10 integrated circuit is an incredible device. It is a complete AM / FM / SW / LW radio receiver in one piece, using only a few square millimeters of silicon. It is so tiny that it could fit on the tip of your finger! **Figure 1** shows a standard version in the SOIC-16 package. This is the chip we will explore here.

Having been involved with integrated circuits since their inception, I am still amazed at the capability housed in such small packages and at such low prices. This chip reminded me of my first crystal radio built many long years ago. In that case I had one chip, a galena type crystal. Then it occurred to me, for about the same cost as my old crystal radio, I now had a full-fledged SSB radio — one based on a small silicon chip — about the size of the original galena crystal!

SSB Receiver on a Chip

In this article I'll provide information on how I built this ultra low cost SSB multi-band receiver, dubbed NanoSSB RX because of its Arduino Nano legacy. It will probably be unlike any SSB receiver you have seen.

With a bit of online searching for parts, this project's cost was very low, just a few chips costing less than $20. The hardest part for me was surface mount soldering the main chip to the SOIC holder. This can be done with a hot air station or manual soldering. It is a skill that we need in this age. I also used an accurate signal generator and an old Dell PC with a USB port, a sound card and speakers to make it work.

But, don't get too excited about this SSB receiver. It will not replace your ham receiver. It has some definite short comings: AGC and AVC cannot be changed, BFO needs calibration and there is no noise blanking. But it does have a DSP engine, good opposite sideband rejection, wide coverage (0.1 MHz to 30 MHz), six built-in audio filters, low parts count, reasonable sensitivity and low power. If you like to explore new technology you may become as fascinated with this chip as I have.

My initial reason for considering this receiver was to use it as a low cost WSPR receiver to monitor various bands. There are other uses, discussed later, but my main focus will be on WSPR and data modes.

There are some interesting hardware aspects to this NanoSSB RX. It employs only a few modules (**Figure 2**): an Arduino Nano, interface buffer module and a Si4732-A10 chip. Power is supplied by the USB port of the PC while the audio is provided by the PC sound card and speakers.

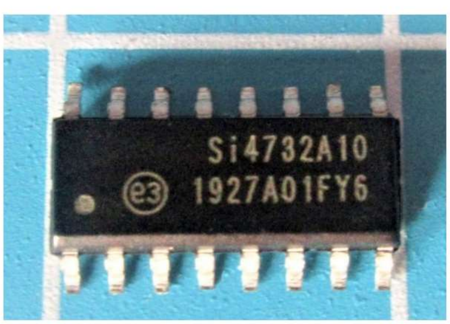

Figure 1 — The Silicon Labs Si4732-A10 integrated circuit multiband radio. This version is in a SOIC-16 package.

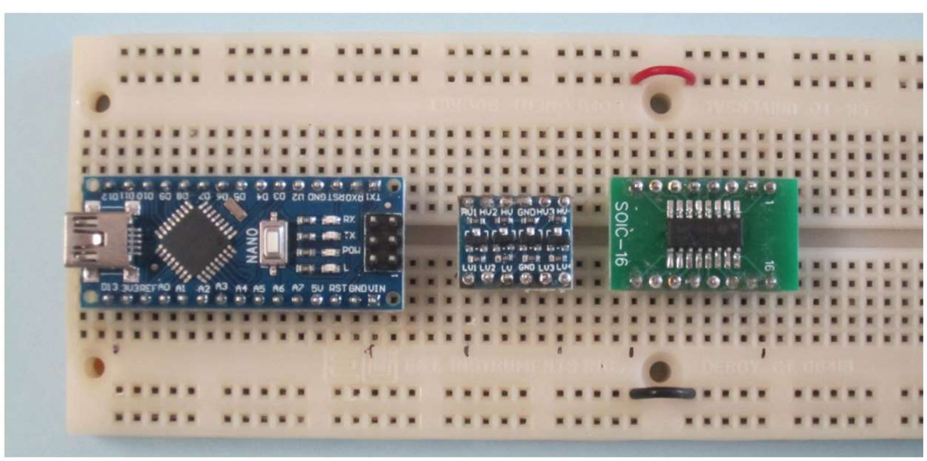

Figure 2 — The three modules are used in the project. From left: Arduino Nano, buffer and the tiny Si4732 mounted on SOIC adapter.

A suitable antenna completes the radio.

In what follows we'll discuss the genesis of the project and provide details about how the Si4732-A10 chip works. Then we'll show some examples of usage and potential problems. Read on to see how I built this unusual SSB all-band receiver.

Project Background

Silicon Labs introduced the family of Si4735 ICs in 2013; they were the industry's first fully integrated, 100% CMOS AM, FM, SW, LW radio receivers. They offered unmatched integration and PCB space savings. Si4735 devices require minimal external components and less than 20 mm^2 of board area. However, these ICs did not offer single side-band (SSB) capability. Over time Silicon Labs began providing a SSB upgrade for the ICs for some dedicated applications. The standard ICs did not have the SSB capability.

In 2016 Vadim Afonkin, KB1RLI, decided to try to work with this chip and make it receive both CW and SSB. He wanted to create a fox hunting receiver. He used a patch to the Si4735 that would enable it to do this and made it available on his repository.

Ricardo Lima Caratti, PU2CLR, realized in 2019 that the patch was a crucial element and started work on a Si4735 Arduino library on GitHub **[1]**. The initial idea was to build a receiver by using an Arduino, a few components and the SI4735 device. He soon realized that the receiver based on Si4735-D60 could go far beyond the initial proposal, including amateur radio on SSB.

This library is a valuable asset and has provided experimenters with Arduino code for the Si4735. A **si47xx@groups.io [2]** and a Facebook group **[3]** have been formed to support this effort. Eventually the library was enlarged to include the Si4732-A10 used in this project. Based on Caratti's examples, several types of SSB receivers, some with OLED screens have been developed. Even a radio kit **[4]** has been designed by David Martins, CS7AEK.

Up to this point no one has developed a Si4735 based SSB receiver for data like WSPR. The difficulty with WSPR is trying to set a receive frequency with enough accuracy and consistency to hit a 200 Hz wide WSPR band within a few Hz. Normally the Si4735 is designed to tune in 1 kHz increments. Thus the last 3 digits are unknown, so the tuned frequency could be off by 1000 Hz. This problem can be mitigated using a BFO. But first, what is a patch?

Firmware Modification

As noted, the Si4735 generic chip does not support SSB. So a firmware patch is used to give it this capability. Simply put, the patch is a piece of software used to change the behavior of the SI4735 device. Typically patches are used to fix bugs or add improvements and new features of the firmware installed in the internal ROM of the device. During operation, the patch is executed internally by the microcomputer unit (MCU) within the device.

In this case the patch to the SI4735 (in binary form) must be transferred to the internal RAM of the device by the host MCU (Arduino). Since the RAM is volatile memory, the patch stored in the device gets lost when you turn off the system. Consequently, the content of the patch has to be transferred again to the device each time after a turn on of the system or reset of the device. But since the patch is stored in the Arduino, it can quickly restore the patch to the Si4735 each time power is applied.

The generic Si4735 has AM, FM, SW, LW in the firmware. So when the patch is applied these functions are lost. Caratti **[1]** has shown how to rapidly switch between these functions and SSB. However, for this project I chose not to do this switching.

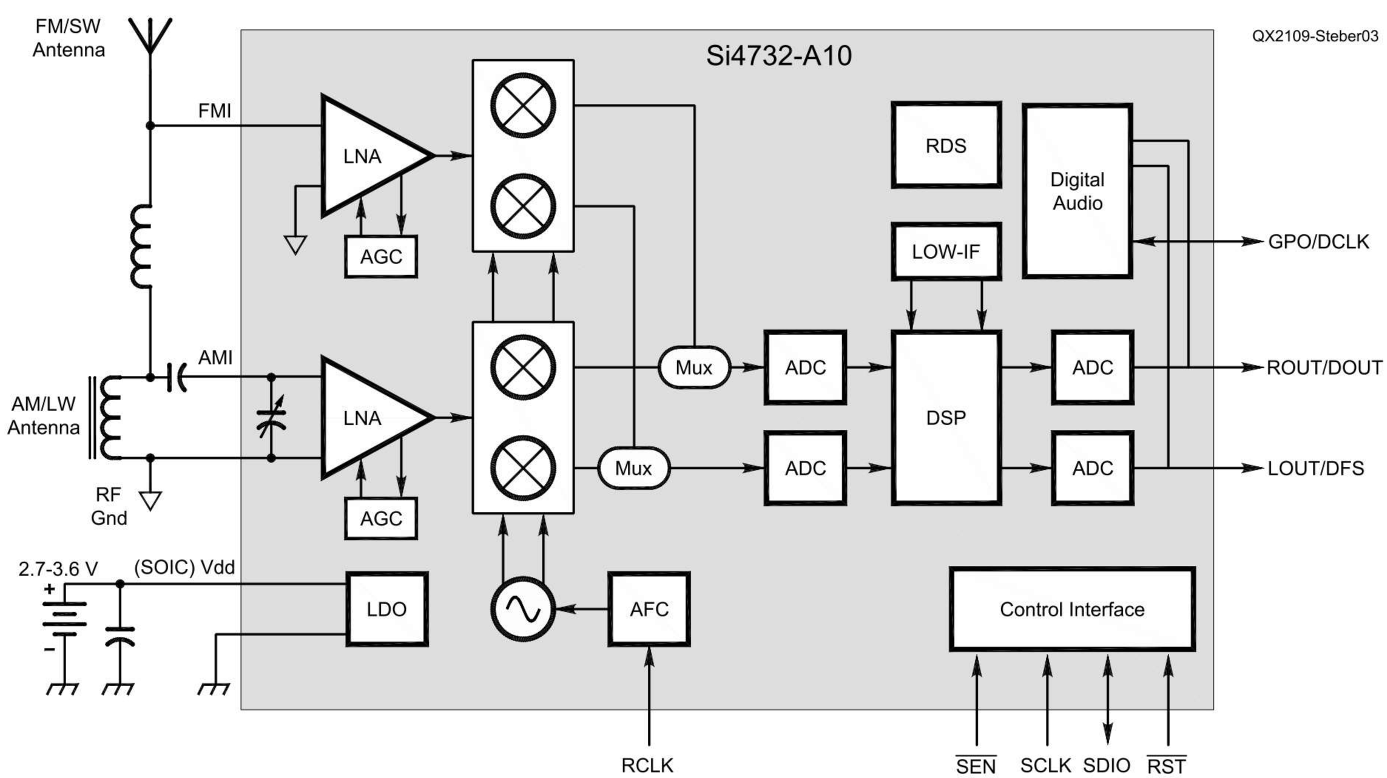

Figure 3 —Block diagram of the Si4732-A10.

Thus, my receiver works only in SSB mode.

Features of the Si4732-A10 Chip

Mouser lists the Si4732-A10-GS chip for about US$13. But you can find it for as little as $5 on eBay or AliExpress. There are many features crammed into this little package as shown in **Figure 3**.

The chip operates at 3.3 V nominal. So, any connections to other logic elements must be converted to this logic level. That is the purpose of the buffer module shown in **Figure 2**. There are two RF signal inputs, FMI and AMI. The AMI input is for AM, SW and SSB. The FMI is used for FM radio only.

This digital CMOS AM / FM radio receiver IC integrates a complete broadcast tuner and receiver function from antenna input to analog or digital audio output. In FM mode, radio signals are received on FMI and processed by the FM front-end circuitry. In AM mode, radio signals are received on AMI and processed by the AM front-end circuitry.

As a shortwave (SW) receiver the Si4732 was the first fully integrated IC to support AM and FM, as well as SW band reception up to 30 MHz. The Si4732 offers extensive features such as digital tuning and no factory adjustments. Other SW features include tunable step sizes in 1 kHz increments, adjustable channel bandwidth settings, advanced seek algorithm, and soft mute.

NanoSSB RX Design

I decided to build an SSB receiver that could be controlled from the USB port. It is based on the design of Ricardo Lima Caratti, PU2CLR, (**SI4735_03_POC_SSB.ino**, an Arduino file in the "examples" section of his library **[1]**). It is a proof of concept for SSB without much functionality. For a beginner, it is a good starting point.

Operating from the USB port has advantages since you can control features easily and see results. But the USB port can introduce noise into the receiver. Working from the USB port also makes commanding the Si4732 much slower.

The hardware of the SSB receiver consists mainly of the three modules shown in **Figure 2** that are connected together as shown in the schematic of **Figure 4**. There is very little wiring between the modules, and there is no external power supply since dc power is derived from the USB port.

The Arduino Nano is a small, complete, and breadboard-friendly board based on the ATmega328P processor. My fully assembled module was described on eBay as: Nano Development Board with ATMega328P, Mini USB, and CH340G for Arduino V3.0.

Mine included a free USB cable. Prices ranged from US$3 to US$9. Its low price stems from the fact that it is widely used in robotics, embedded systems, and automation projects. It is relatively easy to program using the Arduino IDE. Most importantly it comes with a CH340G serial port interface and a bootloader.

The 4 Channel I2C Logic Level Converter, Bi-Directional Module (5 V to 3.3 V) can be found as a module on eBay. Mine came from Wire and Kits (US$4.59 for 5 pieces). Using this module avoids having to wire-up the individual transistors and resistors.

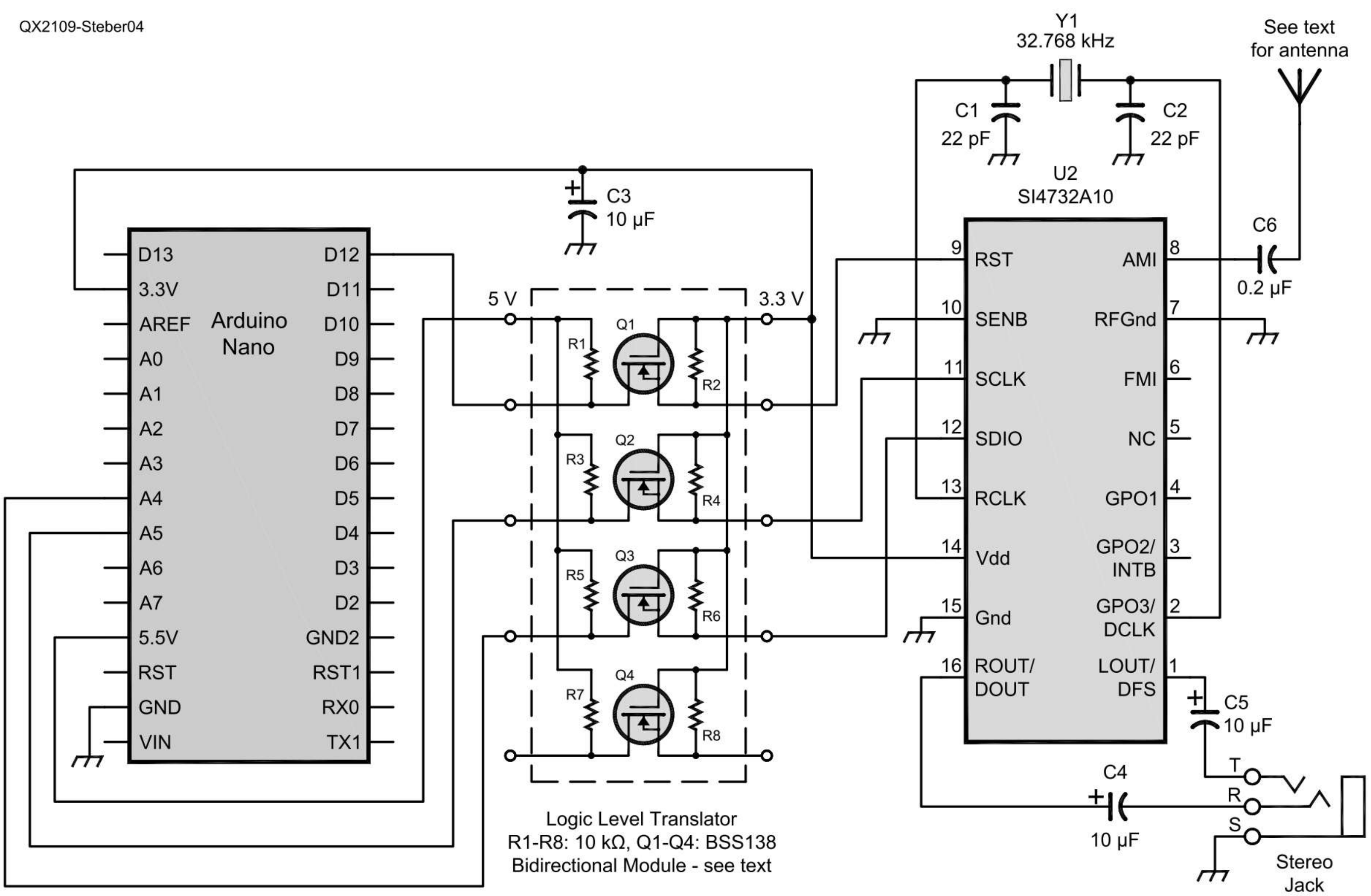

Figure 4 — Detailed schematic diagram – complete NanoSSB receiver.

Other parts include a stereo jack, 32.768 kHz crystal, and some capacitors. More will be said about the crystal later. The antenna connects to the AMI pin through a capacitor. While this will work, it is dangerous as static charge may destroy the chip.

Various techniques were employed to build this SSB receiver. As a *first pass* these modules were mounted on a solder-less breadboard strip (**Figure 2**). This worked well for loading the firmware and testing the software. Since my antenna was located some distance from the circuit and fed through coax, there was little noise pickup. But some computers can generate a lot of noise, so pay attention to this aspect of the radio.

Starting the Project

The fun began after the modules were mounted on the breadboard and wired together as shown in **Figure 4**. The audio output was connected to my PC microphone input so the audio system and speakers could be utilized. A dipole antenna with balun was connected via coax to AMI.

Now the firmware must be loaded into the Arduino Nano using the Arduino IDE **[5]**. I used an older version 1.8.3, which runs in Windows XP on my old reliable Dell desktop computer.

Now connect the Arduino Nano to the PC with a USB cable. My computer immediately recognized a new COM port (COM 11), which appeared in Device Manager under Ports (COM & LPT). This verified that the CH340G serial port interface was working.

Next, start the Arduino IDE. The PU2CLR Github repository **[6]** has the complete library and examples. To keep it simple, the example SSB program noted earlier was loaded. Arduino Nano was selected as the target in the IDE. After compiling, the firmware was downloaded to the Arduino Nano. When it was started the radio burst into life

It was fun tuning stations and exploring the features of this SSB radio. This example uses the Arduino IDE serial monitor to communicate with the Arduino Nano and send commands. This method works fine to get started and to get confidence in the circuit and software operation. But I soon yearned for better and more complex control. I wanted something that would work well with amateur radio data modes like WSPR. None of the other Github examples seemed to meet my requirements, so I modified this sketch and interfaced it to a small Visual Basic program. This is when I discovered issues with setting the frequency accurately and other problems.

Frequency Accuracy

The SSB patch has inherent commands for setting a beat frequency oscillator (BFO) that should allow tuning the frequency down to 1 Hz. It does not work like a traditional BFO that mixes one signal with another. It's just a way to increase the tuning resolution. This is needed because the main frequency commands of the Si4732 can tune only in 1 kHz increments. So, the BFO fills in the lower three frequency digits. Say you wanted to tune a WSPR signal at 14.095600 MHz. Typically you would set the main frequency to 14.095 MHz and the BFO to 600 Hz.

However, the main frequency setting is not exact. While the BFO range is very large and covers both positive and negative frequencies (–16383 Hz to +16383 Hz.), it simply adds this frequency to the residue that is there from the main tuning. Consequently the exact BFO frequency, needed to achieve a specific frequency, is unknown. In many cases, such as listening to SSB voice it doesn't matter since the BFO can be adjusted to make the voice sound normal. But for data modes such as WSPR, which are located within a 200 Hz band, we must know the center of the band to within a few hertz.

This problem stems from the fact that a single 32.768 kHz crystal is used for the main clock. Provisions have been made by Silicon Labs to use crystals in the megahertz range. Tests by me and others confirm that this works for AM / FM modes but not for SSB mode. So we are stuck with using the 32.768 kHz crystal.

Using 32.768 kHz crystals can be troublesome. When I was testing my receiver I found that it would not consistently return to the same frequency. It could be off by 96 Hz. After much testing, the crystal was found to be the problem.

Figure 5 shows two crystals that I was using, as well as a Maxim 32.768 kHz module (DS32KHz/DIP) that I tested. The tiny crystal was causing the problem. Using the physically larger crystal eliminated the problem and provided consistent frequency setting.

The DS32KHZ was used to see if temperature drift could be mitigated. It is accurate and works well. It must be connected to the RCLK input. The down side is that it is expensive. I have stayed with the original crystal oscillator with good results in a temperature controlled room. However, if there were major temperature variations, using the module would be better.

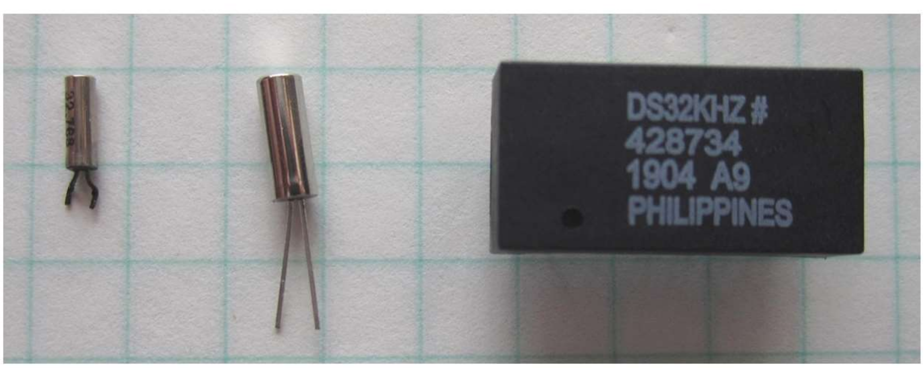

Figure 5 — Various crystals and module tested in the Si4732 SSB radio project.

Calibration and the BFO

At this point I had a SSB radio that would tune with repeatability but not accuracy. Then it occurred to me to use an accurate signal generator with a short antenna to simulate the transmit carrier of a WSPR station. Next, the WSPR dial frequency was set in the Si4732 radio. This resulted in an audio tone produced by the Si4732. This tone was observed on the PC using the audio spectrum analyzer in Fldigi **[7]** or WSJT-X **[8]**. Adjustments of the BFO frequency were made to make the audio frequency exactly what it should be (1500 Hz) for WSPR.

Table 1 shows the calibration BFO values I obtained in this manner for several WSPR bands. Normally BFO frequencies are given as negative values in the SSB patch; I converted them to positive values for easier reading. Errors in the BFO frequency can be seen by comparing the last two columns.

Fortunately these BFO values are very

repeatable. So, in my program, I simply save these "calibrated" BFO values with my favorite WSPR frequencies. It works well and has been running for many weeks without the need to re-calibrate. Now WSPR bands can be selected with a single click.

Figure 6 shows a screen shot of my *Visual Basic* program. In the lower panel are provisions for controlling many of the features of the SSB receiver such as frequency selection, BFO frequency, sideband mode, audio filtering and volume. My favorite radio and BFO frequencies can easily be saved and recalled. This makes it handy to change WSPR (and other) bands rapidly.

Si4732 Anomalies and Discoveries

There are some features that would be nice to have in this SSB receiver such as noise reduction, slow AGC, adjustable LNA, and controllable AVC. These features are mentioned in the SSB programming guide, but unfortunately they do not work. However, for most data modes, having the AGC constantly turned on works okay.

One of the nice discoveries included in the SSB patch are the six built-in audio filters. They are DSP based and include two CW band pass filters and four voice bandwidths. One band-pass filter is 1 kHz wide and centered on 1 kHz. It's very useful for copying NAVTEX and CW. The wider 2.2 kHz low-pass filter is perfect for WSPR.

Antennas and Preselector

Using a plain wire antenna works with the Si7432 but is not recommended unless static electricity protection is provided at the Si4732 antenna input. Silicon Labs recommends using an ESD diode with small parasitic capacitance like the California Micro Device CM1213 with whip and wire antennas.

There are not any specifications on the impedance at the antenna connectors. Preliminary testing by the author has indicated a magnitude of about 1000 Ω at the AMI input. So it should work well with many antenna combinations.

My antenna here is a dipole with a 1:9 balun feeding coax. It is taped to the ceiling of the room. Although it is not tuned on all my WSPR bands, it works well — and the balun seems to help. Since the Si4732 AMI input is wide band, a tunable preselector works wonders at reducing adjacent interference. This is an often overlooked aspect of SDR radios.

Table 1 – WSPR bands BFO calibration table. All WSPR bands use USB.

WSPR Band	TX Carrier Frequency, MHz	Dial Frequency, Hz	BFO, Hz
160 m	1.838,100	1.836, (600)	620
80 m	3.594,100	3.592, (600)	670
60 m	5.288,700	5.287, (200)	210
40 m	7.040,100	7.038, (600)	625
30 m	10.140,200	10.138, (700)	820
20 m	14.097,100	14.095, (600)	575
17 m	18.106,100	18.104, (600)	850
15 m	21.096,100	21.094, (600)	825
12 m	24.926,100	24.924, (600)	725
10 m	28.126,100	28.124, (600)	625

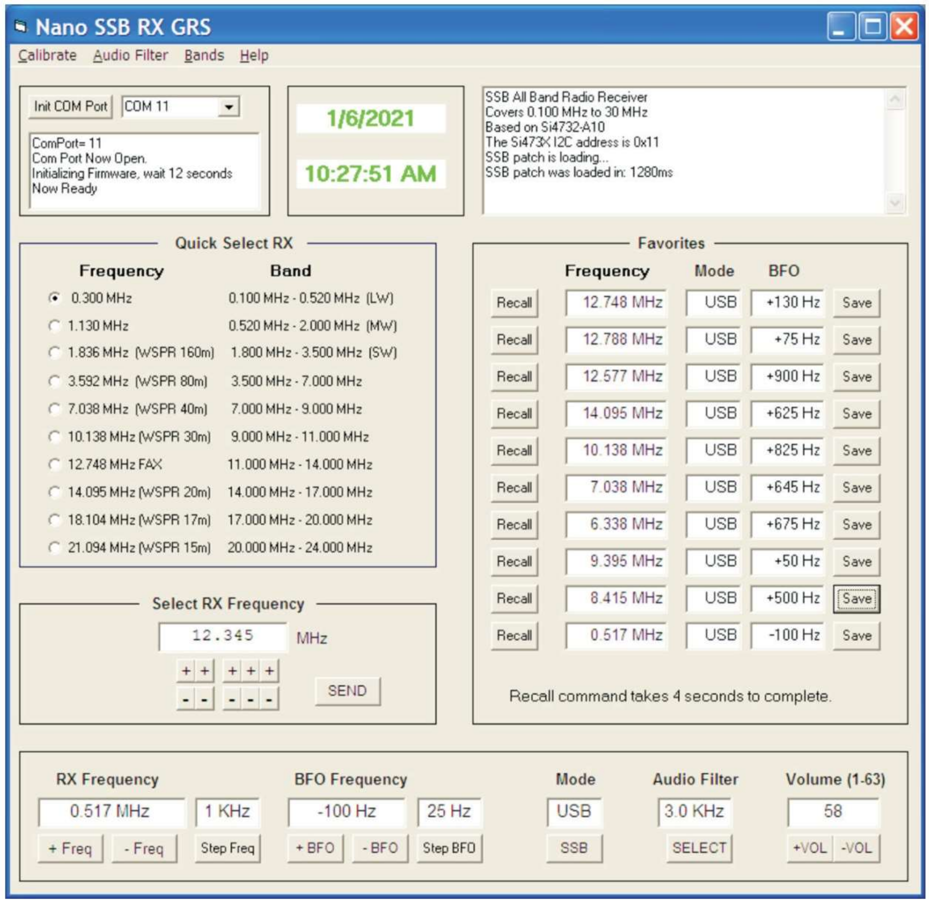

Figure 6 — Screen shot of the NanoSSB Visual Basic program for controlling the Si4732.

The preselector used here was described in *QEX* **[9]**. Mine has four bands, covering 0.1 MHz to 30 MHz, and a manual tuning capacitor to peak the signal. The preselector greatly enhances the signal by reducing strong adjacent signals that would cause the Si4732 AGC to reduce its gain, thereby masking weak signals. With all the local noise and close-by AM stations, it would be almost impossible to copy a weak NAVTEX station at 518 kHz without a preselector.

There is a problem using the tunable preselector. Normally you would select a band and tune the capacitor for peak response at your selected radio frequency. However, this doesn't work because the AGC is always ON in this receiver and masks the peak. My workaround was to calibrate the dial scale of the tuning capacitor for the frequencies of interest using a signal generator and scope. Set the signal generator to a given frequency and connected to the preselector input. The scope is used to observe the preselector output. Then, adjust the tuning capacitor for a peak in the output signal, and mark its position on the dial scale.

Receiving WSPR and Other Data Modes

Decoding WSPR transmissions was

very easy with the Si4732. The audio output is connected to the microphone input of my PC. This way my PC's recording and volume controls could be used. WSJT-X (or any other WSPR decoder) that utilizes the soundcard can be used. This works well for decoding FT8 and other digital modes.

Fldigi decoder also works well with this little receiver. Station W1AW is received regularly at 7.095 MHz broadcasting in CW, Baudot, PSK31 or MFSK16 modes. It has also been used to decode NAVTEX at 518 kHz with excellent results. Although NAVTEX signals are designed to propagate only 250 miles at night, I have been successful in receiving many stations, such as Portsmouth, Charleston, Miami and a Canadian station on Lake Superior, many of them 600 miles or more in distance. US Coast Guard transmissions at 8.4165 MHz, 12.748 MHz, and 12.579 MHz of WEFAX and SITORB were received strongly here.

NanoSSB RX Final Thoughts

Presented here are the results of experimentation with the Si4732. This chip is a marvel of technology. Although it was not primarily designed for SSB, it can be made to work in this mode. The DSP in the chip works well for sideband rejection and audio filtering.

Realistically speaking, this chip performs like many other low cost shortwave receivers on the market. In SSB mode the Si4732 (or Si4735) has no noise reduction or any way to control the AGC for SSB. The BFO is not accurate for setting WSPR or other data bands unless it is calibrated as discussed here.

This chip is a good receiver for CW, WSPR, FT8 and other data modes such as NAVTEX. It is a versatile performer, covering frequencies from below the AM broadcast band to 30 MHz.

From a cold start, it takes a few minutes for the frequency to stabilize. This is expected since there is no temperature compensation. This drifting is particularly noticeable at the higher frequencies above 10 MHz. After this period it's relatively stable. You can tell when it stabilizes by looking at the signals in a waterfall plot in a WSPR program.

In later testing, I found that the conducted noise pickup of the Si4732 was reduced when it was powered by a separate supply. Here the 3.3 V power from the Arduino Nano was replaced by a separate low noise dc source. This also seems to improve the stability of the crystal oscillator.

Using the Si4732 NanoSSB receiver is enjoyable. If you have any interest in this chip please join one of the groups mentioned here. Hopefully you enjoyed this article as much as I had writing it. Many thanks must go to Ricardo Lima Caratti, PU2CLR, for all his work in producing a nice Arduino library for the Si47xx family of chips.

[Photos by the author].

George R. Steber, PhD, is Emeritus Professor of Electrical Engineering and Computer Science at the University Of Wisconsin-Milwaukee. He is now retired, having served over 35 years. George, WB9LVI, has an Advanced class license, is a life member of ARRL and IEEE and is a professional engineer. He has worked for NASA and the USAF.

His last article for ARRL was "An Ultra Low Cost Vector Network Analyzer" in the Jan./Feb. 2020 issue of QEX. *George also recently penned an article on the amazing story behind "The Discovery of Radio Waves" in the Jan./Feb. 2019 Issue of* Nuts and Volts Magazine. *He also addressed the conundrum of expanding space with constant energy density in his article on "Dark Energy and the Expanding Universe" in the Mar./Apr. 2019 Issue of* Nuts and Volts.

George lectures occasionally on science and engineering topics at the University. He is currently involved in cosmic ray research and is developing methods to study them on a global basis. When not dodging protons, pions and muons, he enjoys WSPR/FT8 amateur radio, racquet sports, astronomy, and jazz. You can reach him at **steber@execpc.com** *with "Nano" in the subject line and email mode set to text.*

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NanoVNA SMD Tweezers

Build this tweezers probe for connecting to and measuring SMD components with a NanoVNA.

As an MF/HF/VHF circuit design hobbyist I have long wished to own inexpensive instrumentation that I could use to measure passive RF surface mount device (SMD) components at the intended frequency of operation. One slick but pricey handheld commercial instrument has a mechanical design based on the tweezers concept. For two pin passive RCL SMDs with exposed pins on opposite ends of the chip the tweezer probe concept permits a quick and easy connection method by simply clamping the tweezer contacts onto the component terminals. However a significant disadvantage of at least one commercial instrument that uses the tweezer concept is its frequency of measurement is 10 kHz or less.

The tweezer probe concept can also be useful for component identification, since most L/C SMD chips do not have any markings. If they become separated from the original packaging they cannot be visually identified. A tweezer probe accessory for a frequency agile L/C meter can provide a convenient method for measuring the value and frequency dependent characteristics of an unmarked chip.

The recent development and marketing of an inexpensive, handheld portable, battery powered vector network analyzer (VNA) instrument has opened up a whole new measurement horizon for the RF design hobbyist on a budget. Known as the nanoVNA, it offers measurement bandwidth capability up into the UHF region, which is more than sufficient for the measurement of components intended for most HF and VHF applications. Internet links for some informative sources are provided in the notes.

This article describes the design, construction and use of a low cost tweezers probe for the nanoVNA that adapts the nanoVNA for measuring LCR RF passive SMDs across a user specified swept frequency range up to 150 MHz. Supplementary info is provided at **www.arrl.org/QEXfiles**.

Figure 1 shows the nanoVNA with the tweezers connected to the channel 0 (CH0) port via a 2 W SMA dc - 6 GHz coaxial fixed attenuator, (**https://www.aliexpress.com/**), which provides improved measurement accuracy in some cases. The cable connected to the CH1 port is not used for this application and is left terminated with a 50 Ω resistive load. The calibration box that is shown above the nanoVNA is used for providing reference standards

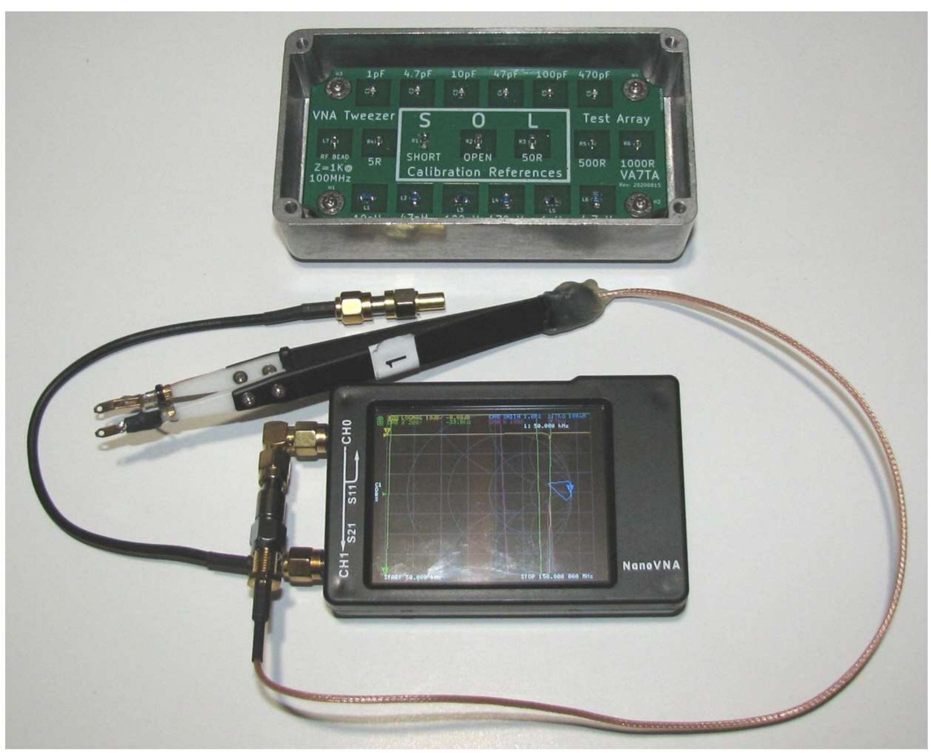

Figure 1 — NanoVNA tweezers connected via 6 dB attenuator.

for tweezer probe calibration, and to also provide a range of LCR tight tolerance SMD references for performing measurement comparison checks. Accuracy examples are reported in **www.arrl.org/QEXfiles**.

NanoVNA Tweezer Construction

Following several failed attempts to obtain an inexpensive tweezer design that would be reasonably practical for a hobbyist to make, and that would also stand the test of time, I settled on the design shown in **Figures 1 to 7**. This design meets my requirements, and continues to work as described after making hundreds of measurements.

Figure 2 shows the specialty parts needed for making a pair of tweezers. All the parts were purchased online. The total cost for the pair of tweezers including cable, spade terminals, one 6 dB attenuator and one 90° SMA adapter was less than $20. I built two tweezer probes to have a spare available, and because there was very little additional cost to make a second probe. Additional supplies not shown are tiny cable zip ties, shrink tubing, hot glue (or equivalent bonding agent), parts needed for the reference box, and general electronic shop supplies.

The SMA-to-SMA RG178 coaxial cable jumper **[2]** shown in **Figure 2** is one meter long. I purchased a prefabricated 2 m long SMA cable, and cut it in half to provide two 1 m coaxial leads needed for the pair of tweezers. A very important feature of the RG178 coax that it uses a PTFE dielectric, which can withstand soldering temperatures without melting. With its small diameter and stranded center conductor RG178, it is sufficiently flexible for this purpose. Although the photos show the cables with female SMA connectors, a cable with male connectors would be a better choice because it would permit direct connection to the nanoVNA without the need for an adapter (although a 90° male-to-female adapter is recommended). Also the cost would be slightly lower.

The tweezers **[3]** have tips made of material that seems similar to PTFE (they are described by the seller as ceramic) and can also withstand soldering temperatures. The tips appear to have good RF insulation characteristics.

I purchased the gold flashed spade terminals **[4]** as a lot of 10. The extra quantity purchased proved to be a wise choice as a few were wasted in the process of learning how to attach them to the tweezer tips.

The preparation of the two cable ends are created by bisecting the coaxial jumper to make the pair of leads is shown in **Figure 3**. As shown, I removed about two inches (5 cm) of jacket. I threaded the center conductor through the braid at the edge of the jacket. Then I stripped about a quarter inch of dielectric off the ends exposing the center conductors for soldering to the spade terminals.

Figure 4 shows the spade terminals attached to the tweezer tips, which I found to be a bit of a tricky procedure. I slid the spade lug onto the tip with the point of the tip extending underneath the small tab that pokes out the back of the lug. I tightened the wire clamps of the lug around the tweezer

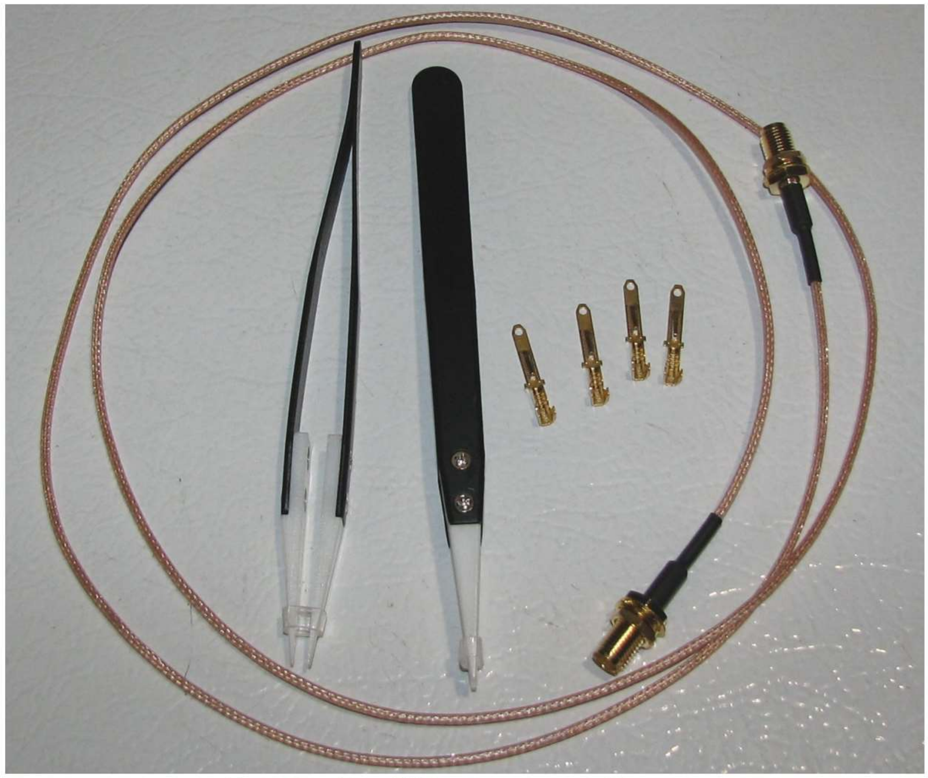

Figure 2 — NanoVNA tweezers assembly parts.

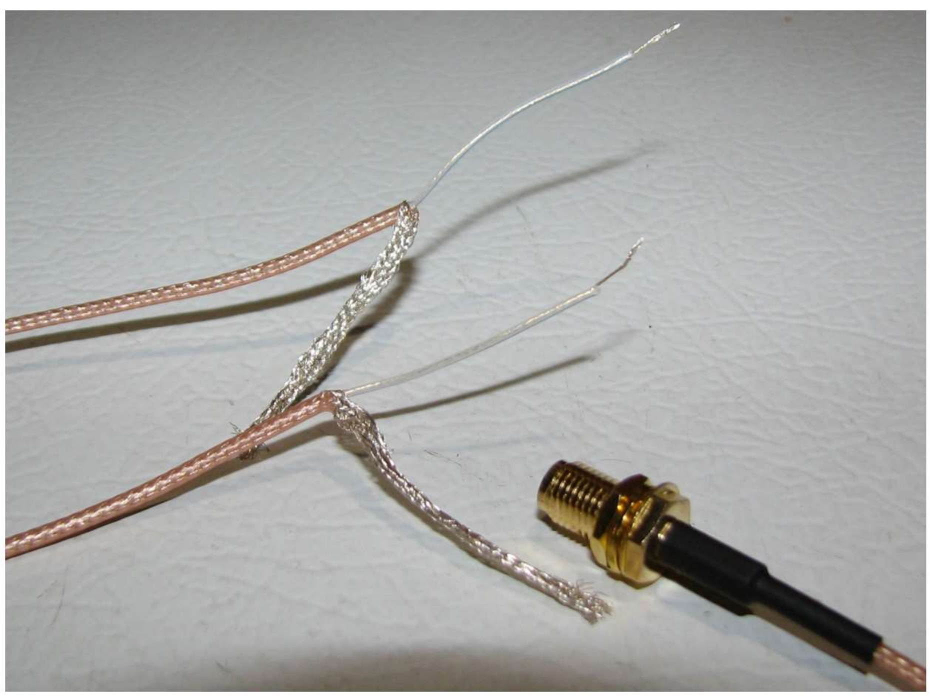

Figure 3 — Dissected cable tweezer connection end preparations.

Figure 4 — Spade lug contact mounted on tweezer tips.

tips with pliers. Then I aligned the tips of the spades so that they became flush with tweezer closer. I then curved the spades towards each other so that only the ends of the spades touched each other when the tweezers were closed. Finally, I applied solder as shown to stiffen the spade backs and to create a form around the tips. I found at this stage that it is pretty easy to pull the spades off the tweezer tips, however, don't despair. Once I attached the cable and applied a small drop of fast setting glue to the clamp area I found that the spades were held in place. The main objective at this point is to have the lugs aligned and attached with a good fit. **Figure 5** is a more detailed view of the spade lug attached to the tips.

Figure 6 shows the attachment of the prepared cable end. The outer conductor is soldered to one terminal and the center to the other. Here strain relief is very important. I used a tiny nylon cable tie to secure the cable jacket to the terminal on the shielded side.

Once I soldered the center conductor to the second terminal, I slid heat shrink tubing over the center conductor and then shrank it to secure the dielectric to the spade terminal. This prevents the flexing of the center conductor wire at the solder connection during tweezer usage. Without this strain relief I found that the wire would break off after only a few dozen measurements due to insufficient bending radius metal fatigue.

Figure 7 shows the completed tweezers.

I applied hot glue to secure the cable to the hinge end of the tweezers to keep the cable clear of the work area. As a final step to secure the tips, I carefully applied a small drop of quick setting Super Glue® to the wire clamp ends of the terminals and allowed it to set with the tips elevated to ensure the glue would not migrate down onto the spades.

A 90° adapter for connection to the nanoVNA is recommended to reduce leverage strain on the nanoVNA port 0 connector. A side benefit is that the 90° adapter helps prevent the rotation of the nanoVNA screen away from the direct view of the user while the probe is being shifted into position for clamping onto the device under test (DUT).

Loose Component Testing Tray

During the early proof of tweezer concept evaluation, I discovered that to prevent loss of parts, a tray with a perimeter wall was needed to place loose SMD components into for measurement. It is pretty easy to have a chip catapult away from the tweezer tips thus a testing tray is essential. An inverted screw-on plastic food container lid about 10 cm (4") in diameter with a 1.5 cm (5/8") threaded lip, as shown in **Figure 8**, was found to serve the purpose quite well. It is important to place stick-on rubber feet on the flat top as shown in **Figure 9**. The rubber feet are necessary to stop the lid from sliding around on the desktop.

At the onset of this development effort I

Figure 5 — Spade lug contacts installed and aligned.

Figure 6 — Cable connections to spade lugs with strain relief.

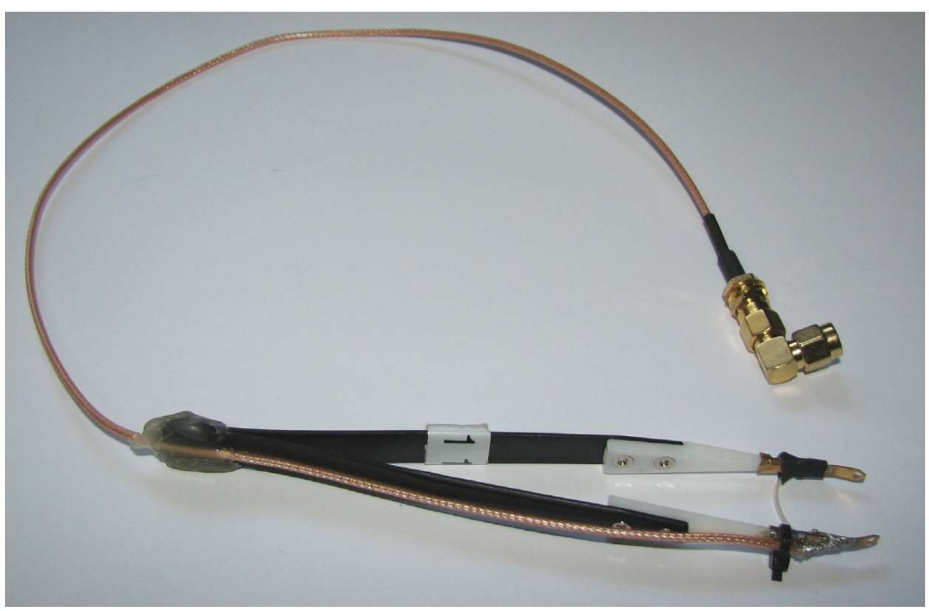

Figure 7 — Tweezers assembly complete showing cable strain relief points and 90° adapter.

Tweezer Tip Calibration and the RF Reference Plane

Those already familiar with the calibration of the nanoVNA will be familiar with the use of the factory supplied coaxial connector references consisting of OPEN, SHORT and LOAD (OSL) SMA components. It is presumed here that owners of nanoVNA instruments will already be familiar with the touch screen menu selections and calibration procedures. Detailed calibration instructions can be found on the nanoVNA user group internet web site; **https://groups.io/g/nanoVNA-users/**. In general following a RESET to clear previous calibration data, the calibration procedure consists of connecting the OSL terminations in sequence to the CH0 RF bridge port, usually via a short coaxial test lead. This enables the nanoVNA to measure and save the resulting complex impedance value data for the OPEN, SHORT, and ideal 50 Ω resistive LOAD for each frequency step within the defined spectrum segment. The device under test (DUT) is then connected to the **same point** used for the OSL terminations. Once the DUT is connected, the MPU cyclically measures the DUT impedance for each frequency step and updates the data record about once per second. By correcting for the previously saved calibration reference data, the MPU mathematically determines the complex impedance of the DUT for each frequency step and updates the user's screen display accordingly. The obtained accuracy of the measurement is mainly dependent upon the RF impedance bridge range of measurement limitations, the calibration accuracy, computational accuracy and the quality of the connection to the DUT. Of significance is the common test connection point that is used for both the calibration OSL references and the DUT. This very significant connection point is the **reference plane.**

For the nanoVNA tweezer probe described here, the reference plane is formed by the tweezer contact tips. To perform the OSL calibration it is necessary to connect the tweezer tips sequentially to open, short and load terminations. This is similar in concept to the familiar procedure for calibrating with the usual SMA coaxial reference plane and the factory provided SMA component reference terminations. To facilitate tweezer probe calibration the reference box shown in **Figure 12** and described in the main text of this article was developed.

Figure 8 — Loose SMD component measurement tray with initial sol calibration references.

carefully glued the 0805 SMD OSL (Open / Short / Load) reference resistors (**Figure 8**) to the inside of the tray for calibrating the tweezers. This was difficult to do and took several attempts as the glue has a tendency to insulate the chip contacts but ultimately it provided the basic essentials needed to prove that the tweezer concept would work okay with the nanoVNA .

Although this simplistic approach is all that is basically needed to calibrate the tweezers, a proper reference box is a much better solution. I made my first reference box by simply soldering chips down onto a prototype board with 0.1 inch spaced isolated pads.

The dark hole that appears near the center of the tray is the test cavity for measuring inductors that will be described in more detail in the next section. The electrical tape patch on the bottom that appears in **Figure 9** is used to attach the bottom plate for the test cavity. The bottom plate consists of a 0.25 inch disk of very thin but rigid plastic sheeting obtained by the use of a paper punch.

Inductor Testing

Details of inductor testing are in the **QEXfiles** webpage. **Figure 10** is a digital microscope view of the underside of the inductor package, which illustrates its vulnerability. The extremely fine copper wire leads are totally exposed, and can be easily broken if rubbed by the tweezer tips. Thus it is necessary to ensure tweezer tip contact is limited to the wrap around ends of the solder terminals. This is very difficult to ensure unless the part is reasonably well fixed in place so that it cannot move around or roll over.

If used with care the test cavity near the center of the test tray (**Figure 8**) can be used to hold 0805 size inductor chips with the wrap around terminals exposed for relatively safe tweezer connection. **Figure 11** shows that when the chip is placed into the cavity upside down the wrap around contacts become exposed. Although the chip remains loose, its range of movement is quite restricted. The cavity consists of a hole slightly larger than 2.5 mm in diameter that was made with a 7/64" drill bit. **Figure 9** shows that the hole is capped on the bottom so that the part cannot fall through.

Using a 1/4" drill bit I manually shaved off the sharp edge of the cavity entrance at an angle (i.e., chamfered) to about half way through the thickness of the tray material. The resulting sloped circular edge guides the tweezer tips towards the wrap around terminals on the exposed chip base. Thus, when upside down in the cavity, the top hat of the chip is pretty much blocked by the 2.5 mm hole diameter near the bottom while the wrap around terminal surfaces are exposed by the chamfered cavity entrance.

It is important when using this method for inductor testing that a magnification hood (or equivalent) be employed to provide a clear view. Before grasping the wrap around terminals with the tweezer spade tips one must ensure the chip is placed properly within the cavity, see **Figure 11**, and that the spade tips make contact only to the ends of the chip away from the vulnerable coil wire. After a bit of practice this is quite easy to do, however it may take a few tries to get a good solid connection. The quality of the connection can be determined by watching the nanoVNA real time display for a steady and proper inductance trace near the Smith chart upper half circumference.

Figure 9 — Bottom of measurement tray with adhesive rubber feet.

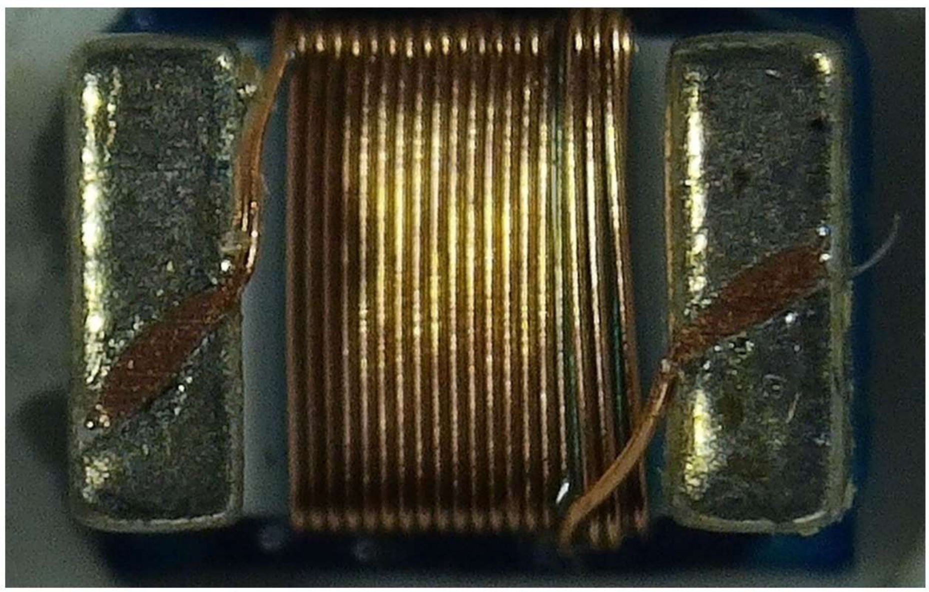

Figure 10 — Microscopic view of 0805 inductor coil vulnerability.

Reference Box Construction

The reference box (**Figure 12**) is based on a professionally manufactured version 2 PCB board design (seems I always find room for improving my initial PCB artwork designs that isn't apparent until the first prototype is tested). The board fits into an economical die-cast aluminum box. The PCB provides stray coupling isolated footprint pads for mounting an array of close tolerance SMD 0805 size passive components. The values of the reference positions are clearly labeled with large silk screen fonts. A proper reference box similar to the one shown here is recommended as in addition to providing a set of comparison reference components. It also provides a tutor platform for gaining experience with using the nanoVNA tweezers. The reference box described here provides footprints for mounting 19 passive RLC components. Three of the pads are used for mounting the components that form the OSL calibration references. The additional 16 are used for mounting tight tolerance RLC components that have a wide range of values. The reference box schematic and details are on the **QEXfiles** web page.

The provision of the die-cast aluminum enclosure protects and stabilizes the PCB during use. The PCB, which can be used as a template to mark the holes for drilling, is mounted with 1/2" standoffs. **Figure 13** shows stick-on rubber feet installed on the bottom of the box to prevent it from sliding around, and also to protect desk top surfaces. The rubber feet by 3M are my favorites as they seem to stick to a surface better than most alternatives.

A parts list intended as a guideline for the reference box to help with parts procurement identification details is available from **QEXfiles**. A PCB manufacturing Gerber file package is also provided for those who may wish to procure a batch of boards. To avoid possible disappointment, I recommended that the PCB files be checked with a Gerber viewer prior to ordering for confirmation of file integrity and for taking a close look at the design details. I have a limited supply of boards available for purchase for those who just want a single board and do not

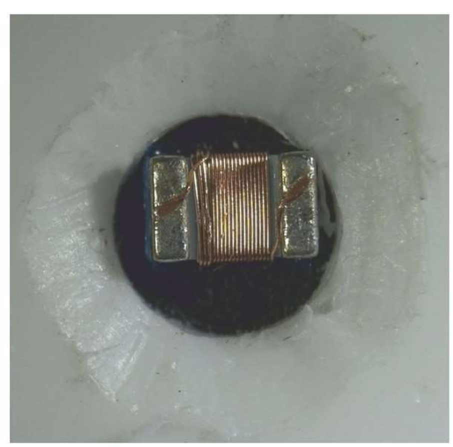

Figure 11 — 0805 SMD inductor upside down in test cavity with contacts exposed.

Figure 12 — Assembled component reference box.

Figure 13 — Rubber feet on bottom of reference box.

wish to have a batch manufactured. Should a local area interest group wish to share the shipping costs, a batch purchase from an online PCB manufacture would typically prove to be the most economical source.

NanoVNA Tweezer Calibration

The tweezer calibration process is fundamentally the same as the calibration procedure for making coaxial cable connection measurements. The only difference is the use of the tweezers for making the OSL reference connections to the reference SMD devices within the reference box instead of connecting the factory supplied SMA coaxial references. For further details regarding the calibration reference plane see the **Sidebar 1**.

The calibration procedure for the use of the nanoVNA tweezers is relatively convenient compared to the steps needed for conventional SMA connection calibration. Using the tweezers it is very easy to quickly switch between the three OSL references. Once the tweezer calibration is completed the calibration and setup data can be saved in one of the nanoVNA memories for future convenience, just as is done with coaxial connections.

Prior to calibration, the frequency spectrum segment for measurement must be decided upon. The nanoVNA is designed to provide 101 frequency steps per sweep. For tweezer calibration any spectrum segment between 50 kHz and 150 MHz can be specified. Although it can be convenient to sweep a wide spectrum segment, if it is too wide the gaps between the resulting large frequency steps may result in a failure to make measurements at some important frequencies of interest. For example if set for a wide 50 kHz to 150 MHz sweep the resulting 1.5 MHz step size could be too large to properly measure components intended for use in a relatively narrow bandwidth circuit.

For this article it is apparent that calibration should be done for at least two sweep ranges. A range of 50 kHz to 150 MHz would cover the HF and VHF segments in roughly 1.5 MHz steps, and a range of 50 Hz to 15 MHz would cover the LF to MF to HF segments up to the 20 meter band with roughly 150 kHz steps. These two ranges will be used here with some minor exceptions as found necessary for particular cases.

Any of the 5 nanoVNA memory locations can be used for storing calibration and display setup settings. Here, memory 1 will be used for storing the wider 50 kHz to150 MHz sweep setup data, and memory 2 for the narrower 50 kHz to15 MHz low frequency segment. Memory 0, which is automatically loaded as default during power-up, was left available for the more conventional coaxial connection VNA applications. Consequently it is important to remember that for this article, each nanoVNA power-up cycle for tweezer testing will require using the menu to recall the tweezer data and settings from either memory 1 or 2 as needed. For the clearest component value readability it is desirable to have the SMITH trace values shown in the top right corner of the screen, (see the Figures in the QEXfiles), away from the Smith chart circle clutter. The trace FORMATS functions will provide the top right display of the component value once LOGMAG trace 0 is disabled after calibration as recommended below. For starters all traces must be set to channel 0 and the scales set as shown. It may be desirable to change the scale and the stop/start frequencies as required to match DUT characteristic ranges. Initially the nanoVNA menu selections should be set as follows:

DISPLAY>TRACE:
Trace 0, Yellow: LOGMAG; scale 10/
Trace 1, Blue: REACTANCE; scale 200/
Trace 2, Green: SMITH; scale 1/
Trace 3, Red: RESISTANCE; scale 200/

Note: All traces must be set to channel 0.

STIMULOUS>
START
50K
STOP
150M (or 15M for the low band)

The following checks and procedures help ensure successful calibration and measurement accuracy. Confirm that all the SMA connector retaining nuts are snug. This is very important, because the nuts can work loose thus should be checked periodically. There are somewhat pricey torque wrenches available online designed specifically for tightening SMA connectors to proper torque specification.

To minimize hand effect capacitive coupling to the tweezer tips grasp the tweezers quite high, with thumb and index finger, around the mid point of the tweezer arms.

Hold the tweezers vertical, i.e. perpendicular to the calibration box PCB while alternately connecting to the OSL reference chips as directed by the nanoVNA firmware calibration function steps.

To reduce screen clutter during calibration, traces 1 and 3 should be disabled so that only the trace 0, LOGMAG, and trace 2, SMITH trace remain.

To calibrate from the menu top, select CALIBRATE > RESET then sequentially connect the tweezers to the OSL references while tapping the OPEN > SHORT > LOAD menu items, then select DONE. Confirm the calibration accuracy as follows:

When connected to OPEN check that the trace is just a small dot is at the right hand intersection of the Smith chart outer circle and the zero reactance horizontal center line.

When connected to SHORT check that the trace is just a small dot and is located at the left hand intersection of the Smith chart outer circle and the horizontal zero line.

When connected to LOAD check that the trace small dot (not a small circle) is in the center of the Smith chart circle.

While connected to the LOAD reference ensure the LOGMAG return loss trace is more negative than –40 dB across the entire spectrum sweep width.

NanoVNA tweezers measurement examples are on the **QEXfiles** web page.

Known Limitations

The tweezers may not be reliable when the measurement is influenced by inductor self resonance especially when the amount of stray self capacity is minuscule. If the reactance trace is curved at the test frequency the apparent inductance measurement result may be higher than the actual coil inductance. An error may possibly be due to a lowered self resonance frequency caused by stray capacity from the testing platform. Practically speaking this may not be a significant limitation since inductors are most commonly used in circuits that operate far below the self resonant frequency.

PC Software USB Port Control Enhancement

Personal computer USB port nanoVNA control freeware can be used to obtain large screen swept frequency response views of the measurements. Two apps that are particularly good are *NanoVNA-Saver* and *NanoVNA-App* **[5]**. The control software can streamline the measurement results acquired via the nanoVNA tweezers by providing swept frequency views of a large number of frequency-dependent passive component characteristics. Using the acquired data from the nanoVNA, the powerful PC software almost instantly calculates a large number of characteristics such as Return Loss, SWR, Quality Factor, Impedance Z, Complex Impedance, series equivalent values, parallel equivalent values and Admittance. Most parameters can be graphically viewed across the frequency spectrum segment of interest. In addition to providing excellent large screen views of component characteristics the screens and associated data can be captured for documenting measurement results. The nanoVNA screen captures shown In the **QEXfiles** page were obtained using the aforementioned apps.

Conclusion

The nanoVNA instrument adds a new dimension of low cost but powerful testing capability to the radio amateur's RF electronics workshop. It can provide a means to measure passive LCR component complex impedance values across user defined segments of frequency spectrum. The nanoVNA Tweezers accessory provides a convenient means for connecting the nanoVNA to SMD passive component packages for determining complex impedances and related values at user specific frequencies within the 50 kHz to 150 MHz range.

The nanoVNA Tweezers and associate components reference box can be an effective educational platform for those who wish to experiment with VNA component measurement and analysis. The measurements provide real-time views of component frequency-dependent characteristics. The use of the tweezers with the reference box can provide experience with many of the nanoVNA menu settings. The measurement results may enhance user knowledge and understanding of the RF characteristics of passive SMD components.

Under personal computer control additional characteristic parameters of interest can be obtained by running freely available advanced PC apps. The apps used to control the nanoVNA via the USB port can acquire the measurement data from a nanoVNA while employing a simple, time efficient tweezer connection to the SMD chips. This provides a convenient method for comparing component characteristics.

I wish to express my gratitude to Dr. James Koehler, VE5FP for our discussions that led to the development of the easy to construct test cavity for inductor measurement and for his ongoing support in general.

*Tom Alldread, VA7TA, was interested in electronics since grade school. In his teens, he repaired radio and television sets. He obtained his amateur radio license in 1965, and upon graduating from technical college obtained his commercial radio operator certification. He graduated from the Capitol Radio Engineering Institute Engineering Technology program. Tom worked in the telecommunications industry as a microwave, multiplex and VHF radio equipment maintenance technician, an instructor, an engineering standards and design specialist, and in the Middle East as adviser for long distance network operations management. Now retired, Tom and his wife Sylvia, VA7SA, live on Vancouver Island. Tom, is a member of The Radio Amateurs of Canada, enjoys operating CW, designing equipment, and supporting emergency communications. He was net manager for the SSB/CW 20 meter Trans-Canada Net (***www.transcanadanet.com***). His interests include microcontroller development projects associated with amateur radio. Tom won second place in the Luminary 2006 DesignStellaris contest and first place in the 2011 Renesas RX contest. Other hobbies include computing, RVing, hobby farming and bicycling.*

Useful internet links

https://groups.io/g/nanoVNA-users/.
https://zs1sci.com/blog/nanoVNA saver/.
http://www.gunthard-kraus.de/fertig_NanoVNA /English/.
https://hexandflex.com/2019/08/31/getting-started-with-the-nanoVNA-part-1/.
https://hexandflex.com/2019/09/15/getting-started-with-the-nanoVNA-part-3-pc-software/.

References

[1] **https://www.coilcraft.com/getmedia/ac56eabb-8678-4ca2-9604-c609886d68c1/Doc1287_Inductor_specifications.pdf**.
[2] SMA male connector RG178 cable 100cm; **https://www.aliexpress.com/item/32566647516.html?spm=a2g0s.12269583.0.0.2d483d67o6TRJA?)**
[3] Ceramic tweezers insulated straight tip ESPLB; **https://www.aliexpress.com/.**
[4] 2.8 mm male spade terminals, gold tone; **https://www.aliexpress.com/**.
[5] **https://github.com/NanoVNA-Saver/nanoVNA-saver**, and **https://github.com/OneOfEleven/NanoVNA-H/tree/master/Release**.

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A Pulse Generator For Making TDR Measurements

This pulse generator and your wide bandwidth oscilloscope comprise a time domain reflectometer.

Time Domain Reflectometry (TDR) is a good method to detect cable faults or simply to measure the length and impedance of transmission lines. A TDR system basically consists of a fast rise (or fall) time pulse generator and an oscilloscope as a display device. It used to be quite impractical for use in amateur radio work when oscilloscope prices were many thousands of dollars, but with prices now below $500 for a 200 MHz bandwidth oscilloscope, this little piece of test equipment has become a reasonable addition to the ham shack. Using it is easy as is shown in **Figure 1**.

Design

The device described certainly isn't laboratory quality, but should be sufficient for most amateur use. The schematic (**Figure 2**) consists of two cross coupled monostable multivibrators (one-shots) to generate a 2 μs wide pulse every 200 μs. The 2 μs pulse width will work to test any reasonable cable length. A narrower pulse width and a faster rise time would allow for better resolution of things like connectors and splices. However that would require a higher bandwidth oscilloscope to detect these smaller reflections. This device was designed to give adequate results with affordable equipment. The oscilloscope should have a minimum bandwidth of 100 MHz to get good results. Note that this is bandwidth and not sampling rate. Lower bandwidths will function, but the transitions will be smoothed and not as easily discerned. All of the following oscilloscope pictures, except for **Figure 10**, were taken with a 200 MHz bandwidth. **Figure 10** uses a 20 MHz bandwidth to show the transition smearing. The 200 μs repetition rate was chosen to give a stable trace on the oscilloscope and to let the line settle before the next pulse is sent. Neither of these time values is very critical and can be modified by changing the resistor and/or capacitor values of the timing components on the one-shot multivibrators.

The output of the 2 μs one-shot is fed to a 74AC00 quad NAND gate to increase the edge rate and drive capability. Two of the gates are used in series. This sharpens the edge rate of the output signal. The 74AC series of digital circuits were a nightmare to design with because of the fast edge rates. Noise and EMI were a constant concern. In this case however that fast, high-current-drive edge rate is exactly what we're looking for. The other two gates could be connected to the complementary one-shot output, if desired, to create a differential TDR output signal. Any unused inputs must be tied to either the power supply or to ground. They cannot be allowed to float.

The circuit draws very little current because of the use of 74HC and 74AC series parts. The larger switching currents happen at a low duty cycle so the overall average current is quite low. I measured about 3.5 mA, and about 1.2 mA of that is from the LED alone. The unit is powered by four AAA batteries. Most test equipment now comes with USB ports. Since the

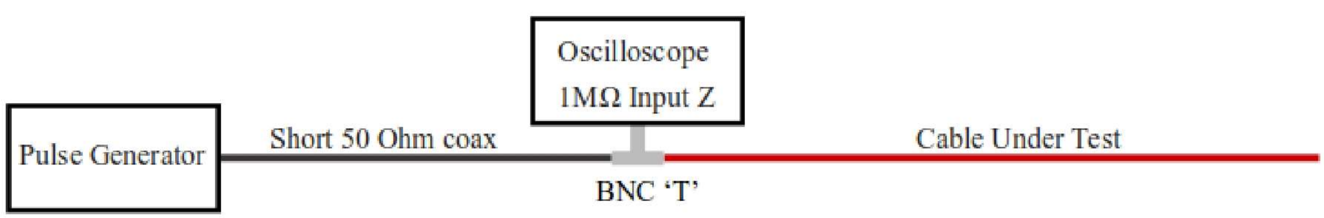


Figure 1 — Cable test setup.

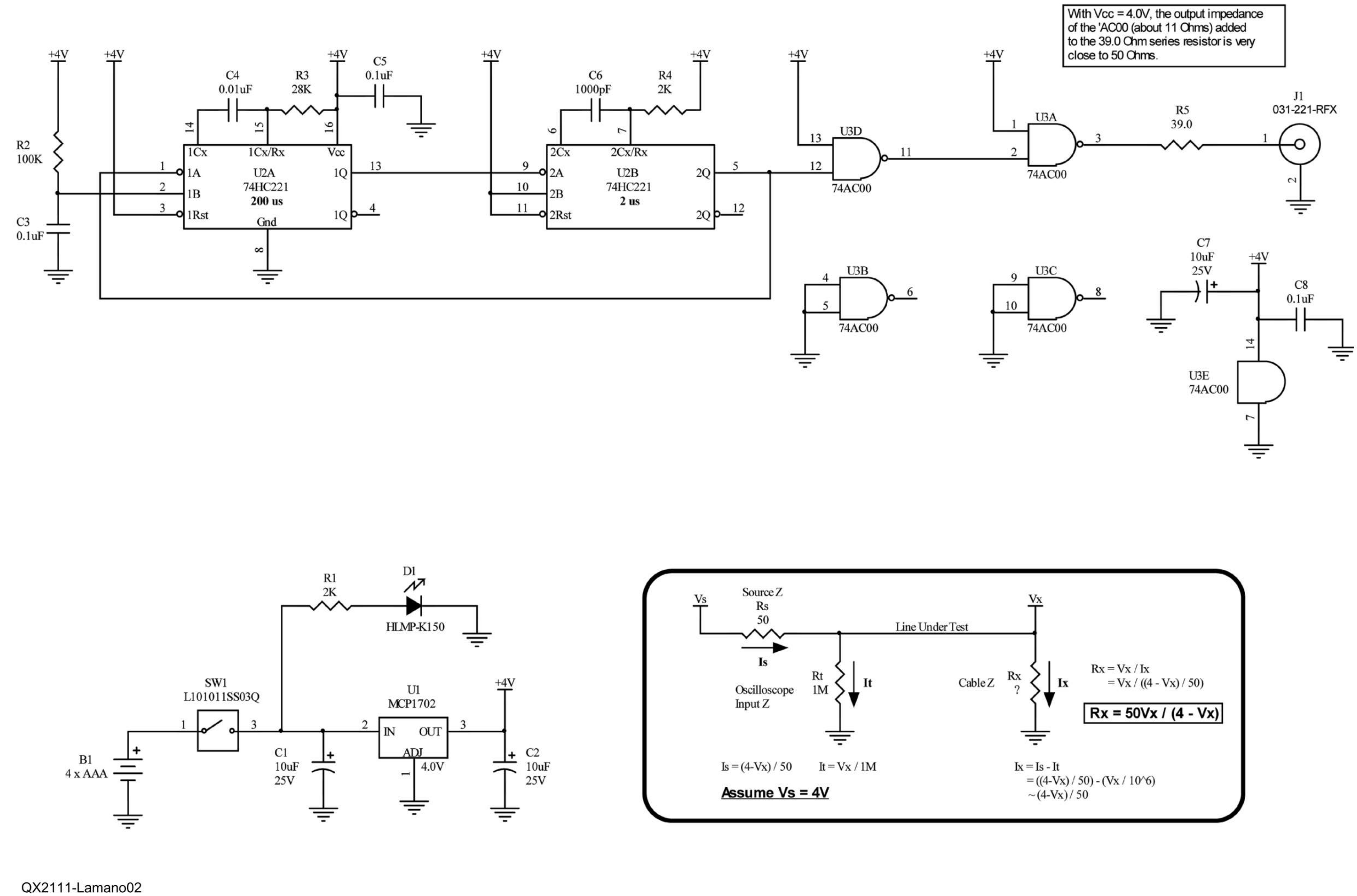


Figure 2 — Pulse generator schematic.

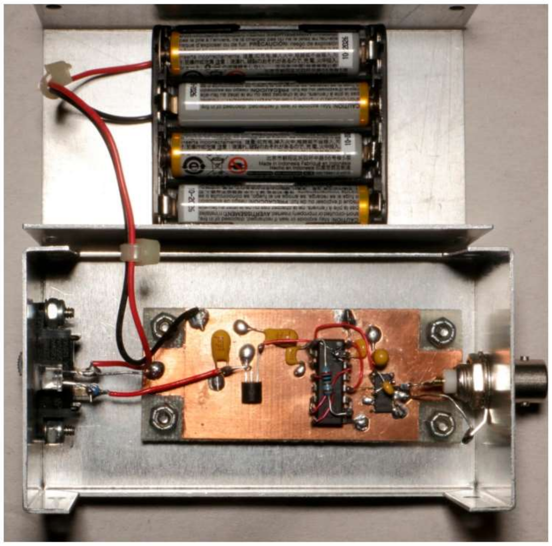


Figure 3a — The complete unit.

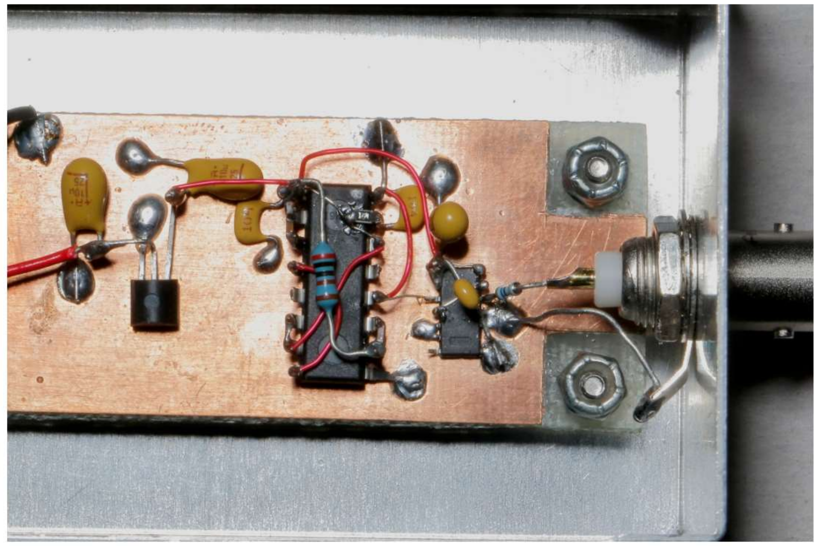


Figure 3b — Close up of the wiring.

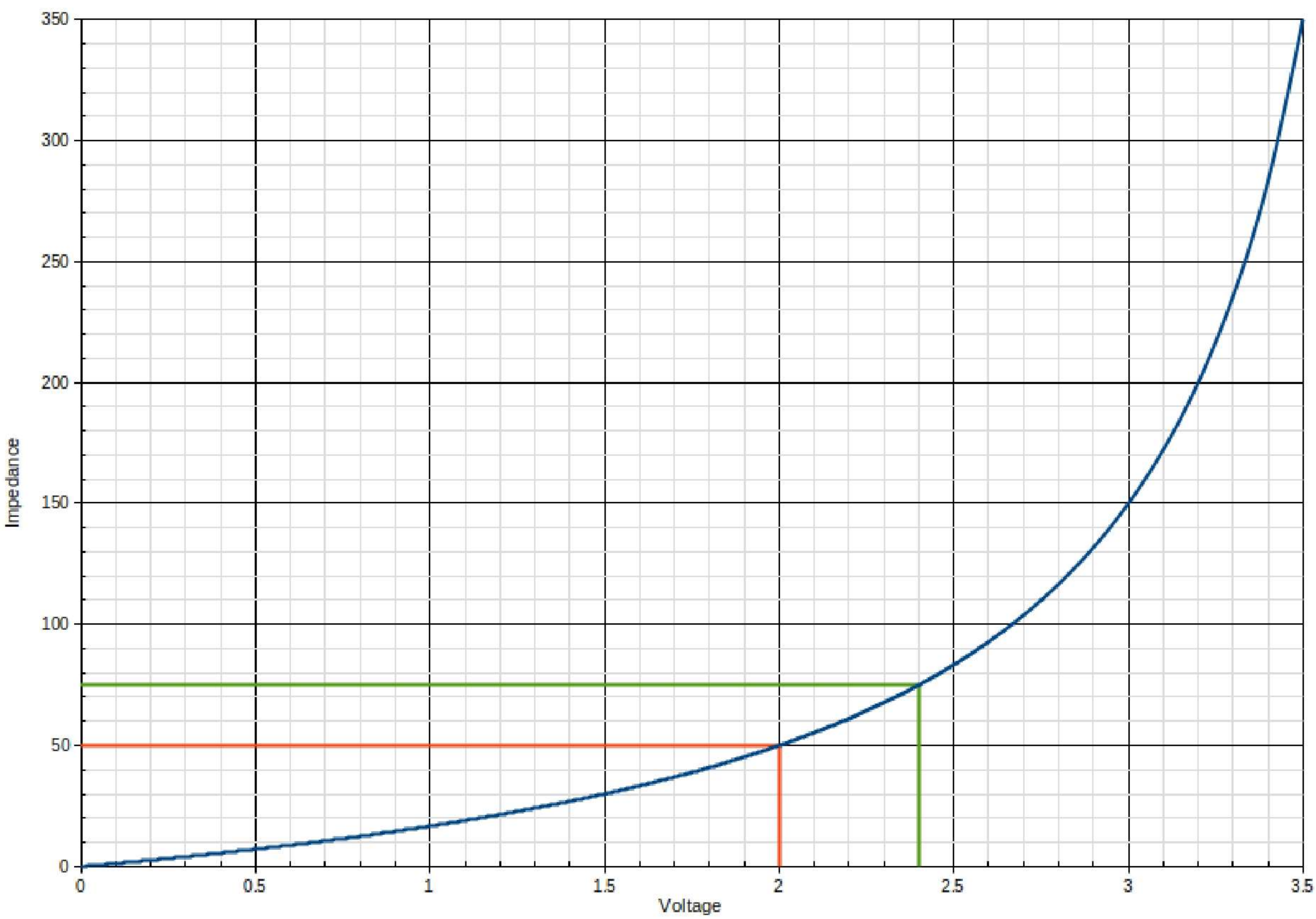


Figure 4 — Voltage to impedance graph.

pulse generator is of little use without the oscilloscope, you can add a USB connector to the design and use it to power the device while doing away with the batteries.

A TDR functions by launching a current pulse into the transmission line. A voltage is generated as this current pulse moves down the line. The voltage is simply the current times the line impedance at any particular point. If the impedance changes, the voltage will change. This is reflected back to the source and seen on the oscilloscope. The distance to the impedance change can be calculated from the time delay and the propagation time of the particular cable. Since the wave travels to the discontinuity and then back, the delay time is one-half the time seen on the oscilloscope. The examples below show how the impedance and length are calculated.

Construction

The circuit is built "dead bug" style on a small (3" by 1-1/8") piece of copper clad circuit board material. This style of construction actually works very well for high speed circuitry because the point to point wiring eliminates the stray capacitance that would exist on a PC board. The copper layer is used as a ground plane to create a low impedance ground connection. This ground plane should be connected only to the enclosure at the output BNC connector to avoid ground-loop currents. All pins of all parts that connect to ground are bent over and soldered directly to the ground plane.

The 74HC221 dual one-shot is in a standard 16-pin DIP. This package is easy to work with. 0805 size surface mount technology (SMT) parts fit between the pins, eliminating the need to run wires when parts are connected between adjacent pins — for example U2A-14 and U2A-15. This part, along with the voltage regulator, can be built on perf board to make wiring easier.

I used the 74AC00 SMT part to minimize lead inductance. It's a little harder to work with, but no discrete components are needed around the part so connecting to it is manageable. Bypass capacitors must be placed as close as possible to the power pin of the 74AC00 to create a stiff supply voltage. The 39 Ω series resistor on the output makes the output impedance close to 50 Ω and swamp out any variations in the output impedance of the 74AC00. This is a small 1/8 watt metal film resistor chosen to minimize parasitic inductance and stray capacitance. It is connected as closely as possible between the output pin and the BNC connector. The enclosure is a 4" L by 2-1/8" W by 1-5/8" H aluminum box. The board itself is mounted on short standoffs. **Figures 3a** and **3b** show the construction details.

Calibration and Use

To achieve decent accuracy, the circuit is powered from a 4.0 V regulator with the output voltage referred to as *Vs* below. This keeps the output pulse amplitude at a constant value. Knowing this voltage allows us to calculate the impedance based on the reflected voltage seen on the oscilloscope.

Ignoring the 1 MΩ input impedance of the oscilloscope, the circuit is simply a voltage divider consisting of the output impedance of the pulse generator (*Rs*) and the transmission line impedance (*Rx*). The 1 M Ω input impedance can be safely ignored as it is orders of magnitude larger than the paralleled transmission line impedance. The voltage seen by the oscilloscope is then

$$Vx = Vs\frac{Rx}{(Rs + Rx)}.$$

Solving for *Rx*, the transmission line impedance is

$$Rx = \frac{Rs \times Vx}{(Vs - Vx)}.$$

In the typical case with *Vs* = 4 V and *Rs* = 50 Ω, this equation becomes

$$Rx = \frac{50 \times Vx}{(4 - Vx)}.$$

This typical situation is plotted in **Figure 4**.

This graph can be used to quickly find a good estimate of the line impedance without performing any calculations. The voltage to impedance values are shown for typical 50 Ω and 75 Ω lines.

If better accuracy is desired, the equation can be adjusted by making calibration measurements with the oscilloscope. First connect the pulse generator to the oscilloscope with the input impedance set to 1 M Ω. Measure the voltage between the baseline and the top steady state value. In **Figure 5a**, this is seen to be 4.040V as Δy in the bottom left corner. Next take a similar reading with the input impedance set to 50 Ω. This is shown in **Figure 5b** and measured 2.048 V. The current through the internal 50 Ω termination is then 2.048 V / 50 Ω or 41 mA. This current must also be flowing through the series output resistor. If we assume the drive voltage is still 4.040 V (it's typically slightly lower because of the loading), we can calculate the output impedance of the pulse generator as

$$Rs = \frac{(4.040 - 2.048)}{0.041} \text{ or about } 48.6\ \Omega.$$

The equation now becomes:

$$Rx = \frac{48.6 \times Vx}{(4.04 - Vx)}.$$

This equation is used in the following examples.

Example 1

The first example consists of 5' 7" of RG-58C/U connected to a BNC to mini-grabber adapter (6" leads), which is in turn clipped onto a leaded, 1/4 W, RN55 size, 100 Ω metal film resistor. **Figure 6a** shows cursor measurements of the coax section. The time delay is 17.4 ns, shown as ΔX in the lower right box. RG-58C/U has a delay of about 1.54 ns/ft. Since the delay measured is the round trip delay, the actual delay due to the cable length is one half that or 8.7 ns. Thus the length calculates to 8.7/1.54 = 5.65' or 5' 8".

The impedance calculation for the coax section is (48.6×2.056)/(4.04–2.056) = 50.4 Ω. **Figure 6b** shows the measurements for the resistor. We have (48.6×2.72)/(4.04–2.72) = 100.1 Ω.

So overall we have good accuracy in this example. The large bump in impedance at the end of the coax section is due to the two 6" wires on the BNC to mini-grabber adapter. These are just two separate wires and the spacing between them is large, resulting in the high impedance bump.

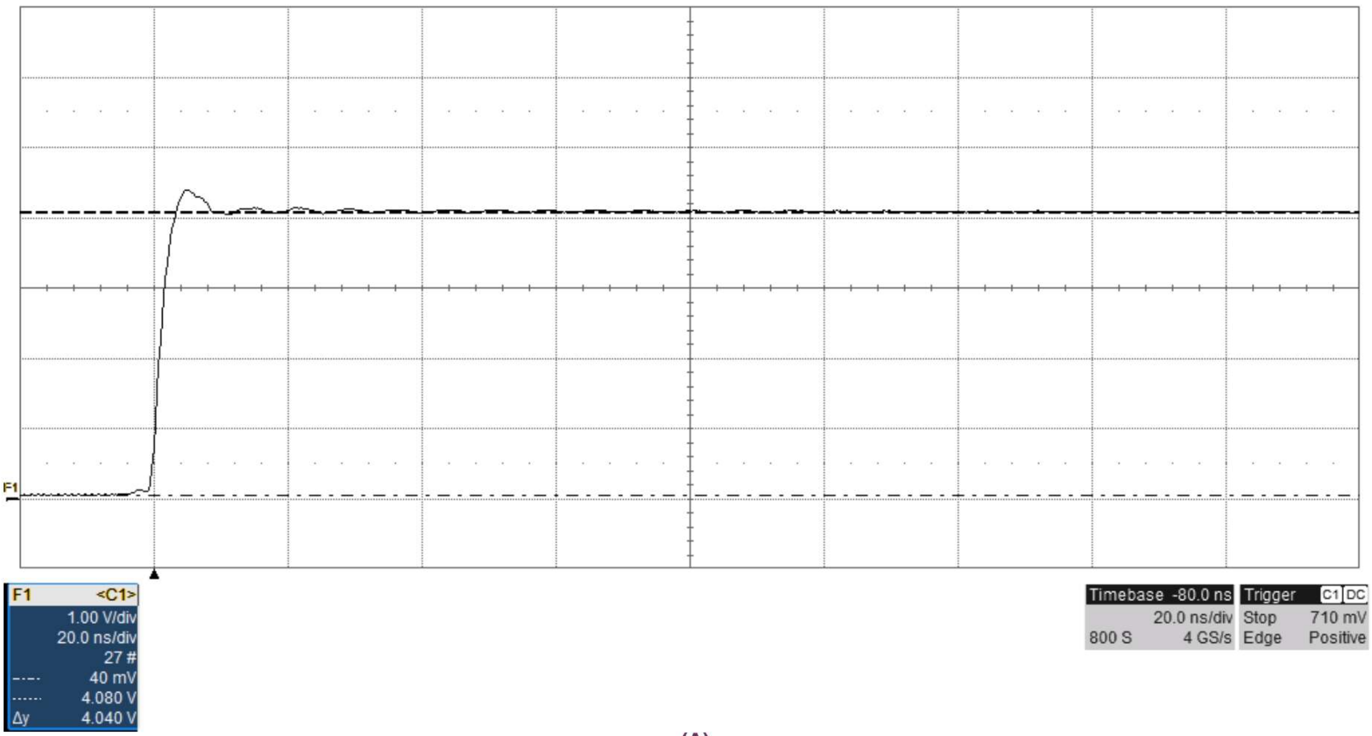
Example 2

The second example consists of 7'9" of Belden 8241 (RG-59/U) with a 47 Ω SMT resistor soldered directly between the center conductor and the shield at the end of the cable. Calculations are as in Example 1 with measurements from **Figures 7a** and **7b**.

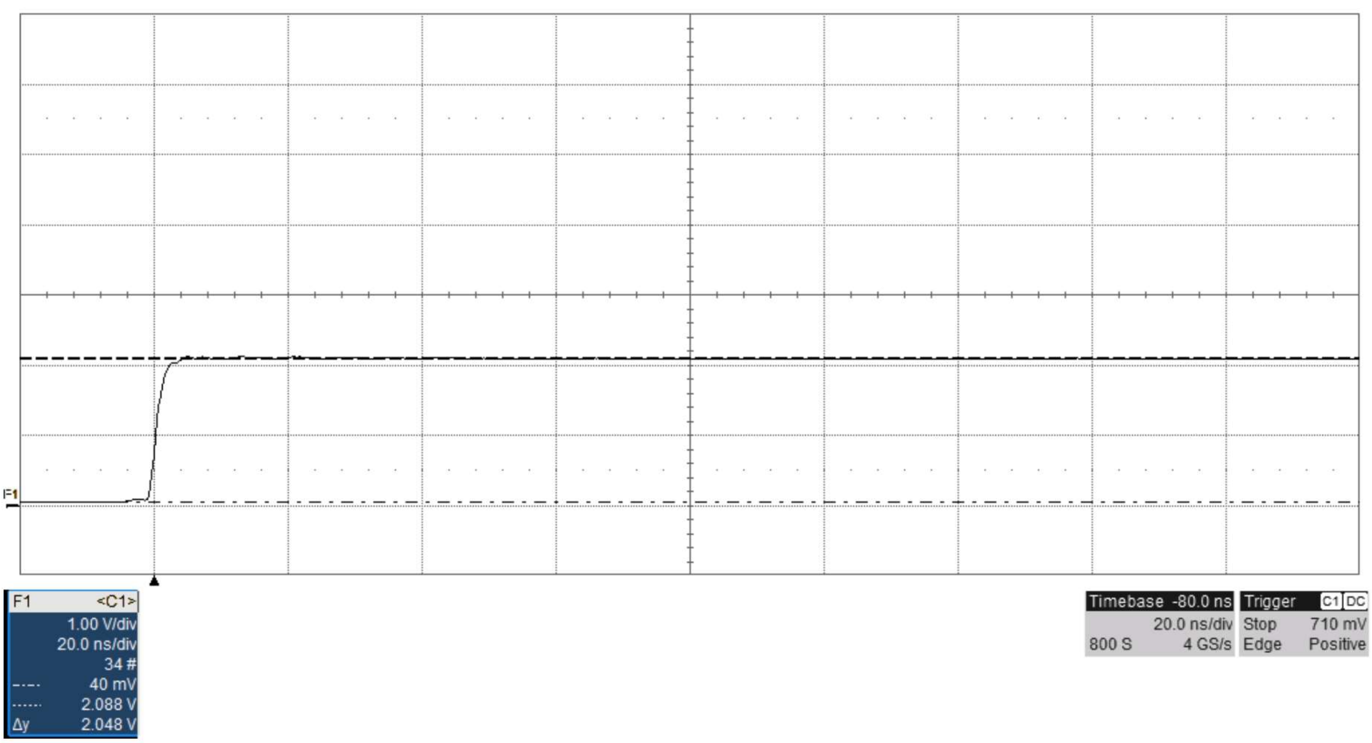
td = 24.2 ns so Cable Length is (24.2/2)/1.54 = 7.86 ft = 7' 10".

Cable impedance is (48.6×2.432)/(4.04–2.432) = 73.5 Ω.

Termination impedance is (48.6×1.984)/(4.04–1.984) = 46.9 Ω.

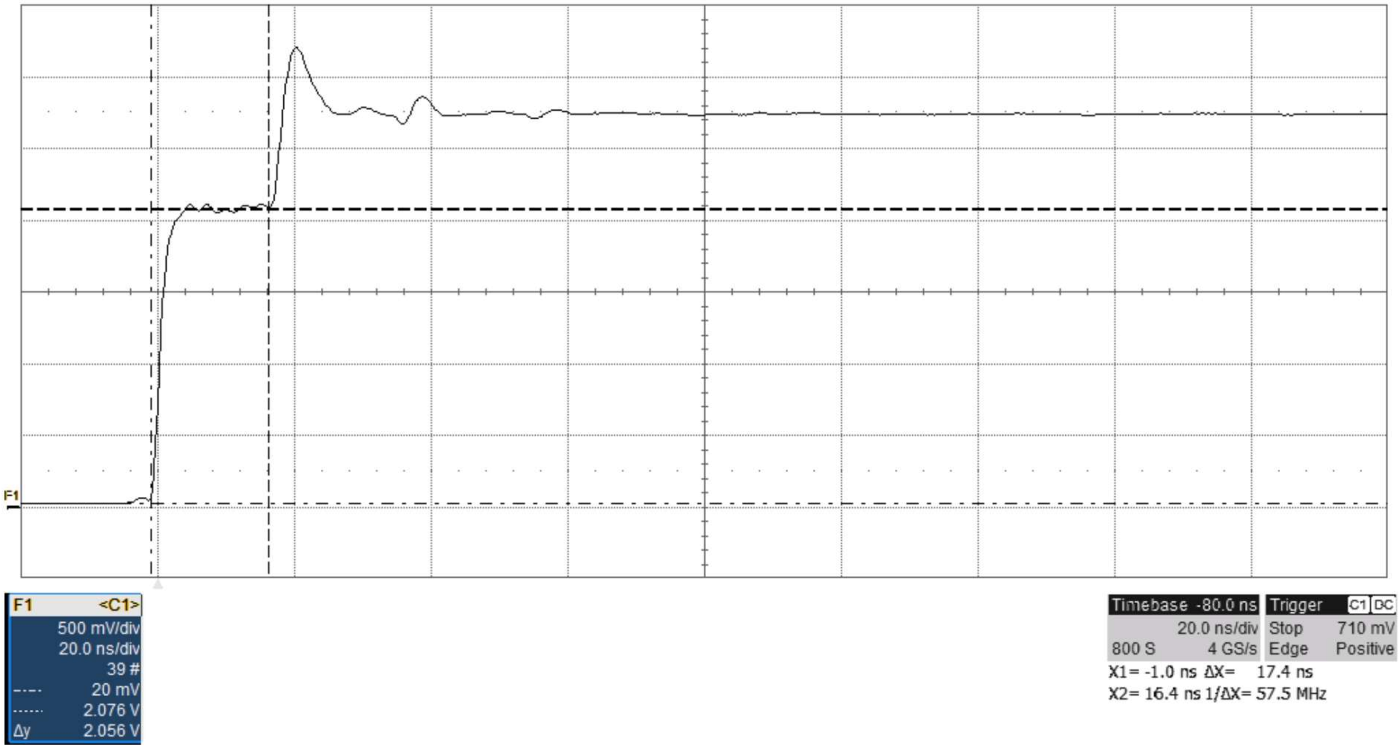


(A)

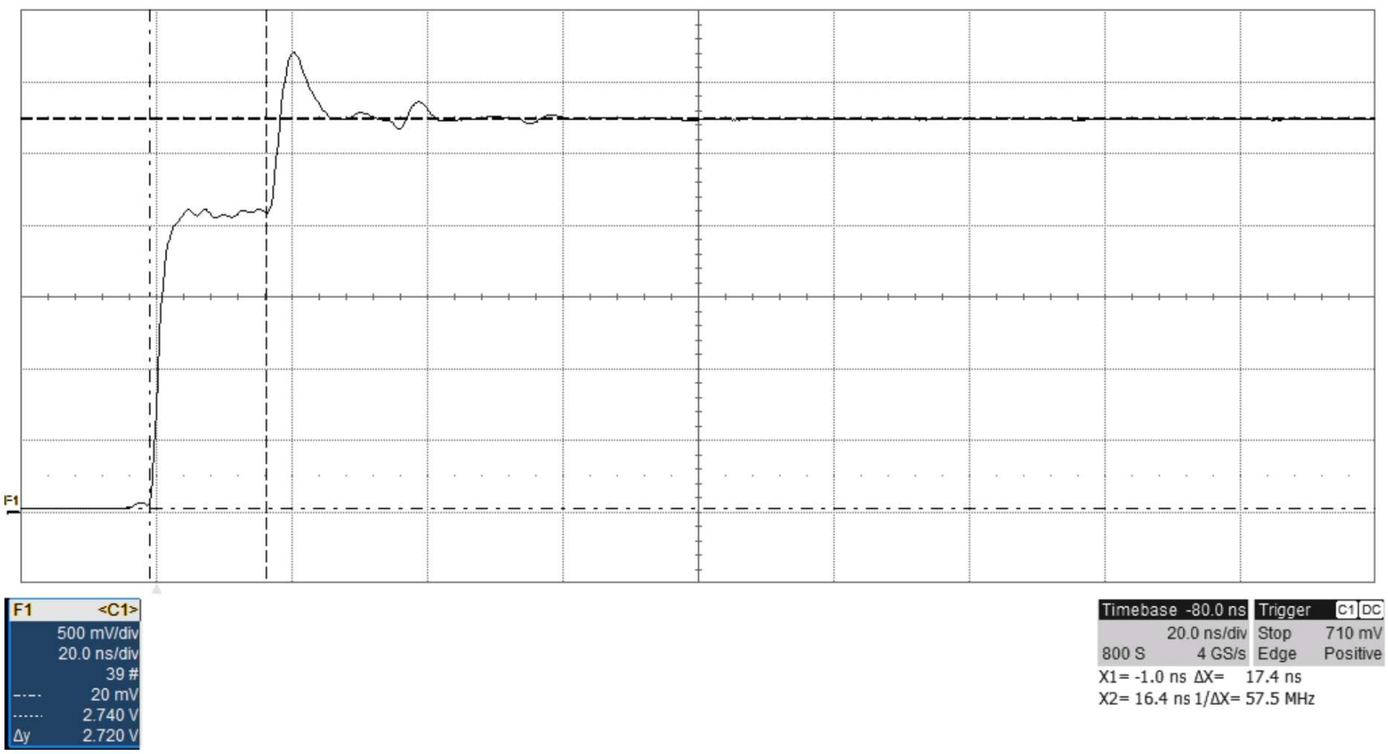


(B)

Figure 5a — 1 MΩ calibration; Figure 5b — 50 Ω calibration.

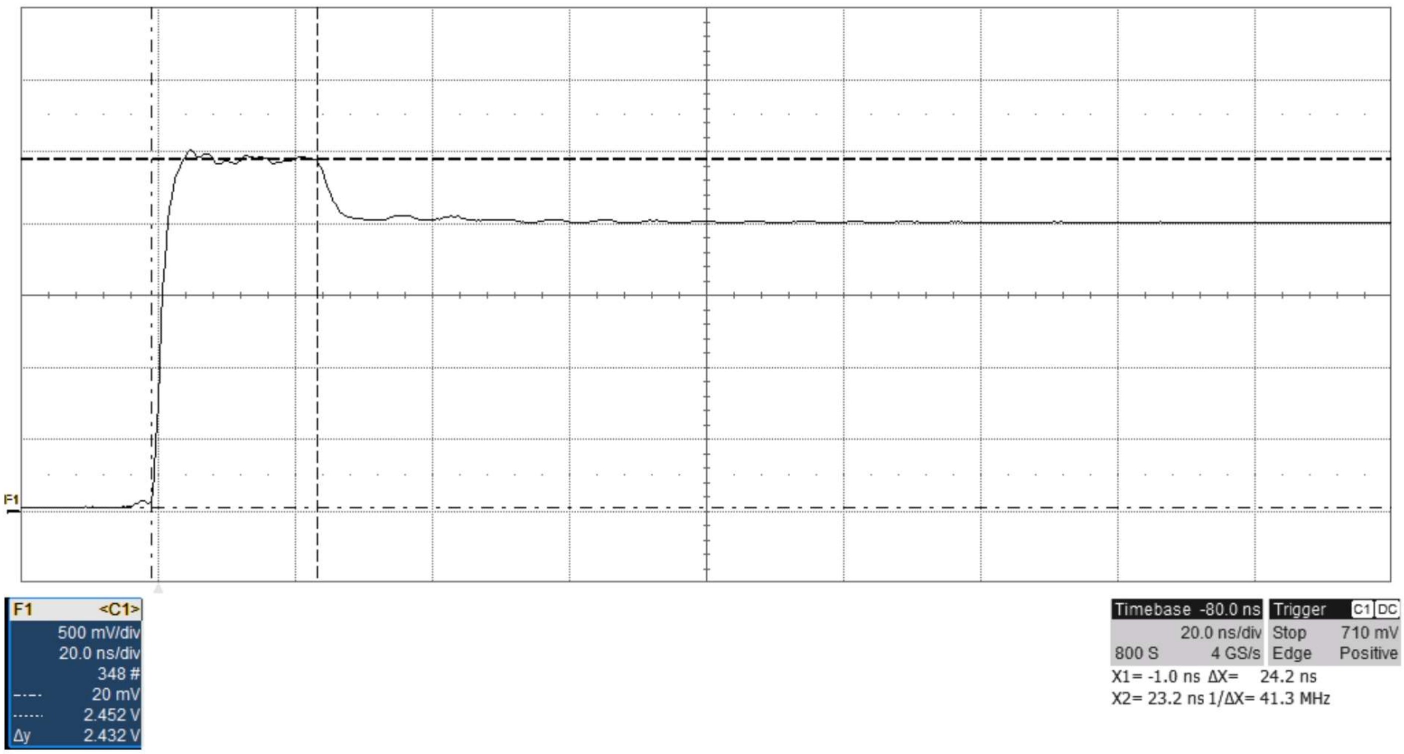


(A)

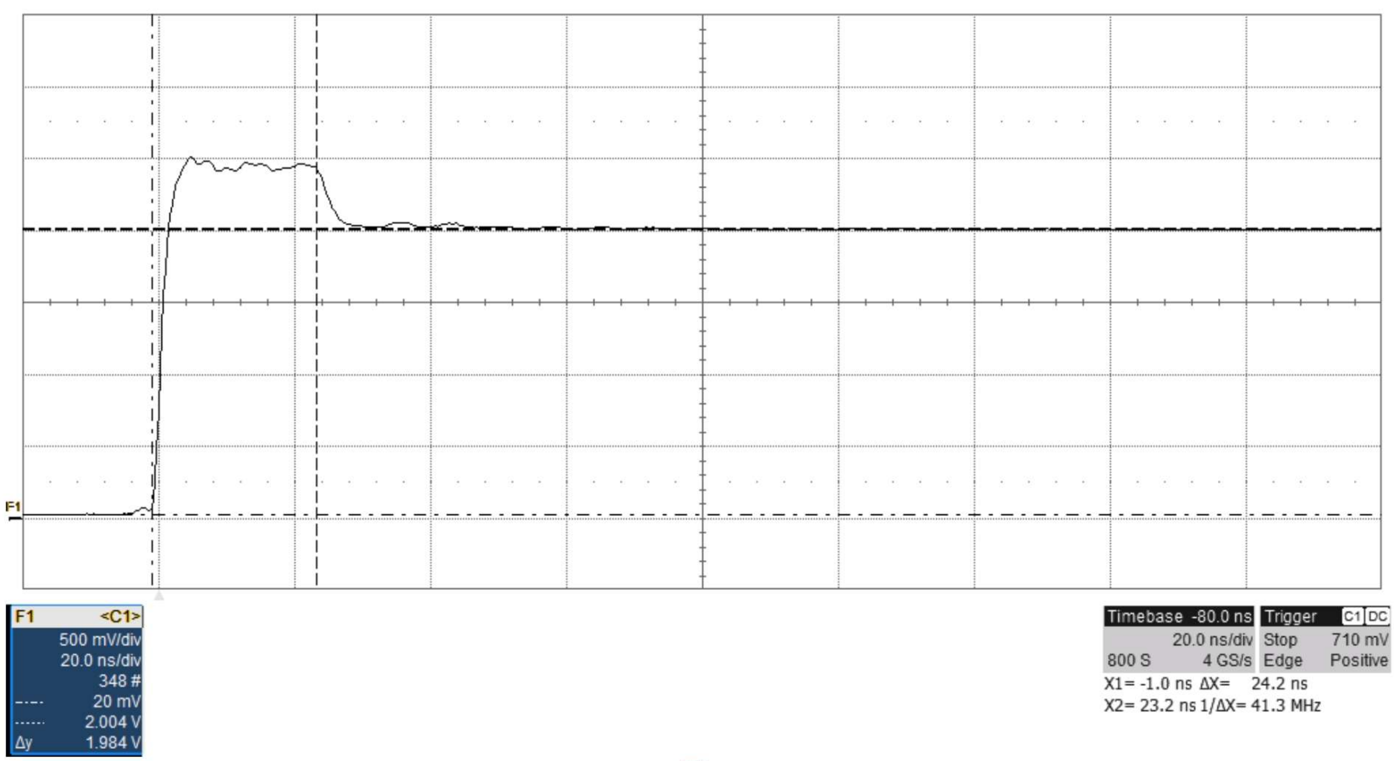


(B)

Figure 6a — RG-58C/U with 100 Ω termination (coax section); Figure 6b — RG-58C/U with 100 Ω termination (termination section).



(A)



(B)

Figure 7a — RG-59/U with 47 Ω termination (coax section); Figure 7b — RG-59/U with 47 Ω termination (termination section).

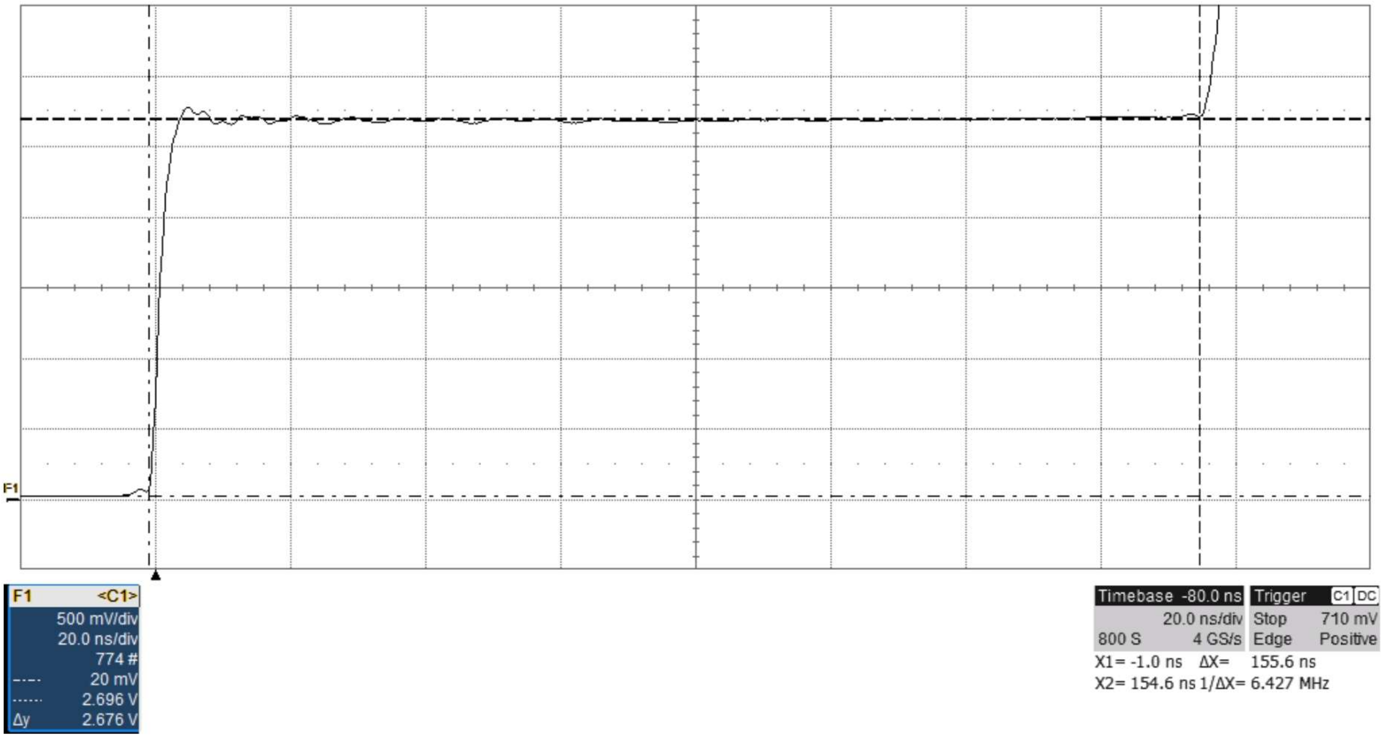


Figure 8 — Open ended length of RG-62AU.

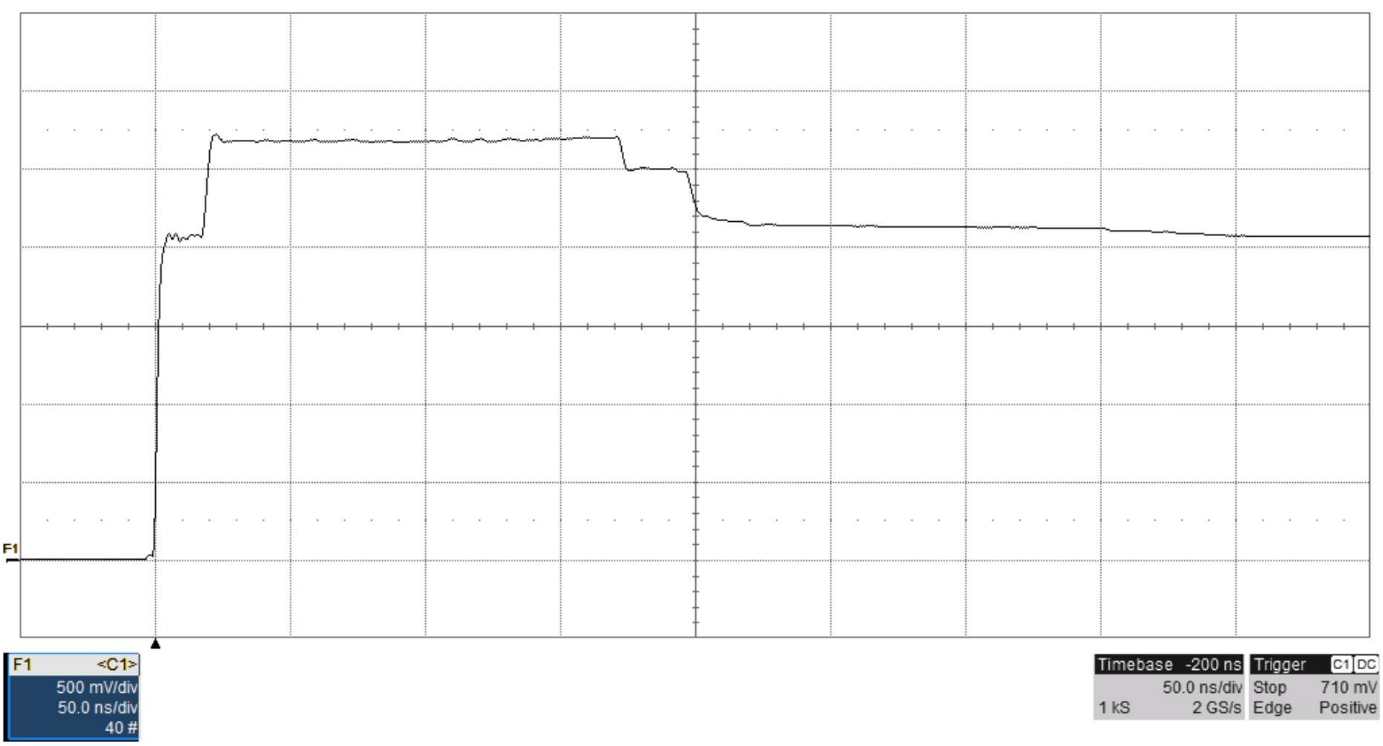


Figure 9 — Multiple cables with 47 Ω termination, 200 MHz oscilloscope bandwidth.

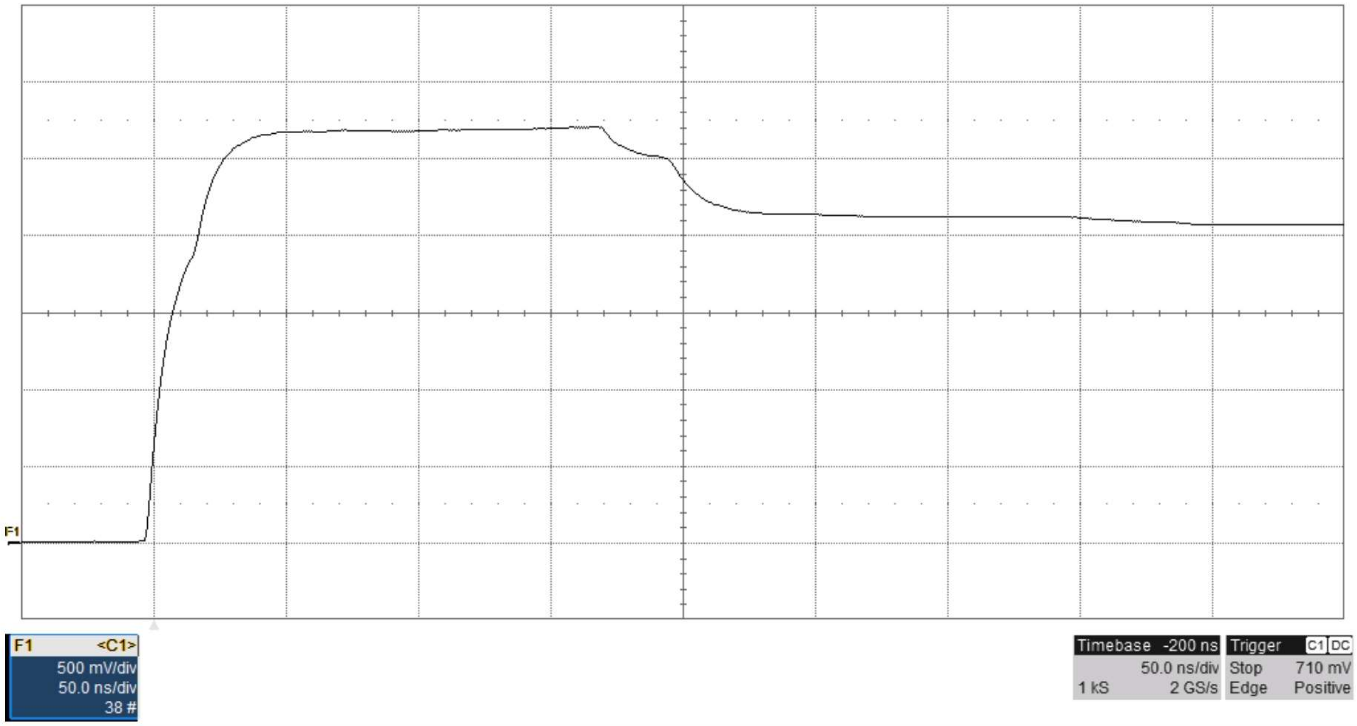


Figure 10 — Multiple cables with 47 Ω termination, 20 MHz oscilloscope bandwidth.

Example 3

The third example is 64 ft of open ended RG-62A/U. This cable has a propagation delay of about 1.21 ns/ft and has a characteristic impedance of 93 Ω. The voltage going off the chart on the right side of the trace is because of the open line. From **Figure 8**,

td = 155.6ns so Cable Length is (155.6/2)/1.21 = 64.3 ft

Cable impedance is (48.6×2.676)/(4.04–2.676) = 95.3 Ω.

Example 4

As a final example, we hook all of these cables together. **Figure 9** shows the RG-58C/U connected to the long run of RG-62A/U followed by the RG-59/U and the 47 Ω termination resistor. **Figure 10** is the same setup, but with the oscilloscope bandwidth limited to 20 MHz. The general shape of the trace is evident and the voltage levels are the same, but measurements of the details are difficult to discern due to the restricted bandwidth of the oscilloscope.

Additional Notes

Some cables are specified in a delay time per distance as in these examples. Other are specified by giving a velocity factor (*VF*). The length calculations are just as simple in that case. Using the *VF* value, the cable length can be found by

$$Length = \frac{0.9836 \times VF \times td}{2}$$
$$= 0.4918 \times VF \times td$$

where 0.9836 is the speed of light in ft/ns, *td* is in ns and *Length* is in ft.

It's good to use the shortest length of coax possible to connect the pulse generator to the oscilloscope. I used a six inch length in these examples. Although the measurements will be close to the same with a longer cable, the only termination for the reflected waves is the output impedance of the pulse generator. While the 1 MΩ oscilloscope input impedance is insignificant, there is a capacitive load from the oscilloscope input and the BNC T. Those cause some additional reflections, and less distance between the pulse generator and the oscilloscope input dampens these out more effectively.

Conclusion

If you already have an oscilloscope, for a few dollars and a few hours of time, this pulse generator will give it more functionality. It's fairly simple to build and will give quite accurate results if calibrated. It can be used to determine the length and impedance of any rolls of unknown coax you may have acquired. It can also find an open or short circuit and where it is located in a length of cable.

This device will not measure the impedance of an antenna connected to the end of the line. The spectrum of the fast edge rate pulse is very broad-band so there is no resonance with the antenna. The antenna will typically show as either an open or a short depending on the existence of or type of matching network.

Larry Lamano, WAØQZY, was first licensed in 1966 while in high school. He graduated from the University of Missouri at Rolla (now Missouri University of Science and Technology) with BSEE and MSEE degrees in 1973 and 1975 with an emphasis on communication systems, transmission lines and antenna theory. His first job was with Collins Radio and his last was with Apple, with several stops in between. He left Apple in 2001 and has done consulting work since then. Larry has always enjoyed designing and building things, whether analog, digital or mechanical, with the goal of understanding the underlying theory of what makes them work. He is a Senior Member of the IEEE and holds US patent 5,845,060.

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Self-Paced Essays — #8 Maximum Power Transfer Theorem

Essay 8: In many circuits it's all about the transfer of power.

In most electronic circuits, we're ultimately concerned with what is going on with power. It is the power, more than the voltage or current alone that gets things done. This isn't always self-evident, as we often work with circuits where the actual power levels are minuscule. One prominent example is in radio receivers, where we routinely work with power levels in the *femtowatt* range. Nevertheless, such power levels are *real.* For this discussion however, we will be looking at power levels where the effects of power are more evident and obvious.

One of the most common tasks in electrical engineering, whether it's at commercial power line frequencies, or at the super high frequencies of microwave systems, is the efficient transfer of power from a *source* to a *load.* The load can be defined as any useful device that consumes energy (power × time), and generally converts it to another form of energy.

The maximum power transfer theorem, also known as Jacobi's Law, states that the maximum power is transferred from a source to a load when the source resistance is equal to the load resistance. Or, perhaps, more aptly stated, when the load resistance is equal to the source resistance. As it turns out, we don't have much control over the source resistance. "It is what it is." Later on in this series, we will discuss an extension to Jacobi's Law for circuits containing *reactance* as well as resistance. This extension is the Conjugate Match theorem.

Although Jacobi's Law does not yield itself to a *rigorous proof* (without using calculus) in the same manner as Ohm's Law, or Kirchhoff's Laws, we can do some "thought experiments" as well as physical experiments to prove its validity.

Let's take the example of a voltage source, such as a simple battery. A battery just sitting on a bench with no load connected produces no power whatsoever. It has the *potential* to produce power, but without a complete circuit it simply provides a *difference of potential.* We find that the power *generated* by the battery is determined entirely by the load.

Let us review the formula for power when we know the voltage and the resistance. We will *derive* this formula. We know that power is most simply determined by: $P = I \times E$, where P is power, I is current, and E is voltage. We also know a form of Ohm's Law: $E = I \times R$, where E is voltage, I is current, and R is resistance. If we want to know the power when we know only the voltage and resistance, we can take $P = IE$, substitute I with E/R, which equals I. We now have $P = (E/R) \times E$, which reduces to $P = E^2/R$.

So $P = E^2/R$ will be our primary formula for the remainder of this discussion. We can ignore current for the time being.

Returning to our bare battery on a bench, let's give the battery voltage an actual value of 12 V. With nothing connected to our battery terminals, our load resistance is *infinite*, as is every open circuit. If we plug infinity into our equation, we have $P = 12^2/\infty$. Anything divided by infinity is zero, so we have zero power delivered — just as important, zero power generated. Now, let's go to the other extreme, a load resistance of 0 Ω, more commonly known as a short circuit. Our power formula gives $P = 12^2/0$. We know that anything divided by zero is *infinity*. Our battery is generating an infinite amount of power, and our load resistance is consuming an infinite amount of power. Wouldn't life be amazing if we could actually have such a situation? But common sense should tell us that this is impossible. You obviously can't produce an infinite amount of power from a 12 V car battery, even if you do have a dead short across the terminals. You can produce a *whole lot of power* this way, but *a whole lot of power* is quite different from *infinite power*! So, what gives?

What gives is that the battery has a certain amount of *internal resistance.* It is only the finite internal resistance of a battery — or of any other voltage source — that limits the power that it can produce. A battery is not a true voltage source, as we assumed in all our previous circuit discussions, but instead is a *power source.*

So, what is the optimum load impedance if we want to extract the maximum available power from a battery? We have already ascertained that the power is determined only by the load resistance, assuming that the battery voltage is fixed.

We can rule out two extremes for our optimum load resistance, infinite ohms and zero ohms. Common sense and logic tell us that the optimum value has to fall somewhere between zero and infinity. That still leaves a whole lot of possible *wrong answers* between those extremes. Let's take a look at our battery with some internal resistance and a load. 10 Ω of internal resistance is very high for *any* decent battery, but we'll use that value for demonstration only, see **Figure 1**.

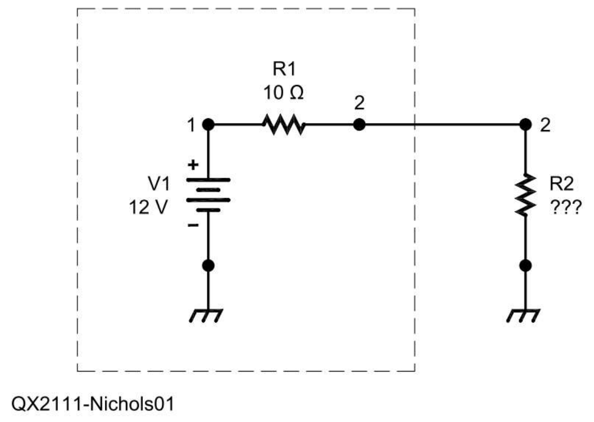

Figure 1 — A battery with internal resistance R1 and a load resistor R2.

Let's start with the assumption that Mr. Jacobi is right. We'll set the load resistance R2 equal to the known internal resistance of the battery R1. Recall from our discussion of KVL and KCL, that we have a voltage divider. The voltage across R2 will be half the supply voltage, the other half is dropped across R1. So we have 6 V across our load. Using $P = E^2/R$, we have 36/10 or 3.6 W. If Mr. Jacobi is right, this is the most power we can extract from our battery. We will also have the same amount dissipated in R1. The *efficiency* of the system is 50% — hold that thought; we'll discuss efficiency later.

If Jacobi's theorem is correct, *any* value of load resistance other than 10 Ω will result in less than 3.6 W of useful power dissipated in the load. Let's test this out. We can try a value below the predicted optimum of 10 Ω, say 5 Ωs, for the load resistance. As with any voltage divider, the voltage at the output is proportional to the ratio of the "bottom" resistance to the total resistance, in this case 5/15, or 1/3. 1/3 of 12 V, or 4 V appears across R2. $P = 4^2/5 = 16/5 = 3.2$ W, which is less than 3.6 W.

Let's now pick a resistance *higher* than the predicted optimum, say 15 Ω. Again, the voltage division is R1/(R1+R2), or 15/25, or 0.6. So 0.6×12 = 7.2 V. $P = E^2/R$ gives us $P = 7.2^2/15$, or 3.456 W, which is also less than our maximum value of 3.6 W. So far, it seems like Mr. Jacobi has been vindicated.

We can try different resistance values, above and below 10 Ω and perform the same calculations. We strongly suspect that nothing will give us more than 3.6 W consumed in R2.

Now, this has been a very roundabout way of "proving" Jacobi's Law, and in terms of a rigorous proof probably causes the mathematicians in our midst to cringe a bit. But in a court of law, Jacobi's Law is correct "beyond all reasonable doubt." Unless we find some case that proves it wrong, we can call the Maximum Power Transfer theorem a *law.*

Incidentally, if you doubt the internal resistance of a car battery, you can demonstrate this easily. Take a digital voltmeter and measure the voltage of the battery terminals while someone cranks the engine over. The voltage will typically drop to 8 V or less.

Now, let's consider efficiency. If we can call our optimized system a "Jacobi Match" for lack of a better term, we have only 50% efficiency. Depending on our specific application, efficiency may or may not be a priority. Efficiency is defined as the useful power consumed in the load divided by the total power generated by the source. In this case that is the battery *before* the internal resistance, and then multiplied by 100%. Efficiency doesn't *have* to be expressed as a percent; it can be a simple proportion. Standard practice calls for *percent efficiency.*

Here's a good place for a homework problem. Show that the overall efficiency *increases* as the load resistance *increases* above the internal resistance of the battery and *decreases* as the load resistance falls *below* the internal resistance of the battery. As always, show your work, and send your answers to **kl7aj@arrl.net**.

One place where efficiency is *extremely* important is in commercial electrical power generation. You want to have a generator capable of providing *many times* the actual power being extracted from it. One might say that the power grid is *lightly loaded.* Or at least it *should* be. You don't want your power generators continually straining at their maximum possible power capacity.

There are several *practical* reasons you don't want the power grid *too lightly* loaded, however, so power companies strive to achieve optimum loading, balancing efficiency with other factors.

On the other hand, one example of where efficiency is of zero importance is in weak radio signal reception. Circuits in receivers are usually matched for maximum power transfer in order to take advantage of the minuscule power levels available from the signal in question [Sometimes receiver circuits are matched for best noise figure — *Ed.*].

Real World

So far in this essay series, we have assumed that wires connecting circuit components are perfect, i.e., they have zero resistance. In reality, not only does any real-world voltage source have internal resistance, but the wires connecting the voltage source to the load also have resistance. For our bench top experiments, we can pretty much ignore wire resistance, but when it comes to practical power transmission, wire resistance becomes significant.

Unlike a "lumped constant" such as a resistor, which has all its resistance concentrated in a single location, a wire has a certain amount of resistance distributed evenly along its length, such as ohms per foot, or ohms per meter. For analysis purposes, the resistance of a long wire can be replaced by a single resistance in series with the load, just like the internal resistance of a voltage source such as a battery. We can determine the losses in a wire using the formula $P = I^2 \times R$. Again, we can easily derive this formula by substituting into $P = IE$ the equivalent value for E derived from a form of Ohm's Law, $E = IR$, which gives us $P = I \times I \times R$ or $P = I^2R$. This promptly gives us the "copper loss" or "conductor loss" of a power line. As you can see, the power loss goes up as a *square* of the current, so anything you can do to reduce the line current is going to drastically reduce the line losses. This is why long-distance power transmission lines use very high voltages; they can reduce the current proportionally for a given total power, and achieve much higher efficiency than lower voltage lines.

We have now presented most of the dc electrical fundamentals in these eight sessions to date. Beginning with our next essay, we will dive into ac electronics, exploring such topics as reactance, impedance, and resonance. Ohm's Law, Kirchhoff's Laws, and the Jacobi's Law all apply, but in a more complex, and we trust, even more *interesting*, manner.

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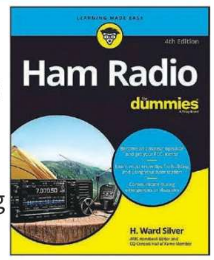

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