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A Forum for Communications Experimenters

Issue No. 282

AA6E built "A Software-Based Remote Receiver System" for the ARRL Staff Club Station, W1HQ. Now staffers can operate the station while W1AW transmits bulletins on all bands from across the parking lot! You can build a remote receiver system, too!

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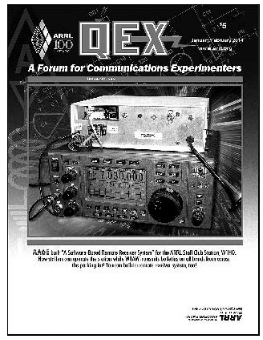
About the Cover

Martin Ewing, AA6E, is an ARRL Lab volunteer. He became aware of the difficulty that Headquarters Staffers had trying to operate the W1HQ Staff Club Station while W1AW transmits bulletins on all bands from across the parking lot. Determined to help find a way to solve this problem, he built "A Software-Based Remote Receiver Solution" for W1HQ. Now staffers can operate the station while W1AW is on the air! You can build a remote receiver system, too.



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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 Street, 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**.

Larry Wolfgang, WR1B

Empirical Outlook

Happy New Year! Welcome to the first issue of *QEX* in 2014. Starting a new year is always exciting, and with the many Centennial activities planned by ARRL for this year, it seems even more exciting than usual.

In September 2013 I ventured to Seattle, WA for another ARRL/TAPR Digital Communications Conference. DCC is my favorite national Amateur Radio event, so I guess it is fitting that I write a little about it.

As many of you know, DCC is a three day event that includes two full days of technical presentations as well as an in-depth seminar on Sunday morning. In addition to the high-level technical presentations on Friday and Saturday, there are always some Introductory Sessions on Saturday. The local hosts this year —especially Tina (KD7WSF) and Steve (N8GNJ) Stroh — did an excellent job of promoting DCC in the local Seattle area. We had the highest attendance of any DCC in memory, and nearly filled the excellent presentation auditorium to overflowing!

This year's Intro Sessions focused on various aspects of digital voice transmission. There are always many attendees who want to learn more about D-Star, and we had that opportunity this year. A new "hot" topic in the digital voice realm was the FreeDV/Codec2 program. This system is of special interest because Codec 2 is an open source Codec. FreeDV uses SSB transceivers to transmit and receive digital voice signals. It is used primarily over HF, although nothing would prevent its use on VHF or higher frequencies.

All of the technical presentations are quite interesting, but a few really stood out for me. Heikki Hannikainen, OH7LZB, did an encore of his 2012 presentation by talking about the challenges involved with running a secure "authenticated" Amateur Radio service application on the Internet with his **APRS.fi** web server. Heikki described some of the steps he takes to ensure that only licensed Amateur Radio operators can put a message out over his system, while not being overly complicated for either the ham who wants to use the system or for the site administrator.

John Hansen, W2FS, stirred up quite a bit of excitement over his "Raspberry Pi Applications in Digital Communications," and especially with his mobile APRS station and a new version of his popular TNC-X: TNC-Pi. For this and other reasons, I've decided I want a Raspberry Pi, to learn about this little computer. I've put one on my Christmas Wish List.

Adam Farson, VA7OJ, described his "Noise Power Ratio (NPR) Testing of HF Receivers." Adam described the measurements that he has made on Amateur Radio transceivers with this technique. At the time of the DCC, we were reviewing an article from Adam about this topic for QEX. I was able to discuss some revisions to the article with Adam in person, and he is in the process of revising it for us. I hope to bring you an article about NPR testing during 2014.

The Make movement definitely has some parallels with Amateur Radio, and it is great to see the enthusiasm that so many of these "do it yourself" experimenters can bring to our hobby. In addition to a video update from Chris Testa, KD2BMH, about his "HT of the Future," which he first described at the 2012 DCC, this year we heard from Michael Ossmann, who described his "Hack RF: A Low Cost Software Radio Platform." Michael is working on marketing his project, which is a 30 MHz to 6 GHz radio, to the Information Security community. He uses an IF of 2.5 GHz to obtain 15 to 20 MHz bandwidth with 20 kbit sampling. You can find more about Michael's project at **greatscottgadgets.com/hackrf/**.

Gary Pearce, KN4AQ, was again in attendance at the DCC, recording the presentations for his HamRadioNow TV website: **http://arvideonews.com/hrn/**. As he has done in the past, Gary will put the video on his website for your viewing pleasure, although it does not seem to be available yet as of this writing. This is a great way to learn about the technical presentations at DCC, but the conference is so much more than those presentations. It is an opportunity to talk with the presenters, share ideas with other attendees, and generally have a great time.

No discussion about DCC is complete without some mention of "The Play Room." Whether or not you are presenting a talk at DCC, you are encouraged to bring projects to display in the Demo room. There were tables with several of the projects presented in talks on display. John Hansen had his TNC-Pi APRS tracking system on display. Michael Ossmann had information about his HackRF project. Mel Whitten had a demonstration of the FreeDV digital voice system.

David Bern, W2LNX, has been experimenting with a Raspberry Pi to control a pair of inexpensive TV rotators to create an Az-El rotator system for satellite antennas. David was presenting this project at the AMSAT Symposium in November, so the DCC was an opportunity to shake out a few bugs. I have talked with David about writing about this project for *QEX*, so that is another one I hope to bring you in the pages of *QEX* in the not too distant future.

Next year's DCC is already in the planning stages, with preliminary efforts focused on holding it in the Austin, TX area on the weekend of Sep 5-7. Watch for announcements and start making your plans to attend now!

Martin Ewing, AA6E

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A Software-Based Remote Receiver Solution

Need to get your receiver off site to avoid interference? Here is how one amateur connected a remote radio to a club station using a mixture of Linux, Windows, *and* Python.

The local interference environment is an increasing problem for ham radio operation, making weak signal operation impossible at some times and frequencies. The ARRL Staff Club Station, W1HQ, has this problem in spades when W1AW, just across the parking lot, is transmitting bulletins and code practice on seven bands with high power. Operating W1HQ on HF in the prime evening hours is not possible. There is no problem transmitting in this environment — it's a receiver problem. We could solve the problem by setting up a full remote base station, but for W1HQ, this is not necessary. A remote receiver is all that we need. That is the origin of this project.

There was only a small budget for a remote operation, but we did have a number of usable receivers, and we had an offer of software support from an eager volunteer. (That would be me.) So we were off and running to develop a low-cost remote receiving capability.

The club wanted a receiver capable of operating at least CW and SSB on all HF bands, controllable from the W1HQ operating desk. It needed to be located far enough from W1AW so that interference was negligible, but close enough so that propagation would be nearly the same at both locations. The system that evolved was a small remote computer that could be deployed at a ham's home (the "host QTH") and that would require little if any local support. The remote would require an all-band antenna of some kind, while it would attach to the host's home Internet connection. At the base station (W1HQ), the station computer would run control software to manage the remote operation.

This article focuses mostly on the software — how we developed a mixed *C* and *Python* (and mixed *Linux* and *Windows*) project with audio and Internet aspects. Interested readers will probably want to consult the code listings. These are provided at **www.aa6e.net/wiki/rrx_code** and are also available for download from the ARRL *QEX* files website.[1] Additional project details are available at **www.aa6e.net/wiki/W1HQ_remote**. Hardware construction is straightforward for anyone with moderate experience.

[1]Notes appear on page 6.

System Overview

Figure 1 shows the overall system design. The BeagleBoard XM or "BBXM" is an inexpensive (~$150) single board computer with a 1 GHz ARM processor, Ethernet and USB connections, and on-board audio capability.[2] It has 512 MB of RAM and

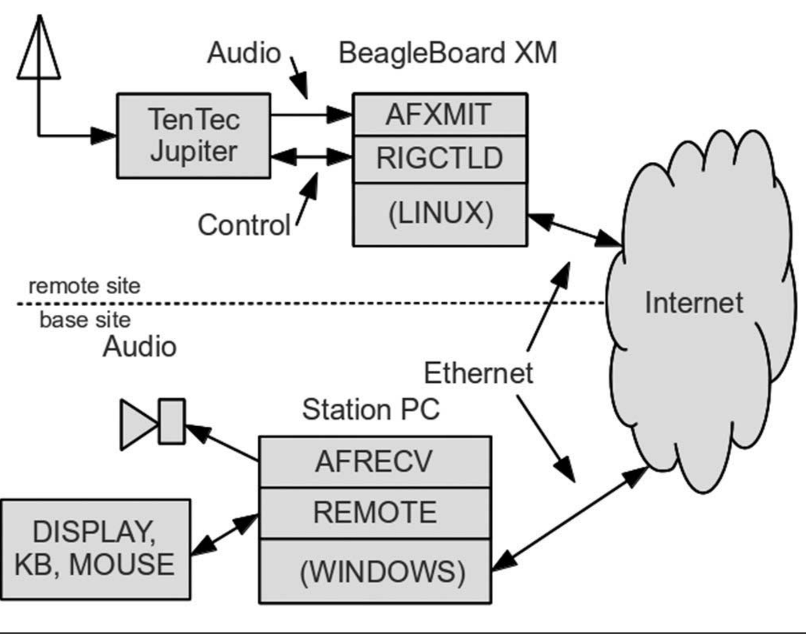

Figure 1 — This block diagram shows an overview of the remote receiver system.

a microSD flash memory module serving as a “hard drive” (typically 8 GB). The BBXM will support a variety of operating systems.[3] We installed *Ubuntu Linux*, choosing to operate in a “headless” mode — without video graphics, mouse or keyboard. In normal operation, the BBXM only communicates via Ethernet to the base station. (A video graphics port and serial I/O port are available if needed for development or testing.)

One required feature for the receiver is full computer aided transceiver (CAT) control.[4] That eliminated some fine older radios that might have been used. In the end, we selected a Ten-Tec Jupiter transceiver. Its serial I/O port can be connected to the BeagleBoard through a USB-to-Serial converter. (The BBXM’s on-board serial port was reserved for maintenance use.)

The BBXM and a power supply were packaged in a small case. Figure 2 shows the remote system and the Jupiter transceiver. Figure 3 shows the internal layout of the BBXM, power supply and audio isolation board. The power supply offers 12 V dc at 2 A to run the transceiver in receive mode.

At the base station location, a 3 GHz Pentium IV PC running *Windows XP* is used as the main station computer, supporting the remote receive operation as well as other station functions.

Software Design for the BeagleBoard XM

We have worked out some software approaches that may be useful to W1HQ and the amateur community. We are providing the software under the GNU General Public License, so you are free to adapt it as you like for your own use and education.[5]

Control

Remote control of the Jupiter transceiver was easily implemented with the Hamlib system.[6] Hamlib provides an interface library coded in *C* that defines an application programming interface (API), allowing an application program to control any of a large number of different Amateur Radio transceivers, such as the Jupiter. Hamlib also provides an Internet server that accepts rig commands via Internet TCP/IP packets in a simple text format. This server (**rigctld**) runs on the BeagleBoard and accepts connections from the base computer over a specified TCP/IP port. Hamlib is available for download from most *Linux* repositories. (Source code and *Windows* versions are also available, but they were not needed for our project.) A Google search for hamlib will return numerous sites for downloads and documentation.

Audio

Creating an efficient Internet audio channel was the largest task in this project. There are numerous streaming audio systems available, but these can have long latencies that don’t allow interactive Amateur Radio communications. We might have chosen to work with an open source VOIP scheme or a service like *Skype*, but in the end we chose to develop a simple transmission scheme that works well in this application.

Figure 2 — Here is the remote control box containing the BeagleBoard XM computer and the Ten Tec Jupiter transceiver.

Our voice-to-Internet application is called **afxmit**. It is written in *C* using the PortAudio framework.[7] **Afxmit** samples the receiver audio at 8 kHz (the lowest standard rate) with 16 bit resolution. (This is overkill for normal Amateur Radio operations, giving frequency response to 4 kHz and much more dynamic range than amateur channels normally require.) The program uses the Speex codec to compress the audio before sending it to the Internet.[8] With normal settings, we require only about 3 kB/s of Internet bandwidth, including Hamlib communications.

Note that the Speex codec in this application solves a very different problem than codecs used for digital voice over RF channels, such as Codec2.[9] For RF communications, a modem sends data *on the air*, using the lowest possible bit rate while being resistant to propagation changes and interference. In our case, we are sending data *on the Internet*, seeking a low bit rate while preserving good communications fidelity.

Given a compressed bit stream from Speex, how should it be transmitted? We first looked at the Transmission Control Protocol often called TCP/IP, which would guarantee error-free end-to-end transfer.[10] The features of TCP, however, actually make things harder for our application, because if there are transmission errors, data will be retransmitted, and the audio stream will be delayed. For real-time streaming data like ours, it’s usually better to forget about missing packets or other errors and just move on with the good data.

In the end, we adopted the User Datagram Protocol (UDP) for audio transmission. Audio data is taken by the BBXM audio system, transmitted by UDP, and finally played in real time by the base station computer sound card. The two audio clocks (input sound card and output sound card) will always have slightly different frequencies, meaning that the playback buffer will eventually overflow or starve. With appropriate framing, the receiver can skip data or insert silent data as needed.

Speex provides a packet every 20 ms, and the BeagleBoard buffers four of these for a UDP packet every 80 ms. There is no guarantee of delivery, and no acknowledgement comes back from the receiving computer. This is a low-overhead method that works well with our real-time audio transfer scheme. An occasional missing packet or an over- or under-flow is no problem. We can drop an occasional excess packet or insert silence as needed on a typical HF channel, and the operator usually does not notice.

Afxmit listens on its UDP port for commands from the base station computer to set the codec parameters and to start or stop sending audio.

Addressability and Security

The remote BBXM has to be addressable from the Internet. Since we are relying on a host Internet account, that means that the host Amateur Radio operator's Internet router needs to be addressable. We use the dynamic DNS addressing provided by Dyn to provide data for an address like *my-address.dyndns.org*.[11] A small program on the BeagleBoard runs occasionally to ensure that the Dyn DNS database has the actual IP of the host's service.[12] Using the host's current numerical address might work for a time without DNS, but ISPs sometimes change your IP address without notice.

To make the BeagleBoard available to the outside network, we also need to insert some "pinholes" in the host router's firewall configuration. Incoming traffic for ports assigned to Secure Shell (SSH) terminal traffic, **rigctld**, and **afxmit** is directed to corresponding ports of the BBXM. With this firewall setup, remote receiver traffic goes straight from the host operator's router to the BeagleBoard and does not depend on the host's own computer in any way.

Login to the BeagleBoard is supported using secure shell (SSH), which provides a cryptographically secure link. Because the base station software initiates its sessions automatically, SSH logons are mainly useful for system maintenance.

A similar level of security can be provided for **rigctld** if needed, by implementing an "SSH tunnel" for traffic for port 4532. Unfortunately, UDP traffic cannot be tunneled this way, so our audio link will always be somewhat insecure without some further work. (Software could restrict UDP responses to certain IP addresses, for example.)

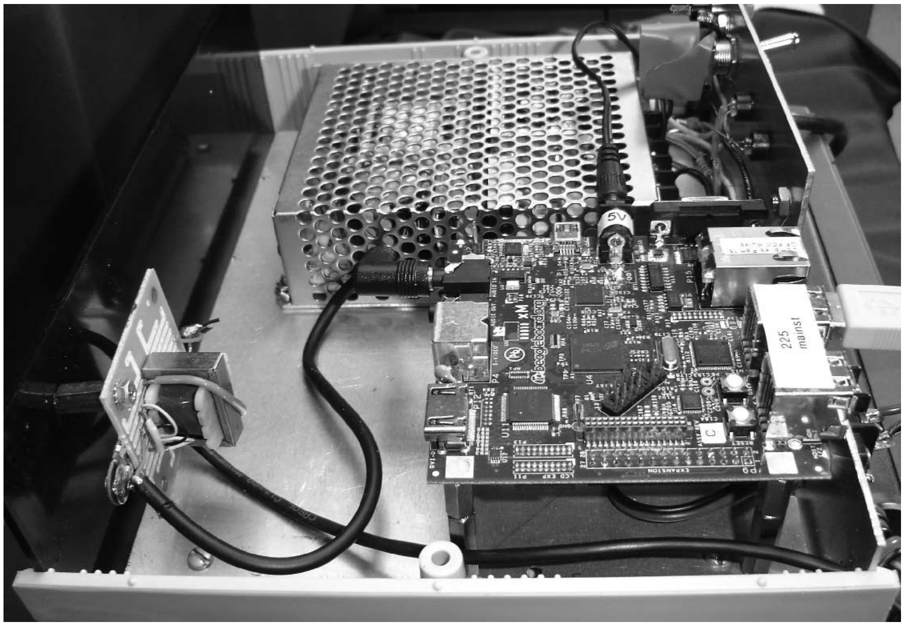

Figure 3 — This is an internal view of the remote control box. The BeagleBoard XM is in the lower right corner of the photo.

Base Station Computer Software

The main remaining component of our system is the software application **remote** that runs in the base station computer. It is written in *Python,* a powerful language that runs well on both *Linux* and *Windows* computers.[13] With the help of the WxWidgets framework for graphical user interface, **remote** provides a virtual control panel for the remote receiver, shown in Figure 4.[14] While this control panel is tailored for the Ten Tec Jupiter transceiver, it could be used with most other CAT controllable rigs with minor changes.

We might highlight the FSpin class in our *Python* code. This defines the control widget that manages the setting of the VFO frequency. It offers "up" and "down" buttons for each frequency digit that allow rapid tuning to a desired frequency. When the FSpin control has keyboard focus, it will also respond to the mouse wheel, which will tune a particular digit up or down. Direct frequency entry from the keyboard is also supported.

Another feature is the SMeter class. It is adapted from the wxWidgets SpeedMeter. Because our Hamlib connection will only offer a new S-Meter reading every second or so, we cannot provide the elegance of some recent transceivers with LCD meter emulations. (A convincing meter emulation requires bandwidth!) Still, it is a useful display, and it is calibrated.

Remote Communication

The user can run **remote** in either a *Windows* or *Linux* based computer environment. A number of things need to happen that are outside the *Python* code. First, **remote** launches a *Windows* batch file (or *Linux* shell script) that starts an SSH session with the remote computer. In a *Windows* machine, we use **PuTTY** and **plink** for this purpose.[15] The SSH command runs a shell script on the BeagleBoard remote that starts the two server processes, **rigctld** and **afxmit**, setting up the remote to listen for commands from the base computer. **Remote** has a module that manages Hamlib commands for **rigctld** via a TCP/IP connection.

A separate *C++* program, **afrecv**, receives the UDP audio data sent from **afxmit**. For a *Linux* base station, **afrecv** was straightforward to code using the PortAudio library. Alas, we needed a version of **afrecv** to run under *Windows*. Could we port PortAudio and Speex to *Windows*? It turned out that porting Speex was straightforward, but we had problems with PortAudio. We finally selected the *Windows* XAudio2 API instead.[16] XAudio2 is part of the Microsoft *DirectX* Software Development Kit. It is a gaming-oriented audio system that is functionally close enough to PortAudio that **afrecv** can invoke either library by conditional compilation. **Afrecv** and Speex project files for Microsoft *Visual C++ 2010 Express* are provided with our other code at the website mentioned earlier.

Remote directs **afrecv** to tell **afxmit** to start and stop audio transmission on behalf of the user. This involves running a batch file (shell script), which can take noticeable time to complete, especially under *Windows*. For faster transmit/receive switching, we provide a command that simply mutes the PC audio, leaving the UDP stream running.

Interface Complication

We originally connected the Ten-Tec Jupiter headphone output straight to the BeagleBoard audio input, but there was some weird behavior. A loud static crash in the receiver would cause the computer to reboot. After some head-scratching and consulting of schematics, we saw that the Jupiter's speaker output and headphone jack are driven by a bridge circuit, with both terminals floating. Our static crash was injecting unfriendly current surges into the computer's ground plane. The solution was an audio isolation transformer, which you can see in the left foreground of Figure 3.

Operating Results

The remote system is currently installed at my home, about 30 miles away from

ARRL Headquarters, where it uses a small fraction of a cable TV Internet connection. The Jupiter is normally connected to an 80 m dipole, which is usable for reception across the HF bands. Differential propagation (favoring the transmitting site over the receiving site, or vice versa) has not been a problem so far, but we hope to eventually move the remote site closer to W1HQ.

The remote capability has given W1HQ the option to be active in the face of severe local interference from nearby W1AW, at a modest cost. What is it like to use the system, and what would we do differently if we were doing it again?

The audio quality is good — good enough to support PSK31, we believe, though this has not been fully tested. One issue is the delay time (latency) when tuning the receiver. Tuning up and down the band is slower than it would be on a local rig. Some of this delay is caused by the Jupiter CAT interface, which (like many radios) uses relatively slow serial 57.6 kb/s communication. There is also a delay in audio transmission caused by audio buffering, the Internet, and the Speex compression we use. We see about ½ second total delay. That's enough to confuse an operator monitoring transmission in real time or scanning the band. It's not a problem for typical transmit/receive switching, but it could be an issue in rapid-fire DX or contest operation. There are software parameters, particularly buffering ratios, that can be adjusted if lower delays are required. The minimum packet length with Speex compression is 20 ms, but compression can be turned off if needed. In general, increased responsiveness requires less buffering, more packets, and more Internet bandwidth.

If we were doing the project over, we would naturally look at newer computer options, if not newer radios. The BBXM is still viable and attractive because of its on-board audio system and its multiple I/O ports. There are less expensive, smaller boards now available such as the BeagleBone and the Raspberry Pi, among others.[17] These both require off-board audio adapters, but a simple USB audio "dongle" will probably work for our 8 kHz monaural requirement. You should be able to reduce the hardware cost and reduce system size with one of these choices.

Python and *wxWidgets* work well for the base station control program (**remote**). With more recent versions of *PyAudio* (a *Python* wrapping of PortAudio), it should be possible to integrate the **afrecv** function into the *Python* main program. This would be especially attractive to a *Linux* programmer who (like your author) needs to port the application to *Windows*. *Python* and *wxWidgets* work well on both platforms.

Building our own remote system has been an interesting and educational challenge, combining a number of technologies, and not least, introducing a new capability to our club station. Adding a transmit capability for two-way remote operation should not be too difficult, using some of the components presented here. The base station code can be readily adapted to other radios, or made to run in another tiny computer like the BeagleBone or Raspberry Pi.

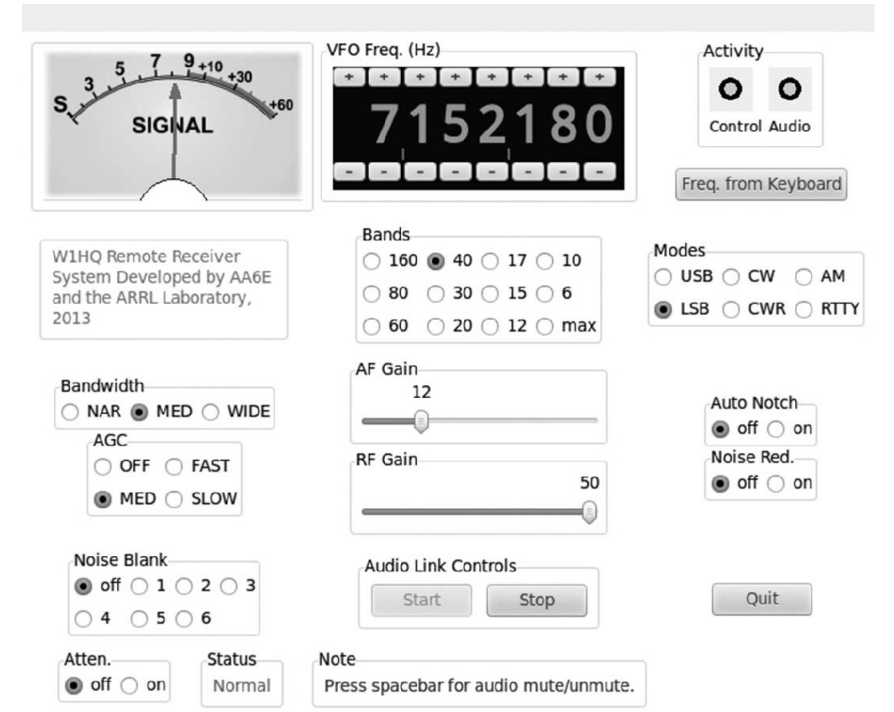

Figure 4 — This screenshot shows the virtual control panel, as displayed on the W1HQ computer.

Acknowledgements

I am very grateful for the support and encouragement of Ed Hare, W1RFI, and the entire ARRL Laboratory staff. Bob Allison,, WB1GCM, kindly provided the photographs.

Martin Ewing was first licensed in 1957 as K5MXF in New Mexico. He studied at Swarthmore College and received a PhD in Physics at the Massachusetts Institute of Technology, specializing in Radio Astronomy, the cosmic microwave background, and pulsars. He joined Caltech Radio Astronomy working on Very Long Baseline Interferometry, designing digital correlators and developing a version of the Forth *computer language for real-time control. At Yale University, he served as Director of Information Technology in the Faculty of Engineering. An ARRL Member, Martin became an ARRL volunteer and Technical Advisor after retiring. At the ARRL Laboratory, he works with Software Defined Radio and applications of small* Linux *computers.*

Notes

[1]The software files associated with this article are available for download from the ARRL QEX files website. Go to **www.arrl.org/qexfiles** and look for the file **1x14_Ewing.zip**.

[2]See **http://beagleboard.org**. More recently, the BeagleBone series has been introduced. See the website for additional information.

[3]Go to: **http://elinux.org/BeagleBoard**.

[4]Computer Aided Transceiver (CAT) is Yaesu's term for a radio's computer control capability. It is now used as a generic term.

[5]For complete details of the GNU software license, go to: **www.gnu.org/licenses/gpl.htm**.

[6]See **http://hamlib.org**.

[7]See **http://portaudio.org**.

[8]For more information, see **http://speex.org**. Since this project began, Speex has been supplanted by Opus, **http://opus-codec.org**, which is recommended for new applications.

[9]See **www.codec2.org** and **www.rowetel.com/blog/?page_id=2458**.

[10]This, and many other computer terms, can be found by searching **http://en.wikipedia.org**.

[11]See **http://dyn.com**.

[12]Martin Ewing, AA6E, "DNS Choices for Your Ham Server," *QST*, Nov 2006, pp 77-78.

[13]See **www.python.org**.

[14]See **www.wxwidgets.org**.

[15]For more information about PuTTY and to download the files, go to: **www.chiark.greenend.org.uk/~sgtatham/putty/download.html**.

[16]You can learn more about Microsoft XAudio2 and download the files at: **msdn.microsoft.com/en-us/library/windows/desktop/hh405049(v=vs.85).aspx**.

[17]For more information about the Raspberry Pi computer, go to: **www.raspberrypi.org**.

Tuck Choy, MØTCC

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Servicing and Upgrading Your Optoelectronics 2810 Frequency Counter

The author shows us how he repaired and upgraded his Optoelectronics frequency counter.

If you own one of these first generation frequency counters that has served as a workhorse in your shack for the last twenty years or more, and you have not yet opened it up to do any service then this article is for you. I bought mine while I was in my first faculty job in the early 1990s, and at that time $120 or more was a lot of money. This model was the least expensive one I could afford, so I purchased one, and it has served me well for over twenty years. According to the manual you are to open up the case and check that the batteries have not corroded every year or so. Well mine were truly gone when I did this recently. The original Ni-Cad batteries were readily replaced with modern Ni-MH units purchased from eBay. I then noticed that on Channel A my unit did not have the millivolt sensitivity that was described in the manual. I also found trouble in Channel B, but more on this later.

To test the sensitivity of my counter I used a 40 MHz oscilloscope and a home-made 10 MHz crystal oscillator that puts out about 1 mW or 0 dBm together with a home-made step-attenuator constructed according to a project described in *The ARRL Handbook* during the 1980s to mid 1990s. Prodding around with my scope probe I soon found that the second stage, U11A MAR 6 amplifier had no gain. See Figure 1.

A check with the ohmmeter on my DMM found that inductor L3 had become open circuited, but this was only half the problem. After it was replaced, my scope probe was busy again and soon I found that C27 had malfunctioned, probably through aging cracks because it was a fragile SMD ceramic device. This was easy to replace and then the unit came to life again, this time working according to spec. My counter was able to remain locked with a signal down to about –43 dBm. This taught me that over the years it must have been a victim to rough handling. Note that the manual says the maximum input to channel A should be no more than +15 dBm, or about 1.26 V RMS, which means it cannot be plugged directly even into a QRP transmitter of 0.5 W output driving a dummy load.

Anyway, my counter is now working according to spec and I am pleased that I was able to service this piece of test gear. I did not know that it was not functioning according to specs until I opened it up to do a service, because Channel A was still partially functional, but I did notice that I had to pump in 100 mV of input to get my readings. So it may be worthwhile giving yours a check. Channel B has higher input impedance and it has back to back diode protection so it can withstand rougher handling, or so I thought. In fact after writing the original draft of this article and putting everything back in the box, I soon found how mistaken I was, but more on this later.

Upgrading the 2810 Counter to a 2600H Model

Now the real fun began. I noticed that my circuit board is marked as a 2600H version 3, and that there are imprints for several components not included in my counter. Studying the manual tells me that in fact those missing components are for the bar graph unit that goes with the 2600H model. See Figure 1. I had most of the parts on hand, except for the 1N6263A Schottky diodes and the Texas Instruments TLC548 ADC chip, which have to be mail ordered. Most of the components were quickly soldered in. Note that all the parts are mainly surface mount devices (SMD) so you will have to practice soldering these devices before embarking on this part of the project. The only resistor that is not SMD is R26, for which I used an ordinary 510 Ω carbon film resistor that has to be soldered from the underside of the circuit board. See Figure 3. Some care is necessary here, because it bridges several other tracks and links up with the inductor, L2, on the top side of the board.

I found the manual has more errors, and that C24 should be connected to the cathode of CR3 rather than as drawn. The circuit board is correct, fortunately. Figure 1 of this article shows the connection correctly. I had to bend the leads of the two inductors, L4 and L5, to fit the tracks, like the original parts in the input amps, L2 and L3. Presumably in those days, chip inductors were not readily available, and I had none on hand either. If you have these chip inductors, you might want to replace all the leaded inductors, because that can improve the frequency response of the instrument.

Do not substitute lower number MAR amplifier types for the MAR 6, because they have less gain or a lower maximum frequency response. A more modern alternative could be the SNA-586 Sirenza MMIC as it goes up to 5 GHz, and has lots of gain. I also found that I had to change R25 to 68 Ω for a better range of zeroing adjustment for the bar graph. Low profile variable resistors for R2 and R3 are preferred, because there is not much clearance from the front panel. These are required later for the bar graph calibration.

Now comes the tricky part. My recommendation is to use a low profile socket for IC U5 (see Figure 2), which has to be soldered from underneath the circuit board. Before doing this, however, you will have to *carefully* remove the liquid crystal display (LCD) in order to cut a wire link that grounds pin 6 of U5. This has been placed there by the manufacturers for the 2810 model to avoid spurious AD data signals going into the microprocessor, which incidentally is an 8951 microprocessor, or a modern day AT89C51 controller, which was one of the earliest to have flash memory. The brave hearted may want to hack this chip and improve the software, but this is not for me.

Once the wire link is removed, you can now solder the socket for the U5 chip, or alternatively solder the chip directly to the board. Now check for voltages of +5 V to pin 8 of U5.

You can now gently replace the LCD. This is much harder than removing it in the first place, so I recommend lots of patience. First place the LCD through a veroboard and straighten all the pins with a pair of long nose pliers, because some of the pins will have been bent during the removal process. This is a 60 pin device although most of the pins on the side towards the switches have been removed. Be extremely careful here because the pins can break easily. This is a manufacturer specific part and in any case 60 pin LCDs are hard to find. I was hoping to source a replacement, preferably with backlight, but my efforts were fruitless after a few hours searching on the Internet. I was told by the manufacturer that they no longer have stock of these parts themselves as it is an obsolete model. If you break this component, it is good bye to your counter, so be very careful and gentle; see Figures 4 and 5.

Now, if you have done all the above modifications as described then you will have converted your model 2810 into a model 2600 Optoelectronics frequency counter. It

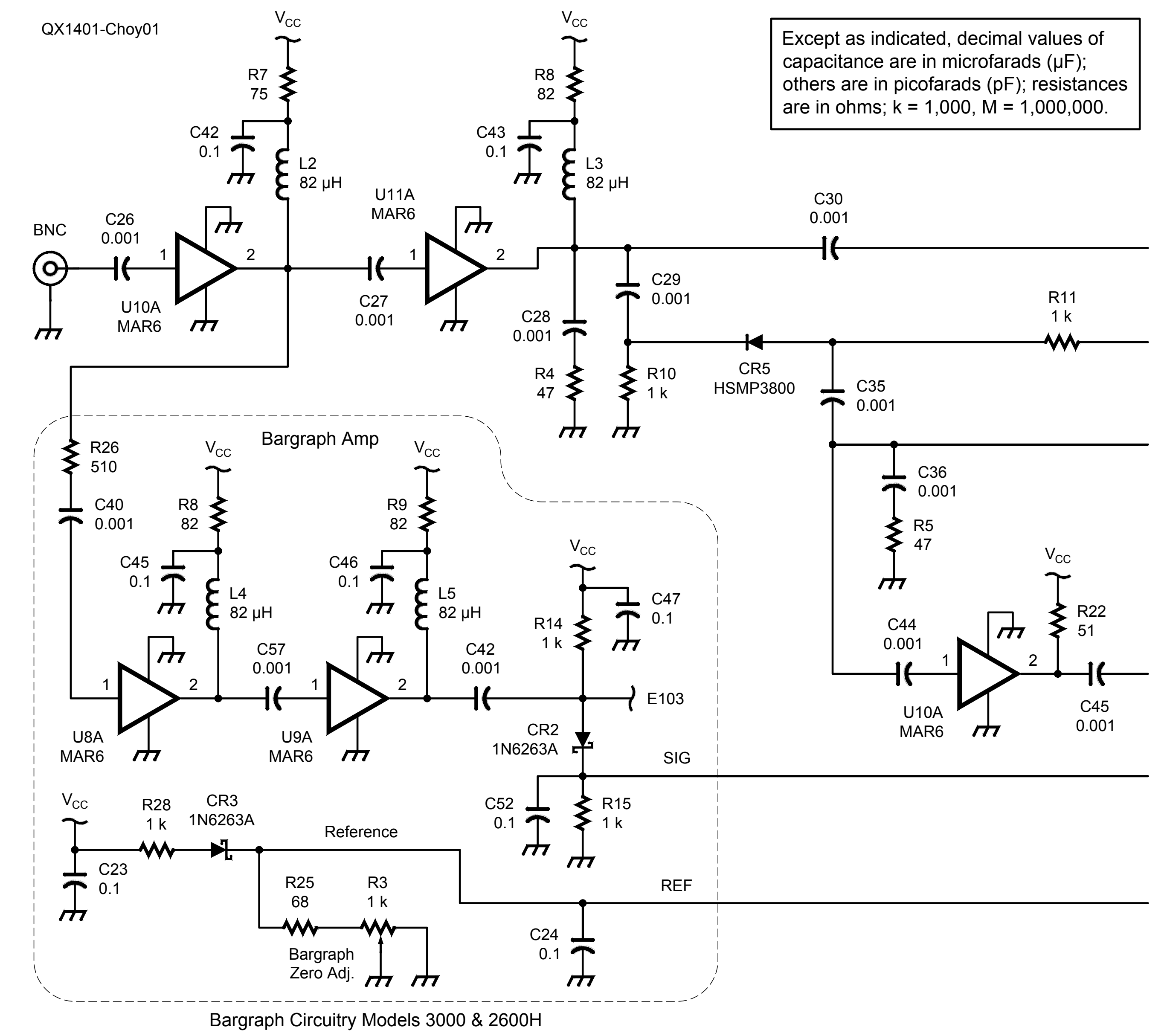

Figure 1 — Channel A input and optional bargraph input circuitry. Note that the owner's manual has errors around CR3, R25, R3 and C24, which are corrected in this diagram.

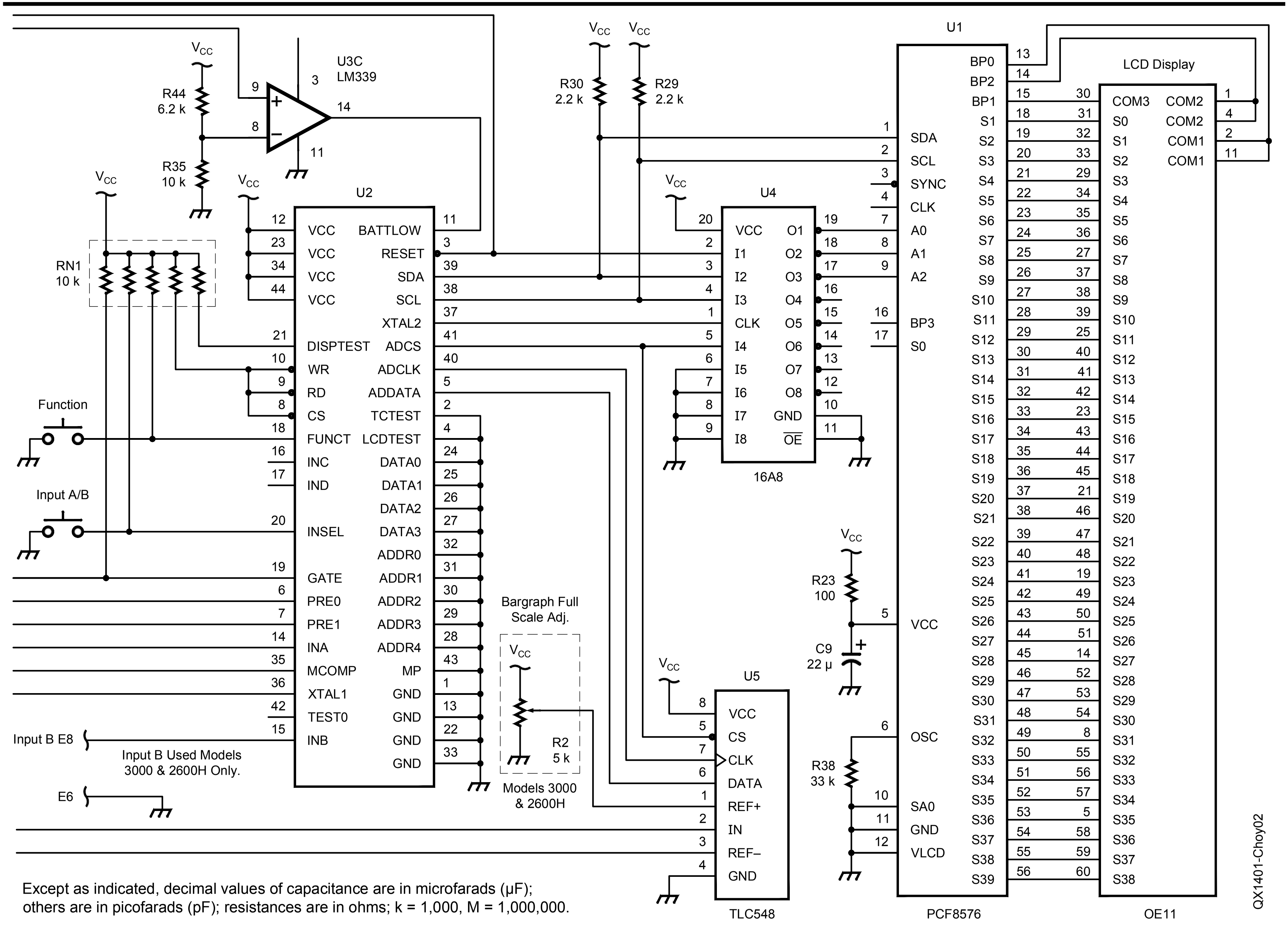

Figure 2 — The TLC548 chip and pot R2 have to be soldered in for the bargraph circuit.

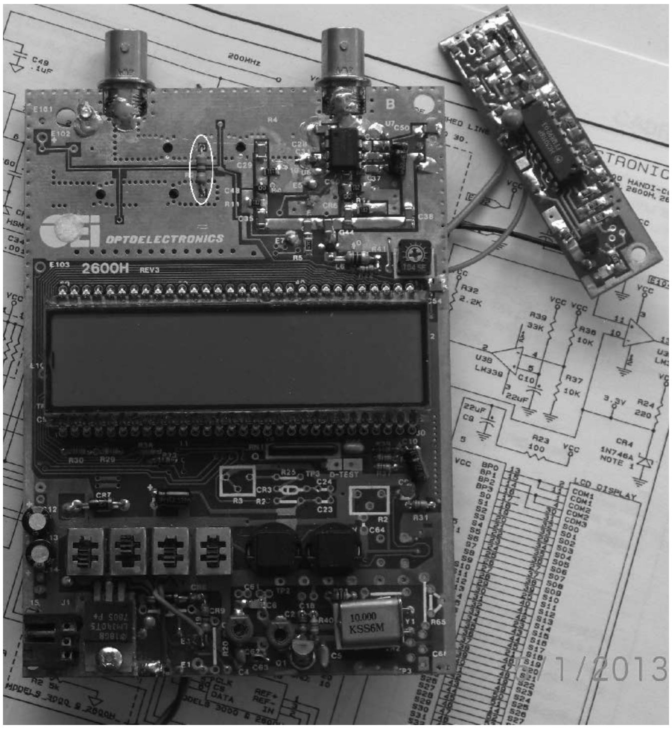

Figure 3 — Main PCB and Channel B input amps board detached from the case. The first component soldered in is resistor R26 shown circled. The remaining parts such as pots R2, R3, diode CR3 and so on are well marked. Solder them in next and check for the voltages by referring to the circuit diagrams Figure 1 and 2.

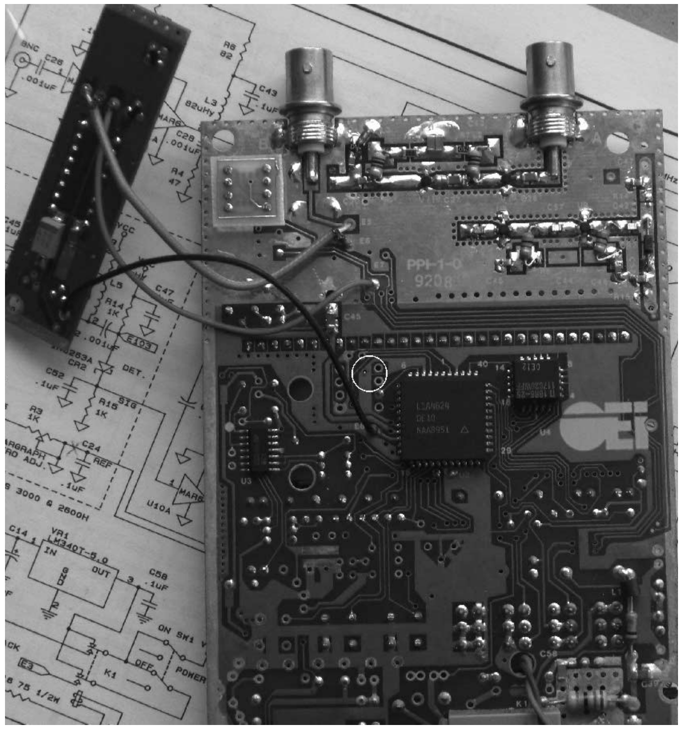

Figure 4 — Underside of PCB showing location of the TLC548 chip U5 to be soldered (shown circled). Note that pin 6 is earthed via a wire link from the top side of the board that can only be accessed by removing the LCD display in Figure 2, so do this very carefully. See Figure 5.

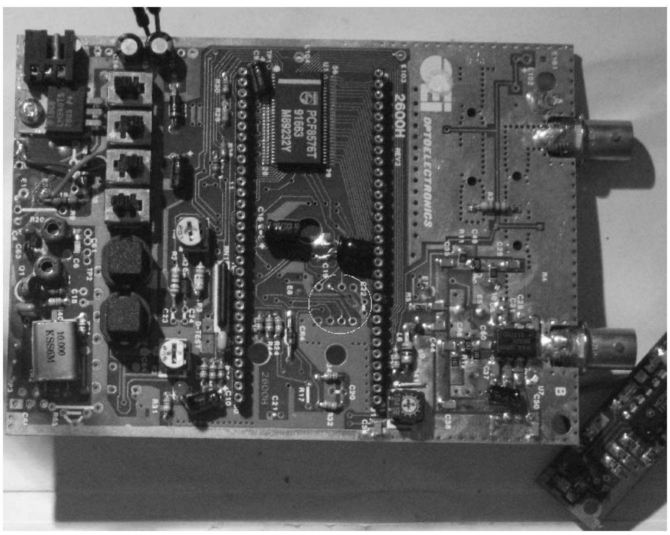

Figure 5 — Main PCB after the LCD display has been removed showing the location of the wire link that was grounding pin 6 of U5 which has now been cut. Without this mod, the micro U2 will not be able to receive ADdata signals from the U5 chip. I recommend soldering an IC socket for U5 which must be wired from the underside of the PCB. Note that a few of the other components R2, R3 and CR3 are now soldered in. The bypass capacitors C23 and C24 are through hole components and its preferable to get the right ones of 2.5 mm pitch to avoid strain on the leads.

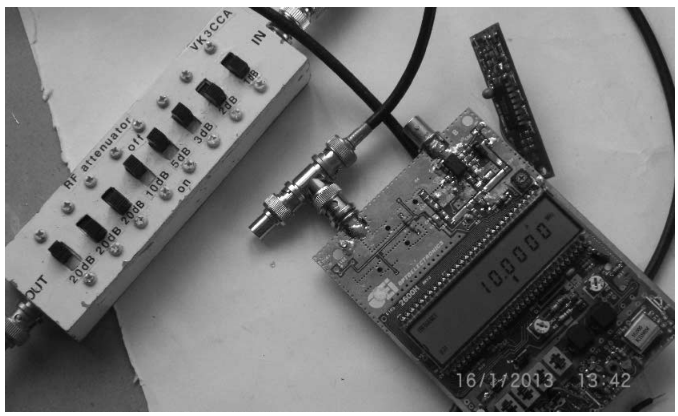

Figure 6 — Unit is now functional and R3 calibrated for 1 bar on –40 dBm. Note that the counter still locks steadily on my 10 MHz signal at –43 dBm from a home-made crystal oscillator which gives out about 0 dBm into 50 Ω.

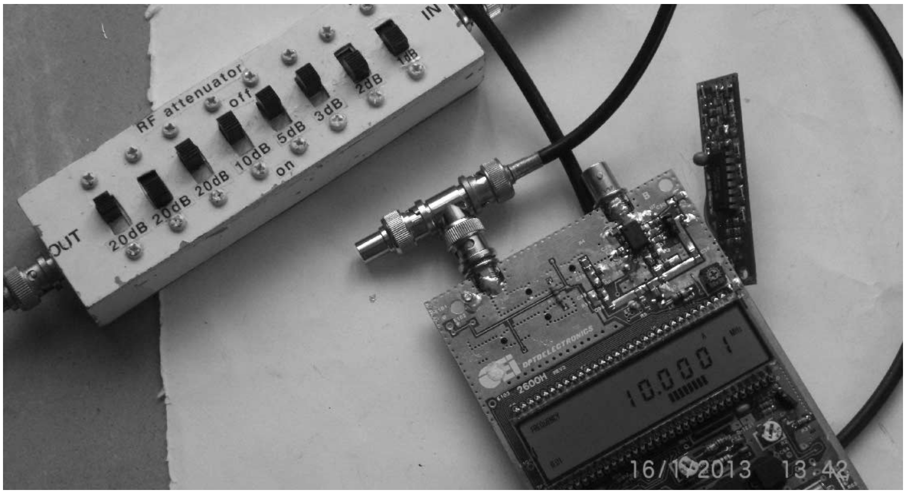

Figure 7 — Unit is now displaying the signal at –23 dBm, after R2 has been adjusted for a maximum of 16 bars on 0 dBm. There are 8 bars lit and each bar is about –3 dBm. Note however that linearity degenerates at both ends of the scale due to the Schottky diode CR2 characteristics.

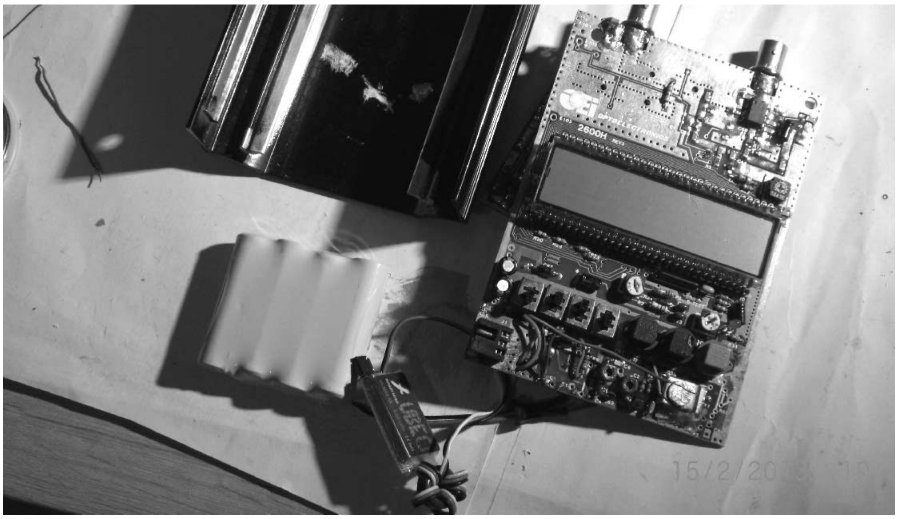

Figure 8 — Modification showing the Murata BG330N posistor in placed as described in the text. The posistor was soldered to the +5 V output from the regulator point on the board and the case grounded, shown by the orange wire here. The original 7805 regulator chip has been replaced in favor of the U-BEC switched-mode regulator shown on the lower left beside the batteries. Note that the posistor cannot be soldered to, you can use silver solder paste for the job if by chance (like me) you have broken its main lead.

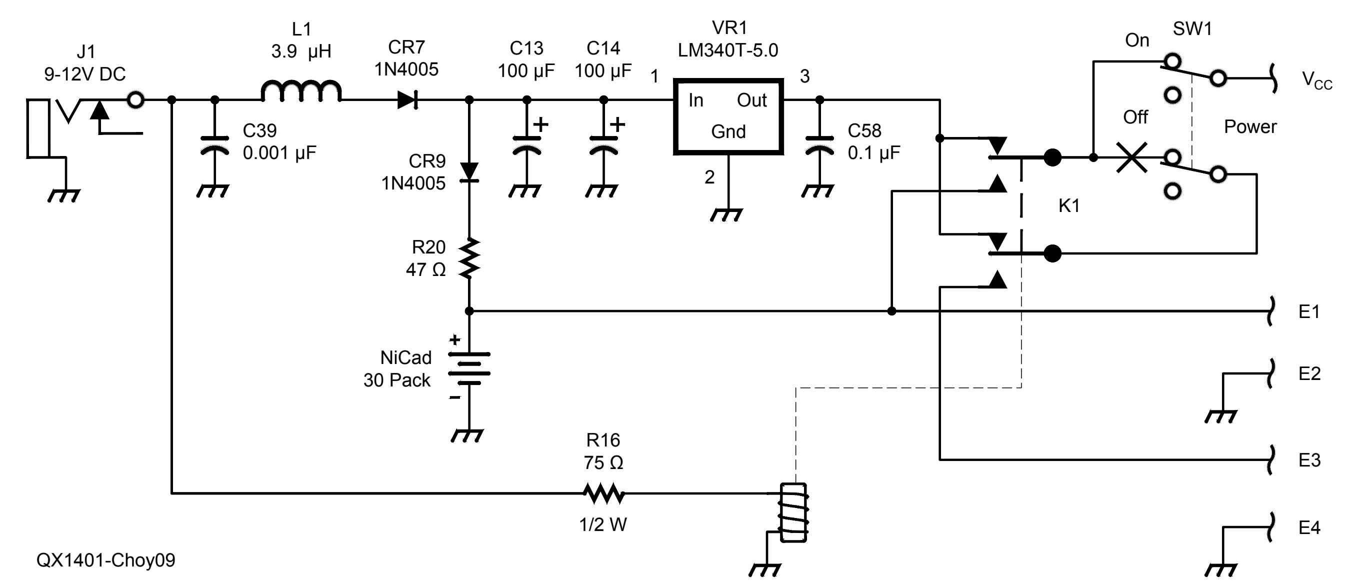

Figure 9 — I wired my posistor to point 3 next to the regulator chip. Unfortunately this does mean that when DC power is connected to charge the batteries, it will come ON even without switching on the counter. To overcome this, you will need to make a break at the point marked X in this drawing and wire the posistor there. However to carry out this mod requires cutting tracks on both sides of the PCB and therefore unsoldering the switch. Do not attempt to do this until you have purchased spare switches, as the switch is very fragile and will very likely break (see text).

remains to calibrate the bar graph readings. For this I used my original crystal oscillator source and adjusted R2 so that just about 16 bars were illuminated for 0 dBm. I then switched in my attenuator. The counter starts to unlock at about –43 dBm. Then I switched back to –40 dBm and adjusted R3 until just about 1 bar was illuminated as the threshold signal. My unit does not have a very good linearity at this end, don't expect good linearity from this circuit because it is only a simple diode detector. If you want better linearity, you will have play around with the biasing on diode CR2. It does give a good relative signal strength indication, which is all I wanted. See Figures 6 and 7.

A Few More Modifications

Before closing the case and congratulating yourself, here are a few more modifications that might be worth considering. At the time I purchased my unit, I was offered the option to replace the unit's crystal oscillator with a TCXO. It was way too expensive then, more than \$50, and it still is. You can get a suitable TCXO from eBay with the same specification of 0.5 ppm for about \$30, but it still seems to be a very costly replacement for a very marginal gain, because the crystal from the manufacturer is a very respectable 1 ppm unit.

The main problem, of course, is temperature stability. If you are only using the unit in your shack, then there is a cheaper alternative. Looking around my junk box I found a Murata BG330N posistor. This unit is a crystal heater that clips onto the crystal and one end goes to +5 V while the case needs to be grounded. See Figure 8. The manufacturer did not ground the case of the crystal, so you may want to ground that anyway, even if you do not want to add the posistor.

N1EQ has written a good article about how posistors work. See **www.n1eq.com/tech/page_05.html**. It is specifically a positive temperature coefficient (PTC) thermistor, which measures 33 Ω cold. At start up, it draws about 100 mA but as the resistance increases with temperature, the current and temperature stabilize and the unit reaches a steady 50°C in my unit after about 10 minutes. (I measured the temperature with a thermocouple.) The current then drops to about 60 mA.

I connected the posistor to the +5 V regulator (not Vcc) output (point 3 in Figure 9) as I do not want to drain the batteries, which are only reserved for field work. Unfortunately this does mean that the posistor comes on even if you just plug in the DC power to recharge the batteries. If you want the posistor to come on only on DC input and when the main power switch is ON as well, then you will need to break the trace at the point marked with an X in Figure 9 and wire it to that pole of the switch. Unfortunately the two poles of that switch are shorted by traces on both sides of the circuit board, so you will need to

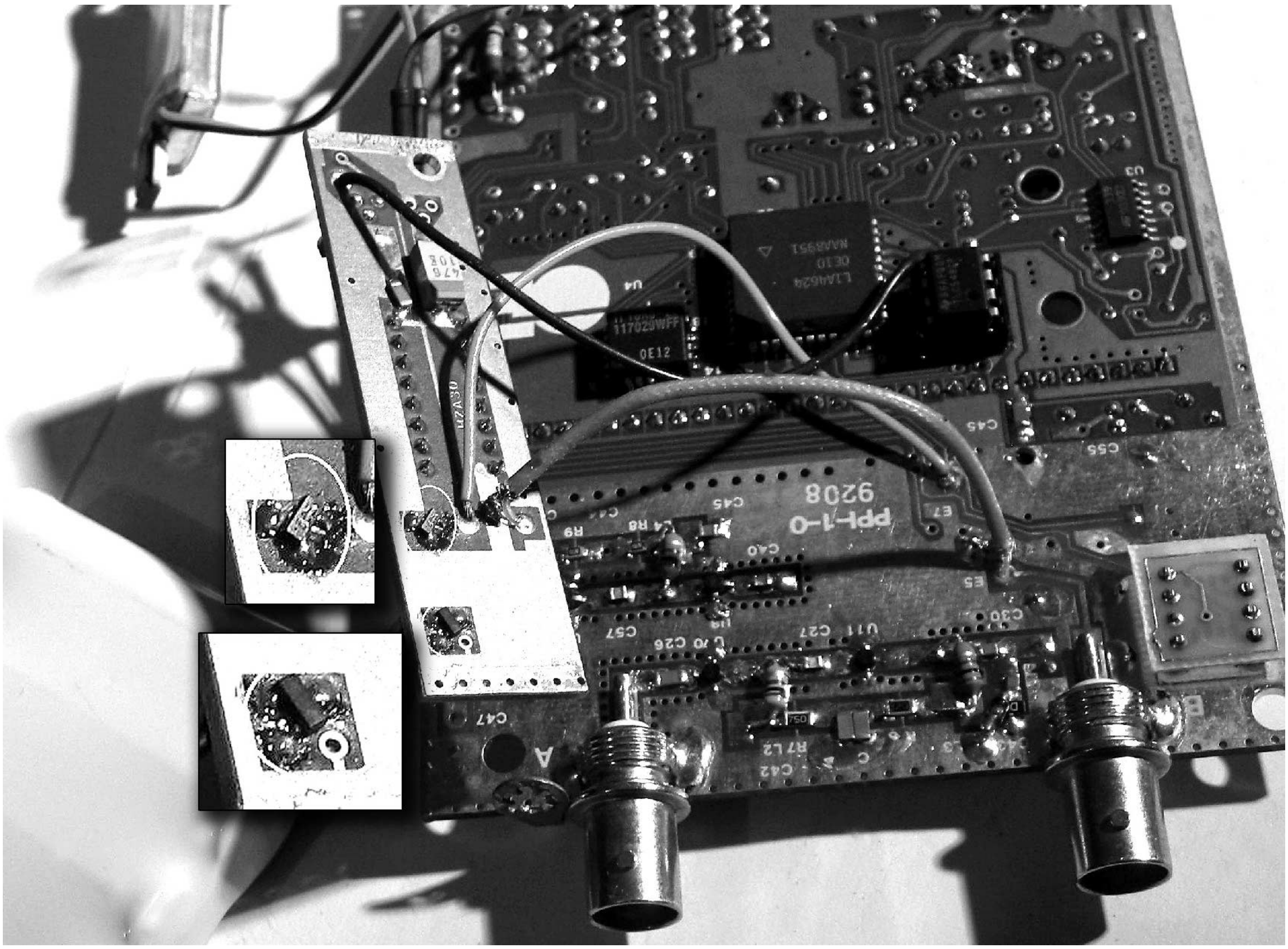

Figure 10 — The channel B amp and MC10116 board. Note the two tiny SMD transistors shown circled and also shown in the enlarged insets. One of these was the culprit for the failure of my channel B board. There is room on the board for discrete devices if you need replacing them as mentioned in the text, as the SMD parts are harder to find.

unsolder the switch to completely break the trace and then re-solder the switch back in. Being clumsy as I am, I expect this switch will break so I did not carry out this mod until some spare switches had been ordered. I do not advise performing this modification without spare switches on hand. Optoelectronics Inc kindly informed me that the part number for this switch is GS-113-0512 and that they are still available from Mouser and Digi-Key in the US.

When the switch arrived from Digikey I completed this modification. As expected, I destroyed the power switch in my attempts to unsolder and remove it. Now the posistor only comes on and warms the crystal when I have external DC applied and breaking this link and the power switch is turned on.

I further discovered a link near the middle of the PC board that feeds the clock signal to the MCU. By breaking this link and rewiring it via a short twisted pair to a 3.5 mm jack that can easily be fitted to the bottom panel close to the relay, I now have the option of using the internal clock or plugging in a rubidium or GPS disciplined 10 MHz TTL signal for timing. Since the counter has a 10 digit display, I can, in principle, get up to 1 parts per billion accuracy with this little unit on most ranges greater than 100 MHz.

The Murata BG330N posistor is a cheap "crystal oven" and it serves my purpose. You can see the unit attached to the crystal at the bottom right corner of the circuit board in Figure 8. When I bought these Murata devices they were just about $2 each, but now they might be hard to find or more expensive. You can try experimenting with other PTC thermistors but you will need to glue one onto your crystal.

You may also wish to replace the unit's crystal oscillator with one that can be heated by a resistor or transistor driving a feedback circuit, which is a lot more work, of course, because there is not much space on the board. There are several such circuits published in various sources but this can be a challenge even for experienced builders. A simpler option may be to buy a TCXO.

Now two other modifications are well worth considering. On an external DC supply, the unit runs hot at the best of times even without the Murata device connected, and high temperature can be bad for the unit's crystal oscillator. The unit uses a 7805 regulator chip, which is an old fashion device. I have completely removed it and replaced it with a switch mode power supply. These are called U-BEC (universal battery eliminator) DC-DC converters, and they take a range of input voltages from 5 to 12 V DC. These supplies can have a choice of 5 or 6 V output. You can see the UBEC supply near the bottom left corner of the circuit board in Figure 8. Some of these battery eliminators have variable output voltages, and can step the input voltage up or down. The great thing is that they are up to 90% efficient and run cool by comparison with the 7805 regulator chip. The one I used is rated at 3 A, and is only a few centimeters in size, so that it can fit nicely into the 2810 instrument casing. Figures 8, 9, and 10 show how I installed it in the 2810 case.

My U-BEC unit came enclosed with epoxy and cost $3 plus shipping, from Hong Kong. They are designed for toy model control applications. The output leads are wound in a small toroid to reduce RFI but my unit has no problems in this respect.

The next and final mod is the most interesting one I have found. If you examine the board and casing carefully you will find that there is a vacancy for a push button switch and one can be readily soldered into place. The front panel actually has a dent that you can cut out for this button, which serves as a FUNCTION switch for the Optoelectronics 3000 model. This is the grey button that you can see under the Gate LED in Figures 12 and 13. Wiring this switch into place will allow you to access the features of the 3000 model, which as you can see from the owner's manual, includes period, ratio, time interval and average period measurements. I think my unit runs into some hiccups here, however, because my board was marked 2600H version 3, and that has to do with the software.

The counter seems to require that you press the FUNCTION button again to stop the count or the hold button to freeze the display for period and time interval measurements. The average period readings seem okay, after several trials, so perhaps mine was an earlier model that has some bugs in the software, or

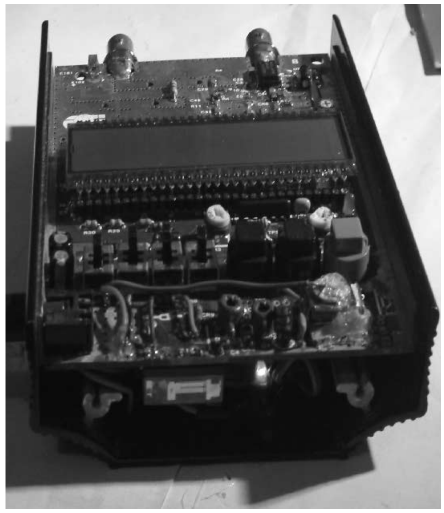

Figure 11 — My fully serviced, upgraded model 2810 to 2600 or almost 3000 model Handicounter. Note the gray push button added to access the 3000 model features, which unfortunately has some software problems. Yours might not have the same problems if it is a later 2810 model so this button is worth adding. Note the U-BEC regular unit underneath, which has a LED which glows when the DC power lead is plugged in.

Figure 12 — All parts returned to the box and with a rubber ducky on the counter (switched to channel A) and one on my 2 m hand-held radio, the bar graph reads full scale from proximity right on frequency when the rig was keyed. No RFI problems have been encountered from the U-BEC regulator.

Figure 13 — Finally my modified Optoelectronics 2810 Handicounter now fully calibrated using a 10 MHz rubidium frequency standard. Note the newly serviced channel B of the counter used, which is shown here. The Murata BG330N posistor clip on the crystal of the unit's oscillator gives it good long term stability of better than 0.1 ppm over 30 minutes and short term of 0.01 ppm over 10 minutes, thanks also to the use of a U-BEC regulator. The bar graph is showing full scale on this channel because my rubber ducky is still connected to channel A, which is picking up the 10 MHz signal.

was a development unit for the 3000 model. Communications with the designers at Optoelectronics confirmed what I suspected —a full feature model 3000 upgrade will require reprogramming of the CPU, so I am out of luck.

Before you finish, I will urge you to check the functionality of channel B. My assumption earlier was that the back to back diodes would protect the unit, but this was quite wrong. In fact my channel B board was totally dysfunctional. Probing around with my scope, I could detect no signals coming out of U201, which is a standard MC10116 triple line receiver and Schmitt trigger, nor from transistor Q203, which was a discrete 2N5139 and not a 4957 as indicated on the schematic. I have known of users having faulty ICs, so I ordered a few just in case. Further examination shows that the input MOSFET, TMPF4416, seems okay and in the end it was a broken down Q202 MMBR 4957 bipolar transistor causing the problem. These are both SMD parts so unsoldering them or one of their leads for testing is quite delicate. The board has enough room for discrete parts if you have them.

Most of these transistors are now rather hard to find, however, and they can be very expensive to replace. I found that for a slight performance compromise you can substitute a BC856 SMD part for the MMBR 4957 and a discrete 2N4416 or 2N5457 for the SMD 4416. My channel B now has 2 mV sensitivity at 10 MHz, but drops to 25 mV sensitivity at 50 MHz compared to the < 20 mV sensitivity as stated in the manual.

The final task is to calibrate the crystal oscillator in the instrument. For this you will either need a GPS disciplined oscillator or, in my case, I had recently purchased one of the Chinese surplus rubidium frequency standards that are available from eBay. The Optoelectronics owner's manual tells you how to perform the calibration by adjusting capacitor C1 and, if necessary, C2. Allow the Murata posistor at least half an hour to warm up and stabilize before you perform this calibration. See Figure 12.

I was able to achieve 0.1 ppm stability over a long term of more than 30 minutes and 0.01 ppm over the short term of about 10 minutes. This is mainly thanks to the relatively cool U-BEC regulator used in my upgrade. Now the job is done and I have the satisfaction of upgrading my older frequency counter to a newer model for about $20 worth of parts and some labor. You can do it, too.

Some other parts that can be substituted are 1N5711 for the Schottky diodes and TLC549 for U5, but I did not have these parts on hand to verify that they will work equivalently. I bought my TLC548 from Farnell, and it cost about $2 in single quantities. The photos in this article (which say a thousand words each) give you some reference points, if you so wish to perform the upgrades. Readers might also be interested to join my Yahoo user group: **http://groups.yahoo.com/group/OptoElectronics2810plus** and participate in the forums and discussions there. I am now looking into the model 3000.

Acknowledgements

I am indebted to Kevin Cox of Optoelectronics Inc in Florida for permission to reproduce the pieces of their schematics in this article, as well as being more than helpful in answering all my queries. Thanks also to Maty Weinberg, KB1EIB, (Production Coordinator at ARRL HQ) for being so patient with my continuous changes to the manuscript while it was being reviewed for publication.

Tuck Choy, MØTCC first got his City and Guilds Amateur Radio certificate 1971 after high school in Singapore, but did nothing with it while pursuing a career in theoretical physics all over the world. He earned a PhD and did post-doctorate work in London, then did further post-doctorate work and served as an assistant professor at several schools. He became a faculty member at Monash University in Australia in 1990. There he took his Morse exams, which were essential requirements for a full license, and received the call sign VK3CCA. His first published homebrew project was a QRP 80 m SSB/CW transceiver using an MC3362 circuit based on ideas from Gary Breed and Drew Diamond. That project won the best technical article award from the Wireless Institute of Australia in 1997.

Tuck is now retired but remains committed to searching for the fundamental principles in physics. He and his wife Debra, who is a professor of linguistics at the Sorbonne in Paris, spend most of their time in the south of France. Apart from the foundations of quantum theory, astronomy and ham radio, he is now busy taking French lessons.

Dr. Sam Green, WØPCE

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An Extremely Wideband QRP SWR Meter

Logarithmic detectors and a simple coupler create an accurate, wide range SWR meter that works from 1 to 500 MHz at less than 100 mW.

A very long time ago, I read an article in some amateur radio publication that explained how performance problems in SWR meters relate to the nature of diode detectors at different power levels. At low power levels, these diodes are square-law detectors, so that output voltage varies linearly with applied power, but at high levels these diodes are rectifiers, so that output voltage varies linearly with applied voltage or the square-root of applied power. I wish I could find that article again.

Most of us learned about logarithmic RF detectors from the 2001 *QST* article that featured the Analog Devices AD8307.[1] I immediately built several pieces of test equipment that included the AD8307 and similar devices, as did many other folks, as evidenced by the flurry of articles.

It occurred to me in 2008, that an SWR meter with a pair of logarithmic detectors in place of the diode detectors would overcome the problems inherent in the diode detectors. As a bonus, a subtraction replaces the division in the calculation that compares the forward indicating voltage to the reflecting indicating voltage because we are now dealing with logarithms. I actually wrote up an invention disclosure for such an instrument before discovering that someone had already patented this apparently obvious idea in 2002. I was disappointed. Look for US patent 6486679.[2]

A *QST* article by Kaune in 2011 featured dual logarithmic detectors in an SWR Meter and led me to check whether the 2002 patent was still in force.[3] If a patent proves to be commercially unsuccessful, patent owners often choose not to pay the renewal fees, which increase as the patent matures. The first fee is due after year seven. I went to the US Patent and Trademark Office Patent Application Information Retrieval website to learn the status of patent 6486679 and was gratified to see the message: "Patent Expired Due to Nonpayment of Maintenance Fees Under 37 CFR 1.362".[4] That is Chapter 37 of the Code of Federal Regulations (Amateur Radio regulations are 47 CFR 97). This patent expired in December of 2010 (the month before the Kaune article), so we are all free to do as we choose with this concept. I was thrilled. This led me to reconsider the approach and what I wanted in an SWR meter.

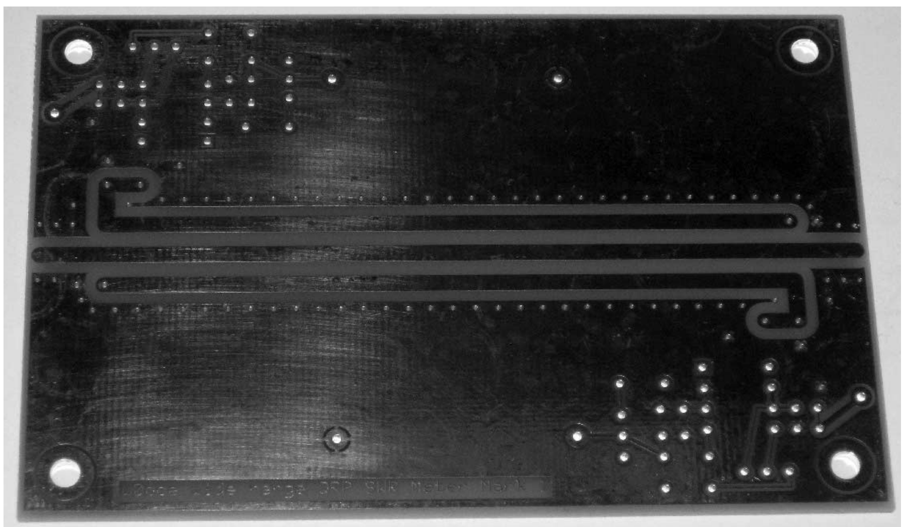

Figure 1 — Bare printed circuit board with couplers shows main and coupled lines.

What I wanted was an SWR Meter suitable for QRP that gives consistent measurements as power level varies. Most instruments cannot handle the low power levels inherent in QRP operation. The excellent sensitivity and huge dynamic range of the AD8307 logarithmic detector allows operation at low RF power levels even with short couplers that have very small coupling coefficients at low frequencies. I started by adding a pair of AD8307 logarithmic detectors to an existing coupler in an old SWR meter and achieved an early success. It turned out that simple transmission line couplers work up to very high frequency if they aren't too long. The limit is ¼

[1]Notes appear on page 23.

wavelength at the highest frequency. Such couplers are what you see in old Heathkit and Citizen's Band SWR meters. They have no ferrites to impose frequency limitations. They just have length, distance between coupled lines, and characteristic impedances of the main and coupled transmission lines.

I decided to use printed circuit techniques in order to make couplers with balanced and controllable characteristics, so I could reproduce them. This turned out to introduce interesting new problems, but it's all about learning, isn't it? The lesson below is that simple microstrip couplers do not work well because modes in the air above the board have different propagation characteristics than modes in the dielectric within the board. Luckily, the fix is not difficult.

The Directional Coupler

Figure 1 shows the bare printed circuit board that hosts the logarithmic detector circuits and constitutes the forward and reverse directional couplers. The transmitter enters the main line in the center from an SMA connector on the left. The antenna or other load is connected via an SMA connector on the right. I designed the prototype to use SMA connectors to learn what frequency response I could achieve. The results are truly remarkable!

The main line couples a sample of the forward signal (from the transmitter to the antenna) to the upper line and then to the logarithmic detector at the upper left. A matched termination at the other end of the line absorbs any contribution from the opposite direction. Similarly, the main line couples a sample of the reverse signal (from the antenna back to the transmitter) to the lower line and then to the logarithmic detector at the lower right. A matched termination at the other end of the line absorbs any contribution from the opposite direction.

Transmission line couplers should be embedded in a uniform dielectric such as air or FR-4 circuit board material. Heathkit style couplers and stripline couplers work because they have uniform dielectric around all of the lines. Stripline is composed of printed conductors embedded in dielectric between two ground planes, whereas microstrip is composed of printed conductors above a dielectric with a ground plane below the dielectric but air above the conductors. Microstrip does not make a good transmission line coupler.

Wikipedia explains: "The λ/4 coupled line design is good for coaxial and stripline implementations but does not work so well in the now popular microstrip format, although designs do exist. The reason for this is that microstrip is not a homogeneous medium —there are two different mediums above and below the transmission strip. This leads to transmission modes other than the usual TEM mode found in conductive circuits." [5]

A second reference (emphasis added) says: "Planar structures (unless they are stripline) have notoriously bad directivity. Directivity (Isolation minus coupling) is determined in these types of structures by the difference between the even and odd mode

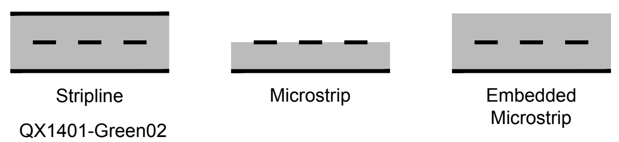

Figure 2 — Cross sections of planar transmission line options.

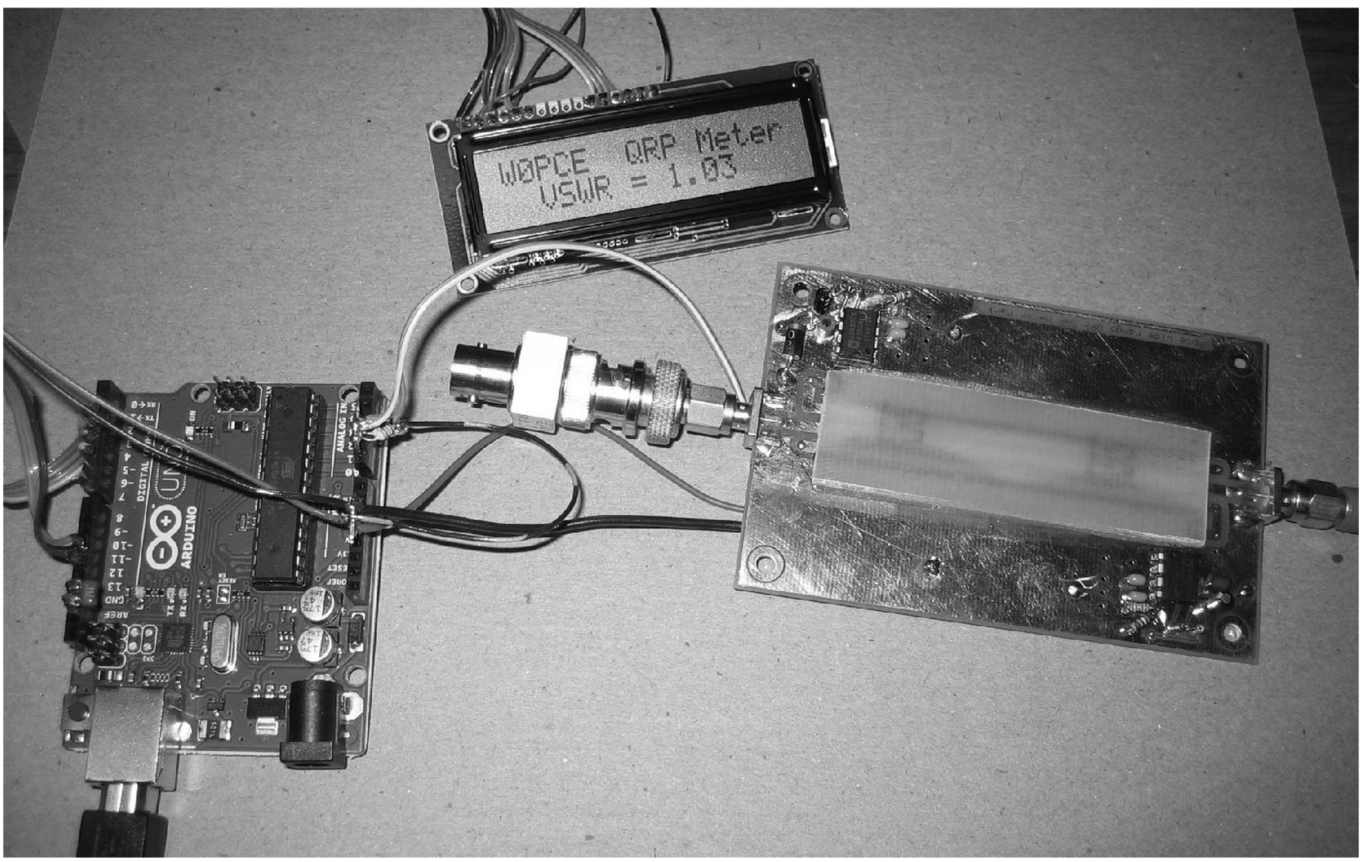

Figure 3 — Working WØPCE QRP SWR Meter.

phase velocities with the best coming when these are equal. In microstrip, the odd mode is mostly in dielectric, and the even mode is mostly in air. To equalize the phase velocities, you need to slow down the even mode which can be accomplished **using a dielectric overlay over the lines** (microstrip case)."[6]

A third reference also suggests the method of adding dielectric material above a microstrip coupler to make it work, and that's what I did.[7] The dielectric above the microstrip should be the same as the material below for the even and odd modes to propagate at the same speed. We call this configuration of microstrip within a thicker layer of dielectric "embedded microstrip." Figure 2 shows that it looks like stripline without the top ground plane.

It is very critical to control the impedances of the main and coupled lines in order to minimize degradations to directivity. The coupled lines can be of any impedance as long as they terminate in their characteristic impedance. The main line must be the characteristic impedance of the transmission line between your transmitter and antenna or tuner, usually 50 Ω. I tried to make all three be 50 Ω.

I found four impedance calculators for embedded microstrip transmission lines on the Internet. Two agree closely, and the other two disagree dramatically. Unfortunately, I started with a bad one, but I got excellent

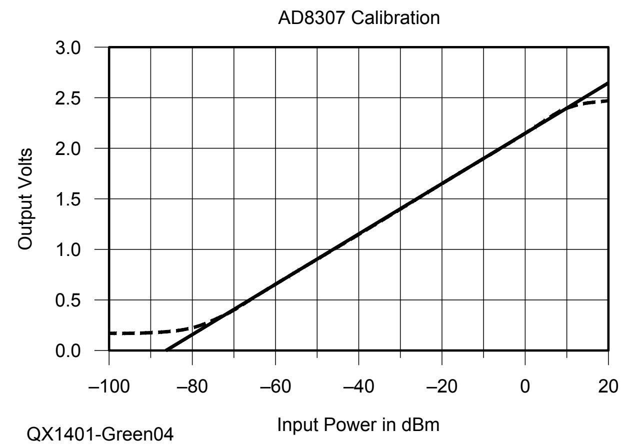

Figure 4 — This graph shows the response of eight separate AD8307 logarithmic detectors calibrated to 25 mV/dB slope and –86 dBm intercept. The solid line is the linear fit and the dashed line is the calibrated response. The repeatability is so good you cannot see any dispersion and the linear portion maps directly over linearized data.

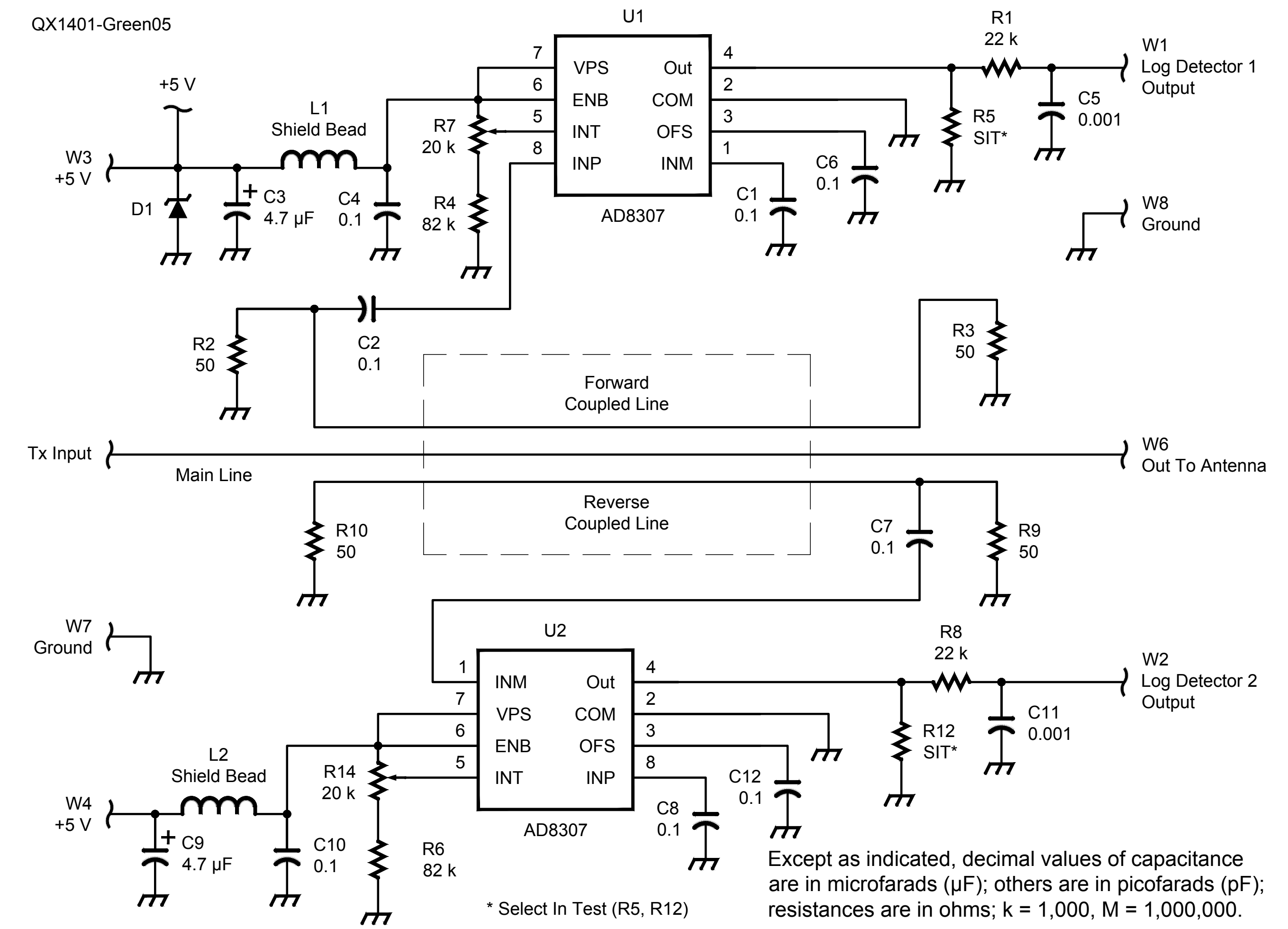

Figure 5 — Schematic diagram of bi-directional coupler and dual logarithmic detector board.

results with one from the Swedish company Multi-Teknik.[8] I designed the circuit board using the Express PCB design tool and their parameters for dielectric constant and trace and board thickness. See **www.expresspcb.com/**.

Figure 3 shows the first working QRP SWR Meter. Note that the dielectric overlay converts the ordinary microstrip to embedded microstrip. SMA connectors that connect to the edge of a printed circuit board prove to be a convenient way to attach to the center main line trace for this prototype.

The Logarithmic RF Detectors

The Analog Devices AD8307 data sheet describes the operation and use of this logarithmic detector.[9] I built a test jig following figure 37 in that data sheet to characterize these devices to assure that forward and reverse measurements are on the same basis. My method sets all devices to a slope of 0.025 Volts/dB and an intercept of -86 dBm. My settings are only as accurate as my power measurement, but they are consistent across devices and allow good matching. I could measure the characteristics and compensate in software as I did in my DDS project, but this time I selected resistors and eventually installed trimpots to set and match the slopes and intercepts of the logarithmic detectors to the desired values.[10]

Figure 4 shows the response of 8 separate sample AD8307 logarithmic detectors following the calibration process. The curved line is the real calibrated response. The straight line is the best fit to the linear portion of each curved line between 0 dBm on the high side and −60 dBm on the low side. The repeatability is so good that you see no dispersion. Calibration forces the linear fit to have a slope of 25 mV/dB and an intercept extrapolated to zero volts at –86 dBm. These figures may vary, but they must vary together. The data indicates a usable dynamic range from +10 dBm down to −74 dBm. Measurement results within this range are very reproducible. It is this huge dynamic range that allows the SWR Meter to accommodate the low coupling coefficients and corresponding low signal levels at low frequencies as well as the high coupling coefficients and high signal levels at high frequencies.

The circuit of data sheet figure 37 also serves as the circuit for the two logarithmic detectors on the printed card except that I add a 0.1 μF capacitor from pin 3 to ground in case this instrument ever finds use at frequencies below 100 kHz. Figure 5 shows the schematic of the bi-directional coupler/logarithmic detector board.

The Math

The outputs of the coupler board are two voltages that indicate the logarithms of the forward and reflected powers from the two couplers. We divide the reverse power by the forward power to get a power reflection coefficient, ρ. Remember that dividing numbers is the same as subtracting their logarithms.

We square the power reflection coefficient to get the voltage reflection coefficient, because we ultimately want the Voltage Standing Wave Ratio. Since we're still dealing with the logarithms, we obtain the square by multiplying the logarithm of the power reflection coefficient by 2.

So far, we've taken the two voltages, subtracted them, and multiplied by 2:

$$\log \rho = 2 \times (Vr - Vf) \qquad \text{[Eq 1]}$$

Then we obtain ρ by raising 10 to the power log ρ.

Finally we obtain the SWR from Equation 2.

$$SWR = (1 + \rho)/(1 - \rho) \qquad \text{[Eq 2]}$$

All this is just a few lines of code in a high level language, as we'll see.

The Arduino

I did all the early development work with a pair of digital multimeters and a calculator to prove the principle. When I finally laid out this board and ordered three from ExpressPCB for about $63 including shipping, progress came rapidly. I had a working board and nothing else ready and just the idea that I should use a computer and some analog to digital converters.

At this point, I first considered the Arduino. It was sitting on top of my oscilloscope, waiting to do something useful. I had never done anything with it except to change the default "BLINK" program that blinks the LED on and off to instead send CQ on the LED. In short order, I learned that the Arduino has several analog inputs and that the programming language supports raising one number to the power of another. That was all I needed besides a display. Doug and Ben, the experts at Gateway Electronics, explained that a sample 2 line by 16 character black on green LCD display in my junk box would serve. I am very lucky to live near Gateway Electronics and usually visit daily.

The Arduino does an amazing job of unburdening your tasks. I expected to spend a week interfacing some kind of display and learning to twiddle the right bits to make it work. It turns out that the Arduino directs you to references that show you how to connect displays it understands and already has the programming library built in. Similarly, the analog to digital converters operate with simple program commands. Figure 6 shows the simple code that performs the basic functions of the SWR Meter. This is all the code from the original working SWR Meter, not just an excerpt.

More bits of resolution would be nice, but 9 to 10 is adequate. I reduced the analog to digital converter reference voltage AREF from 5 V to 2.4 V to get that last bit of resolution. See the sidebar on Arduino Uno ADC References.

If this were a commercial product, I might select another processor that consumes less power or has higher A/D converter resolution, but the Arduino is excellent for rapid prototyping. I ordered several more.

Power Considerations for Portable Operation

The prototype in Figure 3 draws 70 mA from a 5 V supply for the Arduino, the display, and the logarithmic detectors. The backlight for my junk-box display draws another 160 mA, but this display works fine without the backlight in suitable ambient illumination.

Jon Poland, NØWL, suggested I optimize for battery operation by turning the Arduino off between measurements rather than using a delay loop to set the timing. This didn't help as much as I expected because there is other circuitry on the Arduino including a second processor to handle USB communication to the PC, and this other circuitry stays active and consumes over 30 mA.

The solution is to remove the ATMega328P-PU chip from the Arduino and build suitable circuitry around it. Figure 7 shows that the prototype CPU board is similar in layout to the Arduino. Some folks call this a "Pseuduino." Along the way, I purchased more such chips from DigiKey and learned to program them with a bootloader.[11, 12] Then, I needed to program them remotely from the Arduino board. Ben at Gateway Electronics taught me how to program an ATMega328P-PU chip remotely from an Arduino Uno with the chip removed. I find just one reference on-line with only verbal instruction, so I provide a second sidebar to illustrate this method of remote programming.[13] Elimination of the excess circuitry reduced the current drain of the ATMega328P-PU, which still ran full time, to about 16 mA. That means the USB interface and other circuitry drew over 30 mA.

I built a first Pseuduino to replace the Arduino in the SWR Meter and a second for use as a fixture to aid in assembling and calibrating these instruments in a production environment. I eventually turned an Arduino into a Pseuduino so that I wouldn't have to build any more. I describe this procedure in a third sidebar below.

I found an excellent tutorial on how to put

Code Listing

```
#include <LiquidCrystal.h>
// initialize the library with the numbers of the interface pins
LiquidCrystal lcd(12, 11, 5, 4, 3, 2);

int sensorPin0 = A0, sensorPin1 = A1;
float a,b,c,d,e,f;
float sensorValue0 = 0, sensorValue1 = 0;  // store values from sensors
float fudge = 2.40/1024 ; // for External 2.4 V reference

void setup() {
lcd.begin(16, 2);    // set up the LCD's number of columns and rows:
analogReference(EXTERNAL);
}

void loop() {
sensorValue0 = analogRead(sensorPin0);
sensorValue1 = analogRead(sensorPin1);

lcd.setCursor(0, 0) ;
//  lcd.print("W0PCE  QRP Meter  "); // normal operation
a=sensorValue0*fudge ;
b=sensorValue1*fudge ;
lcd.print("Vf=");    lcd.print(a); // diagnostic operation
lcd.print("  Vr=");  lcd.print(b);

lcd.setCursor(0, 1) ;
c=2*(b-a) ;
d=pow(10, c);
e=(1+d)/(1-d) ;
lcd.print("  SWR = ");  lcd.print(e);
delay(500);
}
```

Figure 6 — Arduino code performs WØPCE QRP SWR Meter functions.

the CPU of an Arduino into various power saving modes when it isn't necessary to be active.[14] The ATMega328P-PU chip draws about 2.5 mA in the lowest power sleep mode, including 1 mA for the reference diode. With the display energized full time, the CPU and display together consume 5 mA in sleep mode which lasts for about 90% of the measurement cycle.

I added circuitry to turn on the remaining high current circuitry when necessary. The Logarithmic Detectors consume about 15 mA but only need to be on for 30 ms prior to the two measurements by the A/D converter. The backlight is optional, but I made it light up for about 100 ms after each display update with a repeating period of 500 ms, or for 20% of the time for battery operation. Under these conditions, current drain is under 10 mA without the backlight and 33 mA with the backlight pulsing or blinking after each measurement.

Finally, I found a white on blue LCD display at Gateway Electronics with a very much lower backlight current but which doesn't operate at all without a backlight. This backlight requires much less current than the ATMega328P-PU chip, so it made sense to run the backlight constantly rather than running the CPU to blink the backlight.

Figure 8 shows the supply current as a function of time for the high and low backlight current displays. The bottom line in each is the zero reference. Sensitivity is 10 mA per division in Figure 8A (1 mV per division divided by the 0.1 Ω current sense resistor). Current rises from 8 mA in sleep to 37 mA when the logarithmic detectors turn on and 22 mA when they turn off and the

CPU chip performs the measurement and calculations. Finally the backlight blinks on raising the peak current to 70 mA for 100 ms. Average current was under 25 mA for the display with the high current backlight in this energy saving mode, but the blinking was annoying. Sensitivity is 5 mA per division in Figure 8B (500 µV per division divided by 0.1 Ω). Current rises from 5 mA in sleep to 30 mA when the logarithmic detectors turn on and the CPU chip performs the measurement and calculations. Final current drain with the backlight is now 7.1 mA, which is well suited to battery operation. The 5 mA sleep current includes the ATMega328P-PU chip, the display, the backlight, and current through the reference diode that supplies AREF. Yes, I could save another 1 mA by applying power to the reference diode only during measurements. Perhaps I will.

Figure 9 shows the final prototype with the backlit 2 line by 16 character white on blue LCD display. Figure 10 shows the inside of the final prototype. I have since added nickel-metal hydride AAA cells that fill some open space in the cover and charging circuitry. A relay disconnects the battery when power is available from the wall-wart. This proved simpler than the alternative semiconductor circuits I tried. The wall-wart charges the nickel metal hydride cells through a constant current circuit.

I also tried a 2 line by 40 character black on green LCD display provided by Herb Ullman, AF4JF. It has no backlight and requires suitable ambient illumination. This enabled sufficient characters to implement a bar graph for analog display. Pavel Vachal,

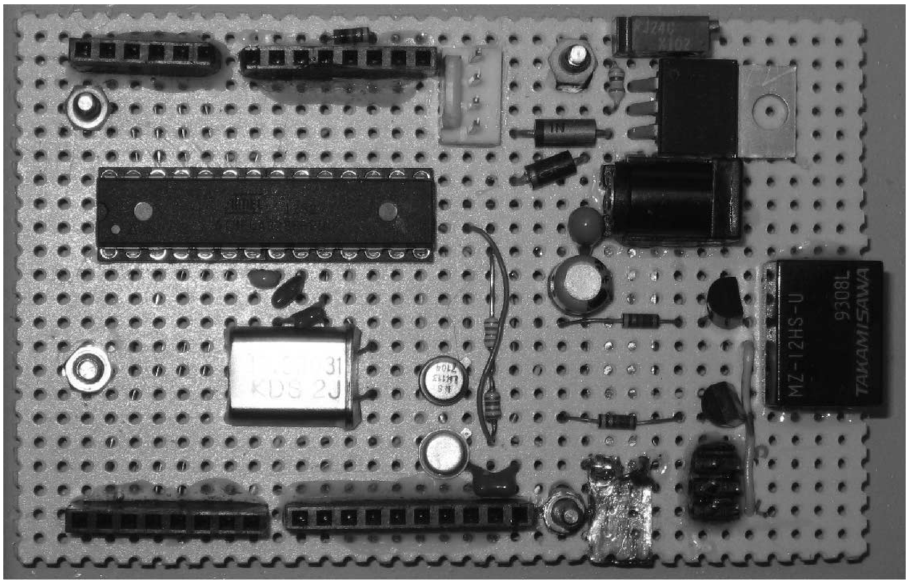

Figure 7 — Early version of Pseuduino copies Arduino functionality without USB interface.

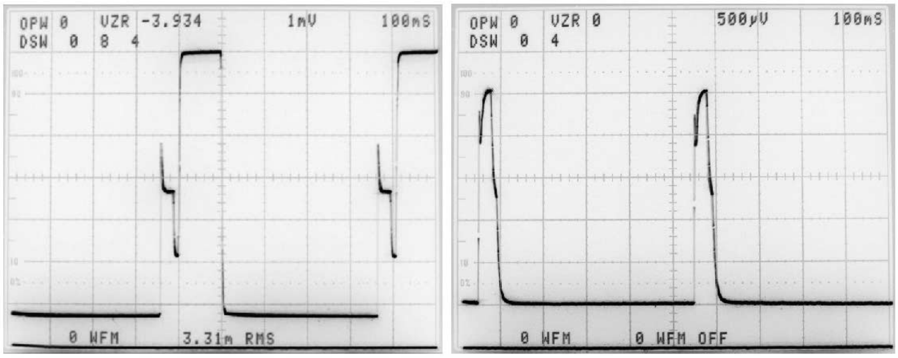

Figure 8 — In Part A, the supply current profile shows 8 mA during sleep with pulses to 70 mA for 100 ms for the backlight. In Part B, the supply current profile shows 5 mA during sleep with pulses to 30 mA during measurements.

Arduino Uno ADC References

There seems to be some confusion in how to use the various voltage reference options for the analog to digital converter in the Arduino Uno.

The best guidance I found is: **arduino.cc/en/Reference/AnalogReference?from=Reference.AREF**

Place the statement

analogReference (type) ;

within the curly braces of the **void setup() { }** statement.

Options for "type" must be **all upper case** and are:

DEFAULT, which provides an internal reference of about 5V. Mine measures 4.74V.

INTERNAL, which provides an internal reference of about 1.1V. Mine measures 1.087V.

EXTERNAL, which uses any voltage between 0 and 5 V applied to the AREF pin.

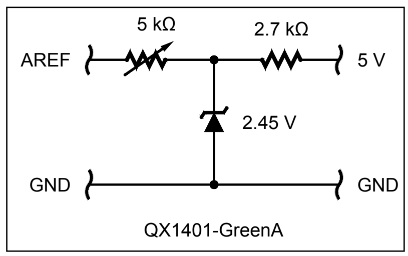

Figure A — External 2.40 V Analog Reference Supply.

If the user applies a voltage to AREF for use in the EXTERNAL mode, that voltage struggles against the internal source when the **DEFAULT or INTERNAL** mode is active.

To illustrate the problem, set the Arduino Uno to default mode and plug an LED into the pins AREF and Ground. Unless the LED is in backwards, it will glow brightly, indicating a current flow of tens of milliamps out of the AREF pin. If you place a voltage reference diode across these pins, a similar current will flow through it in DEFAULT mode.

The Arduino site above suggests a resistor between the AREF pin and the external reference voltage as in Figure A. This resistor decreases the actual reference voltage, so accuracy suffers, but this also provides a means to trim the external reference voltage to a lower desired value.

I used a 2.46 V reference diode fed with about 1 mA from Vcc through a 2.7 kΩ resistor. Then I connected the reference diode to AREF through a potentiometer. At about 1.5 kΩ, the reference voltage at AREF reduces to 2.40 V, the value I desired.

Figure 9 — White on blue LCD display from Gateway Electronics operates at low backlight current.

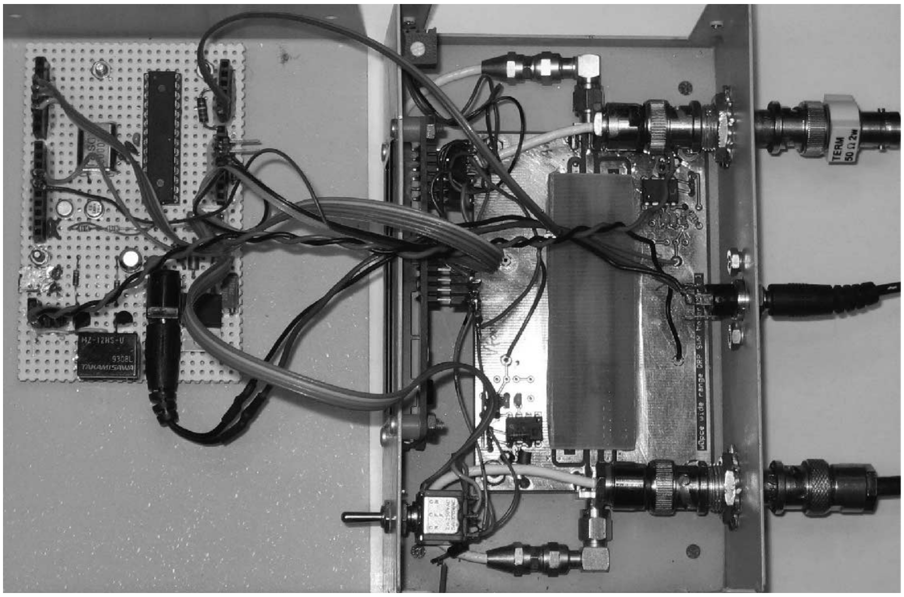

Figure 10 — Inside of recent prototype shows assembly details. Battery fits in open space of cover.

OK1DX used this approach, and it looks neat.[15]

I placed an actual analog meter on a PWM output for a true analog display. This could lower the cost of parts, but current drain is much higher, because the CPU chip must stay active and never enter a low power sleep mode. Still, this enables a familiar interface except that the operator no longer needs to set the full scale reading in the forward direction before switching to obtain a reading in the reverse direction. The correct reading just appears at the meter with no switching and no complex cross-needle indicator.

Figure 11 shows the accuracy of this instrument in measuring SWR over a wide range of load resistance at a sub-QRP power level. I performed these measurements as best I could by placing small resistors with the shortest possible leads within a coax connector. With a 7 Ω termination, the ideal SWR should be 7 and the instrument measures between 5 and 6 over the entire frequency range. Similarly, with a load resistor of 500 Ω, the ideal SWR should be 10 and the instrument measures between 5.7 and 9.1 over the entire frequency range.

Recent Efforts

Recent attempts to make it easier to manufacture this unit led me to simulate a true stripline version by replacing the unclad FR-4 overlay with one that uses a single sided copper clad FR-4 overlay. This required adjusting the trace widths. I wasn't as lucky this time, and the mainline impedance measures 56 Ω. This limits the minimum measureable SWR in a 50 Ω system to about 1.2, but the exercise shows

Program CPU Remotely From Arduino Uno (At the Suggestion of Ben at Gateway Electronics)

Connect the TX, RX, RESET, and GND lines of the remote ATMega328P-PU chip and the Arduino Uno without the ATMega328P-PU chip installed as in Figure B. Either connect 5 V or let the circuit where the remote ATMega328P-PU chip is running provide 5 V. Then simply program sketches into the ATMega328P-PU chip as if it were still plugged into the Arduino Uno. This does not work unless the crystal is 16.0 MHz, as on the Arduino Uno. Remove the RESET line if you remove Arduino power to allow the remote ATMega328P-PU chip to run.

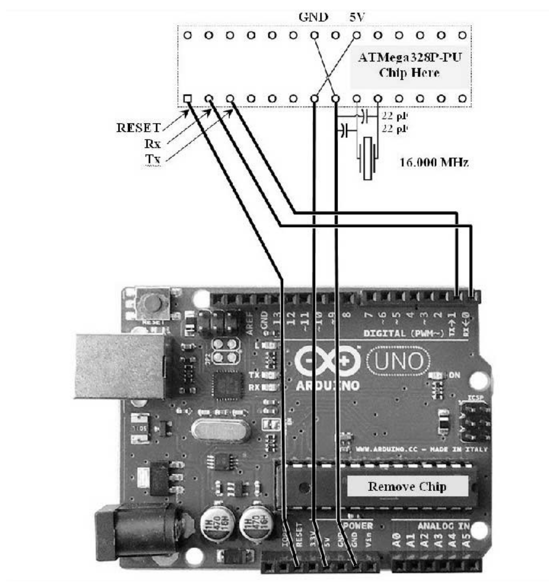

Figure B — Remove ATMega328P-PU Chip and connect as shown to program remote ATMega328P-PU Chip.

that stripline works, and we are presently trying to find someone to manufacture such boards inexpensively.

Finally, I received several requests to incorporate power measurement. When I finally lashed a third logarithmic detector onto the simulated stripline board, this proved to be a surprisingly simple upgrade. The first try at power measurement was flat within ± 0.3 dB from 1 to 30 MHz. With some attention to equalization, the third try was flat within ± 0.3 dB to above 150 MHz.

Drawbacks

Are there any drawbacks or problems with measuring SWR at such low power levels? You bet! It turns out that when you connect to a real antenna instead of a dummy termination, the reverse log detector senses signals from the antenna that may dominate the small return from a low SWR antenna and erroneously raise the apparent SWR. For this reason, I will consider shortening future versions of the sampler to make them less sensitive. Slightly increasing the spacing between the main transmission line and the sampling transmission lines will yield the same result. For now, it is best to use this instrument well above the lowest power levels.

Availability

Lee Johnson, NØVI, and I are trying to turn this into a product or a Saint Louis QRP Society (SLQS) club project, if we can produce accurate couplers at low cost.[16] The main transmission line impedance is critical to performance. An air gap under the FR-4 layer would degrade performance, so we want to make the coupler in stripline rather than embedded microstrip.

Assembly of a kit would require installation of at least four surface mount chip resistors and six surface mount chip capacitors, more if we include power measurement. I characterize and match the logarithmic detectors to optimize performance and recently developed a simpler method to perform this previously burdensome task. For these reasons, the coupler should probably be provided as a complete calibrated assembly. Check Lee's website for more information about the availability of kits.[17]

Conclusion

This instrument enables fairly accurate SWR measurements for really low power operation over an incredible frequency range from below 160 meters to above ¾ meters. Accuracy degrades gracefully as power decreases. Results are acceptable at the lowest HF frequencies down to 30 mW! With slightly more power, this instrument proves useful at 100 kHz and below.

Measurements directly to the SMA connectors on the prototype coupler are accurate up through UHF. With added adapters and coaxial cable to convert to BNC connectors, performance is still very accurate up through VHF and more than usable to 500 MHz.

The prototype works over the frequency range from 1 to 500 MHz at less than 100 mW and accommodates 100 W up to 15 meters, 70 W up to 10 meters, and less with increasingly higher frequencies as coupler efficiency increases. Increasing the spacing between the main transmission line and the sampling transmission lines or shortening these lines would allow higher power at higher frequency at the expense of less sensitivity at the lowest frequencies.

This was an incredibly enjoyable and rewarding project. I have used personal computers to control circuits in other recent projects that appeared in *QEX*, but this was my first attempt at embedded programming since I spent nearly two years programming a DSP in assembly language in 1992 and 1993. I had the Arduino programmed and running in 2 days. What a kick!

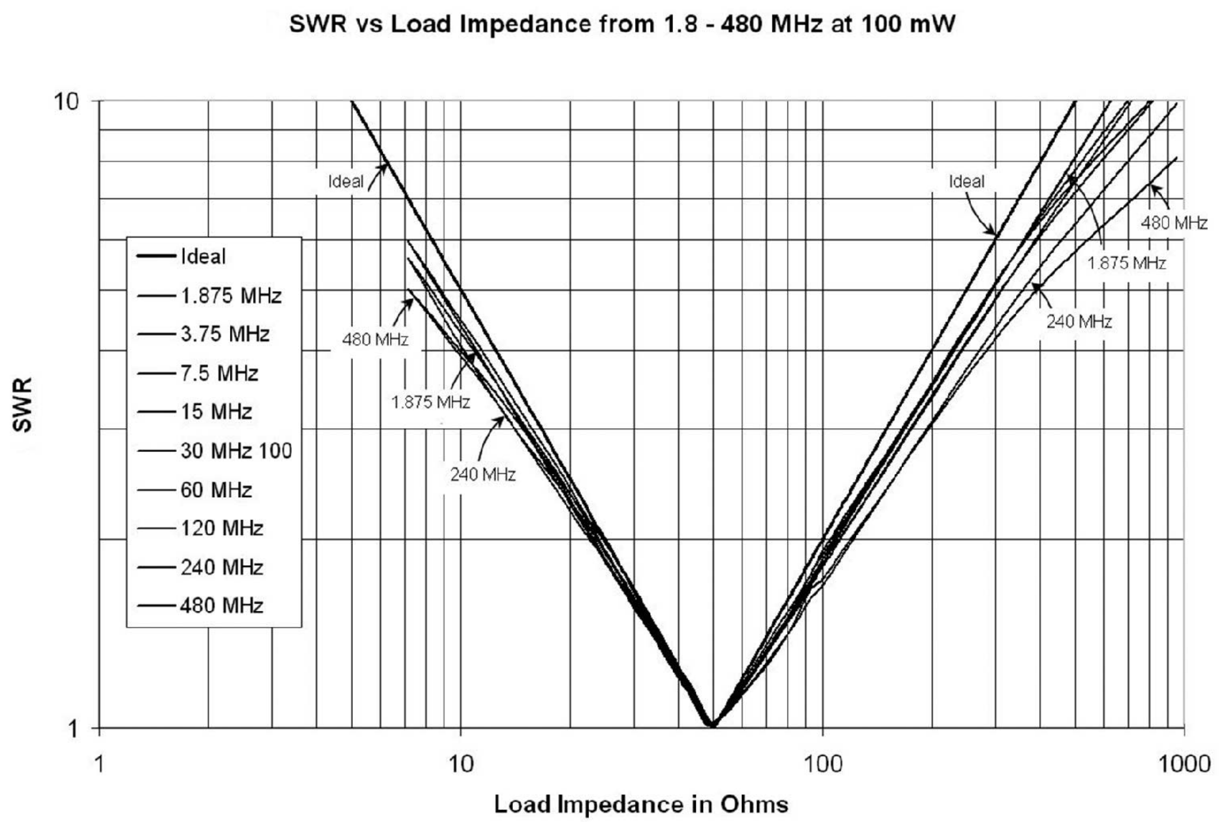

Figure 11 — Accurate measurement of SWR versus load resistance at low power over wide frequency range.

*Dr Sam Green, WØPCE, is a retired aerospace engineer. Sam lives in Saint Louis, Missouri. He holds degrees in Electronic Engineering from Northwestern University and the University of Illinois at Urbana. Sam specialized in free space optical and fiber optical data communications and photonics. He became KN9KEQ and K9KEQ in 1957, while a high school freshman in Skokie, Illinois, where he was a Skokie Six Meter Indian. Sam held a Technician class license for 36 years before finally upgrading to Amateur Extra Class in 1993. He is a member of ARRL, a member of the Boeing Employees Amateur Radio Society (BEARS), a member of the Saint Louis QRP Society (SLQS), and breakfasts with the Saint Louis Area Microwave Society (SLAMS). Sam is a Registered Professional Engineer in Missouri and a life senior member of IEEE. Sam holds seventeen patents, with one more patent application pending. Contact Sam at **w0pce@arrl.net**.*

Notes

[1]Wes Hayword, W7ZOI, and Bob Larkin, W7PUA, "Simple RF Power Measurement," *QST* June 2001, pp 38-43.

[2]**www.google.com/patents/US6486679**

[3]Bill Kaune, W7IEQ, "A Modern Directional Power/SWR Meter," *QST*, Jan 2011, pp 39-43.

[4]**portal.uspto.gov/external/portal/pair/**

[5]For more details, see **en.wikipedia.org/wiki/Power_dividers_and_directional_couplers**

[6][The reference cited by the author was to a message board that is no longer active. — Ed]

[7]G Haupt., *Electronics Letters*, Volume 10, Issue 9: **http://digital-library.theiet.org/content/journals/10.1049/el_19740109**.

[8]**www.multek.se/engelska/engineering/pcb-structures-2/embedded-microstrip-impedance-calculator-2**

[9]**www.analog.com/static/imported-files/data_sheets/AD8307.pdf**

[10]Sam Green, WØPCE, "A Fully Automated DDS Sweep Generator Measurement System — Take 2," *QEX*, Sept 2012, pp. 14-24.

[11]**www.vwlowen.co.uk/arduino/bootloader/page2.htm**

[12]**github.com/WestfW/OptiLoader/blob/master/optiLoader.pde**

[13]**arduino.cc/forum/index.php/topic,54006.0.html**

[14]**donalmorrissey.blogspot.com/2010/04/putting-arduino-diecimila-to-sleep-part.html**

[15]**ok1dx.dyndns.org/constructions/swrmega/swrmega.html**

[16]www.slqs.net

[17]Lee Johnson, NØVI, will have information on his website when we develop this project into a product: **www.citrus-electronics.com**.

Convert Arduino Uno to Pseuduino

I first built this instrument around an Arduino. In order to operate efficiently from battery power for portable use, I built a copy with minimal current drain. I eliminated all functions other than the ATmega328P-PU and the external reference supply. Folks call such an Arduino copy a Pseuduino.

To simplify the process of making a Pseuduino, I attempted to turn an Arduino into a Pseuduino.

I started with the removal of the surface mount ATmega16U2-MU. This reduced the supply current by about 20 mA.

Then I removed the yellow LED next to the "L" and the green LED next to the "ON". This further reduced current drain by about 8 mA.

Finally, I removed the NCP1117ST50T3G 5.0 V LDO regulator next to the external power connector, which draws 3.4 mA, even with power supplied from the output side.

The LP2985-33DBVR 3.3 V LDO regulator drew less than 100 µA, so I reinstalled it. The Sparkfun hot air rework station made removal of these extra parts relatively simple.

Figure C shows these parts removed and sitting to the right of the circuit board.

Without the ATmega328P-PU CPU, the supply current for this Pseuduino implementation is now less than 550 µA. I replaced the ATmega328P-PU CPU after taking the photo.

To program the ATMega328P-PU Chip remotely in a Pseuduino as in the second Sidebar, simply connect the 5 pins on the unmodified Arduino with the ATMega328P-PU Chip removed to those same 5 pins on this Pseuduino which now hosts the remote CPU.

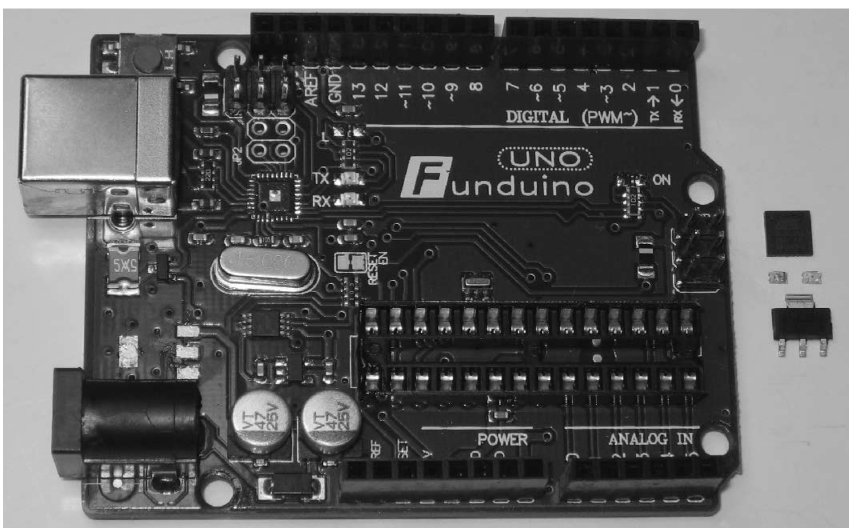

Figure C — Remove surface mount ATmega16U2-MU and two LEDs to reduce supply current.

Bob Simmons, WB6EYV

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A Polar Plotting Direction Finder

Bob describes an interface circuit and computer program that allow a receiver to be used for radio direction finding. The combination gives a graphical presentation of the scanned data as well as reducing the data to a graphical azimuth display.

This article describes a sophisticated polar-plotting direction finder that employs a PIC microcomputer. It requires an external receiver with an analog RSSI (received signal strength indicator) output signal and some kind of directional antenna. It is suitable for portable, mobile, or base direction finder units and offers four different operating modes. The device (called PicoPlot DF) is primarily intended to drive a local computer display, but a dual-range audio "squeal tone" output allows portable operation without a computer.[1]

A free *Windows* display program, *WinPlot*, is typically employed with it to generate a high quality polar-plot display of signal strength versus signal direction.[2] Some assumptions and tricks are employed to simplify the design and make it practical. As a result, a modest degree of co-operation is required from the user. When employed, a directional antenna is rotated through 360° while RSSI data is accumulated in the display program. A switch signals the start and end of the sweep. Upon sweep completion, the display program analyzes the data and generates the polar plot.

Neither the intensity or azimuth direction displays are calibrated. The 12 o'clock display heading corresponds to the antenna direction at the start and end of the 360° sweep, so bearings are relative to this direction. The RSSI data is automatically scaled in the display program so it fills the display. The maximum RSSI value plots at the outside edge of the azimuth scale, and the minimum RSSI value plots at the center of the screen. This ensures a useful polar plot display will be generated, even with antennas that have very low directivity, and regardless of how weak or strong the signal might be. The different operating modes give the direction finder a lot of flexibility. My goal was to create a general purpose direction finder that could be as sophisticated — or as simple as the user desires.

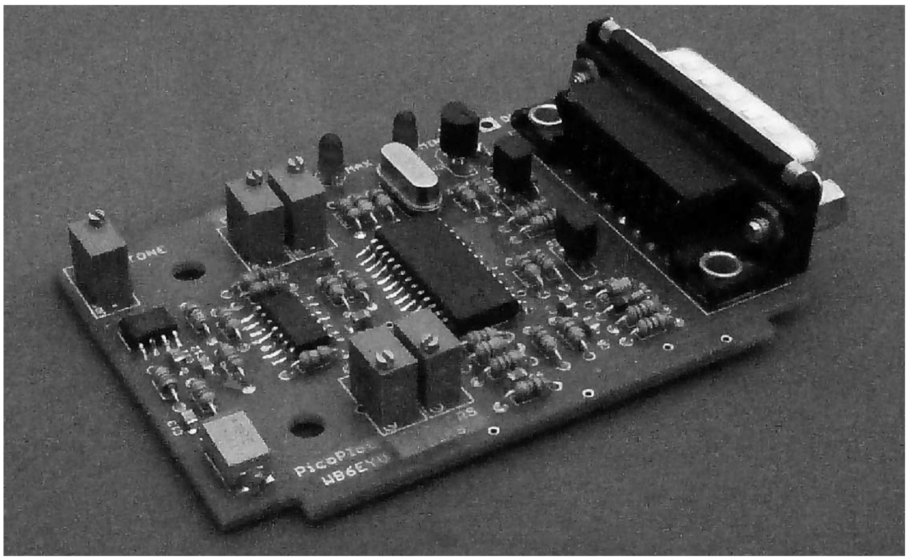


Figure 1 — This photo shows the PicoPlot DF circuit board.

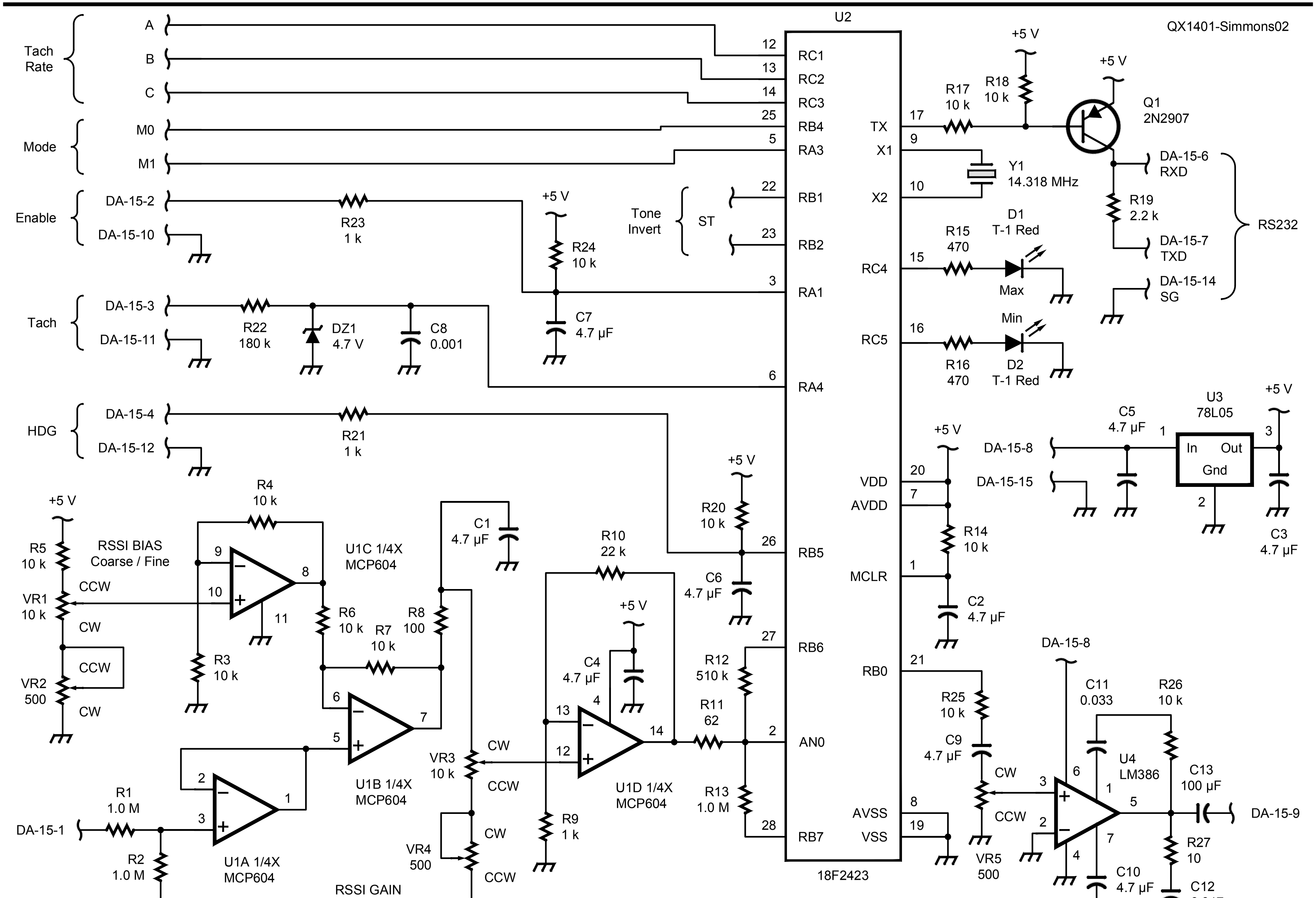
General Description

Most of the "magic" is actually in the display program which does the heavy math required to generate the display. The PicoPlot DF is basically just a DVM with an RS232 output plus some switch inputs to provide antenna information. Two binary "mode straps" select one of four operating modes; three for direction finder operation, plus a test pattern (simulation) mode for bench tests.

Operational amplifiers are used to adjust the RSSI signal from the receiver and translate it into a signal that ranges from 0-5 V dc for measurement by the micro computer. Trimpots are provided to compensate for any dc bias in the RSSI signal and to set the gain to get a 0-5 V RSSI signal at the PIC input. Two LED indicators (MAX and MIN) simplify the trimpot adjustment process, which needs to be performed just once for a particular type of receiver. Exact or careful calibration is *not* required since the display program will further adjust the reported data to automatically fill the display.

An audio "squeal tone" output (with LM386 speaker amp) is provided to allow portable operation without a display computer. The squeal tone employs a

[1]Notes appear on page 30.



Except as indicated, decimal values of capacitance are in microfarads (µF); others are in picofarads (pF); resistances are in ohms; k = 1,000, M = 1,000,000.

Figure 2 — Here is the schematic diagram of the PicoPlot DF circuit. [The 15 pin sub-D connector used for the wiring to the computer is correctly labeled as a DA-15 connector, although it is commonly referred to as a DB-15. The letter after the D describes the various connector body sizes. — Ed.]

lookup table in the PIC to provide a very smooth response curve that closely follows an ideal logarithmic curve of tone frequency versus RSSI voltage. The squeal tone spans 3 octaves from 200 Hz to 1600 Hz with two selectable sensitivity ranges of ×1 and ×5.

SteadyScan Mode of Operation

The SteadyScan mode is the simplest mode and is suitable for portable and base station direction finders where results from a single antenna scan are desired. In this mode, a directional antenna is rotated through a 360° turn while the PicoPlot DF reports RSSI readings to the display computer. An ENABLE switch (manually operated by the user) is closed at the start of the sweep, and remains closed throughout the sweep. Once the sweep is completed, (switch = opened) the display program analyzes the accumulated data to generate the polar plot display.

Two assumptions are made in the display program: (1) The antenna was rotated through exactly 360° while the ENABLE switch was closed, and (2) the antenna was rotated at a constant rate throughout the scan (hence the "SteadyScan" name).

Once the sweep is completed, the display program counts the number of messages received during the sweep and assigns each RS232 message to a bearing relative to one in 360º using a dithering method and based on the assumptions cited above. If multiple messages are assigned to a single bearing, they are averaged together.

The highest and lowest RSSI values in the scan are then identified and used to adjust the data to fill the display. The minimum RSSI value is subtracted from all RSSI readings in the scan, so the lowest reading yields a vector of zero length which plots at the screen center. The maximum RSSI reading is then used to calculate a scaling number which is applied to all the RSSI readings so that the highest RSSI reading generates a vector that will just reach the outside edge of the display.

TriggerScan Mode of Operation

The TriggerScan mode is similar to the SteadyScan mode, but intended primarily for a motor-driven direction finder antenna that performs multiple consecutive scans. Constant antenna scanning will require some kind of rotary RF coaxial connection (a "rotary joint") to prevent feed line coax from "spooling up." Suggestions about this are provided later.

Despite the obvious increase of complexity, this mode enables fully automatic direction finder operation that liberates the hunter for other tasks because the direction finder will constantly generate updates without any user supervision or co-operation. In this mode, the switch closure that signals the start and end of each 360° sweep is a momentary closure applied to the HEADING input. The momentary switch closure is generated whenever the direction finder antenna passes through the heading that corresponds to the 12 o'clock position of the display.

The display program is capable of accumulating data from a scan in progress while simultaneously displaying results from the previous completed scan. The display is updated with fresh data upon completion of each successive scan.

In this mode, the user operated ENABLE switch is only used to alternately enable or disable the RS232 reporting so that RS232 messages can be disabled whenever the antenna rotation is stopped. This prevents the data buffers in the display program from accidentally overflowing. Data from incomplete scans is ignored and discarded. Two successive HEADING pulses with RSSI messages between them are required to trigger each plot.

As with the SteadyScan mode, the TriggerScan mode assumes the antenna is rotated through 360° between successive HEADING switch closures and also assumes the antenna is rotated at a constant angular rate.

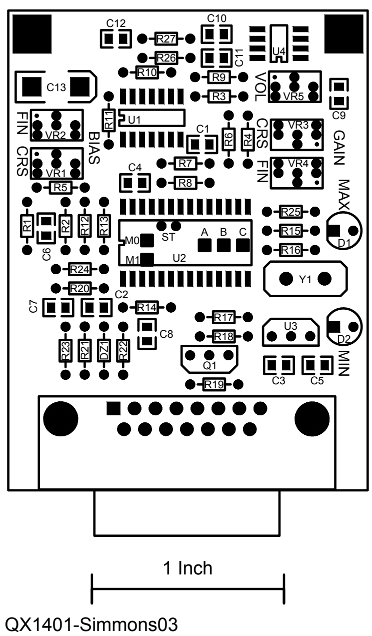


Figure 3 — This diagram is the parts placement guide for the PicoPlot DF circuit board. Note that the author's circuit board file includes two boards side-by-side, so you can obtain two boards from one circuit fabrication.

TachScan Mode of Operation

The TachScan mode is similar to the TriggerScan mode, but it allows the use of an antenna that does not rotate at a constant speed, such as a simple mast mounted antenna that is rotated by hand through a 360° sweep. To accomplish this, the user must provide some kind of rotation clock (like a tachometer or a shaft encoder) to generate a series of pulses that express the antenna rotation at each moment of time. The resulting pulses are fed to the TACH input of the PicoPlot DF, where they are counted and used to trigger an RS232 message when enough pulses have been detected.

Three straps are provided to allow user-selection of the number of tach pulses required to trigger an RS232 message. The available trigger rates range from 1 to 128 tach pulses per message, in binary progression (1, 2, 4, 8, and so on). The exact rate is not critical because the *WinPlot* display program performs additional number crunching work to uniformly allocate the messages across each 360° scan. As a guideline, the straps should be set to limit the number of RS232 messages to a maximum rate of about 40 messages per second. The TACH input is zener protected and actually capable of handling signals as great as 115 V ac from a motor.

Like the TriggerScan mode, constant antenna rotation requires the use of a rotary RF joint, but operation without a rotary joint is possible if the user is willing to stop and rewind the antenna from time to time to unspool the feed line cable.

The RSSI Signal

The PicoPlot DF is designed to accept ground-referenced RSSI analog signals of positive polarity. The default coefficient polarity of the RSSI signal is positive, which simply means stronger signals will generate more positive RSSI voltages. In contrast, some receivers might generate negative coefficient RSSI signals in which stronger signals actually drive the RSSI signal closer to ground. The *WinPlot* display program has an option button to reverse the RSSI coefficient polarity so that receivers with negative coefficients can be used with it. The audio squeal tone also assumes a positive coefficient, but two pins on the PIC micro can be shorted together to reverse this polarity as well.

Obtaining a suitable RSSI analog signal from a receiver is one of the trickier aspects of this design. Few receivers provide this signal, so the user generally must get a schematic diagram of the receiver and find the signal in order to tap in to the RSSI signal. The lack of a schematic diagram doesn't necessarily

Table 1
Strap Settings

Operating Mode	*M0 Strap*	*M1 Strap*
Test Pattern	Open	Open
SteadyScan	Ground	Open
TriggerScan	Open	Ground
TachScan	Ground	Ground

Squealtone RSSI Polarity

Positive RSSI	ST Pads = Open Circuit
Negative RSSI	ST Pads = Shorted Together

TachScan Clock Rate		*A Pad*	*B Pad*	*C Pad*
1	Pulse / Message	Open	Open	Open
2	Pulses / Message	Ground	Open	Open
4	Pulses / Message	Open	Ground	Open
8	Pulses / message	Ground	Ground	Open
16	Pulses / Message	Open	Open	Ground
32	Pulses / Message	Ground	Open	Ground
64	Pulses / Message	Open	Ground	Ground
128	Pulses / Message	Ground	Ground	Ground

spell the end of the story — an examination of the inside of a radio will generally help you find the IF amplifier/detector chip, and obtaining a datasheet for that chip can usually identify which pin, if any, provides a suitable RSSI signal. The RSSI input of the PicoPlot DF has an input impedance of 2 MΩ, (higher than a ×1 scope probe) so there should be no ill effects caused by tapping in to this signal.

RSSI signals in most modern receivers follow a logarithmic curve that spans about 60 dB of dynamic range, so the PicoPlot DF should be useful across a wide range of transmitter distances (down to perhaps 300 feet of range or less depending on the transmitter power level.) Additional technology like an offset attenuator or "body fading" will probably be required for operation at shorter distances due to receiver saturation.

Setting The Trimpots

Adjusting the trimpots on the PicoPlot DF board is a bit tricky because the pots interact with each other to some degree. Changing the GAIN pots will affect the OFFSET pot settings and vice versa. Some "diddling" therefore is required to set them. To set the trimpots, the direction finder receiver should be connected and some means provided to generate an RSSI signal that can be switched back and forth between a full-strength signal level that drives RSSI to its maximum value and a zero-strength level corresponding to a silent channel.

The pots are then adjusted so that the two extremes of the RSSI signal will just illuminate the MAX and MIN LEDs on the board. (Note: the ENABLE switch must be closed to enable LED operation.) The idea is to provide as much RSSI signal dynamic range as possible to the PIC chip so that the measurements can be performed with the greatest available accuracy. Too much gain will drive the op-amp against a rail, and RSSI clipping will result.

This clipping can occur for the minimum RSSI level as well as the maximum RSSI level, or both, so it is necessary to switch back and forth between the MAX and MIN RSSI levels while adjusting the pots. Fortunately, the display program performs its own auto-scaling of RSSI data to fill the display screen, so exact settings of the pots is not critical to proper display of the data.

COARSE and FINE trimpots for both GAIN and OFFSET are provided. These are 12-turn trimpots, with a coarse/fine ratio of 20:1. The MAX and MIN LEDs are set in the PIC code to turn on whenever the RSSI value measured by the ADC lies within 5% of the upper and lower limits respectively. The MIN LED corresponds to less than 0.25 V dc, and the MAX LED corresponds to more than 4.75 V dc at the PIC input. In TEST mode, both LEDs will illuminate while RS232 messages are being sent.

The Squeal Tone Output

When the SteadyScan mode is selected, the squeal tone has two available sensitivity settings or ranges (×1 and ×5) that are selected by a switch on the HEADING input. The HEADING input is not otherwise used in this mode. For the low sensitivity range, the three octaves of tone range correspond to the entire range of RSSI values from the direction finder receiver so that the absolute signal strength can be judged approximately by listening to the tone.

When the high sensitivity (×5) range is selected, the RSSI readings are multiplied by five in the PIC software before translation into a tone. In this mode, the actual tone output will sweep through the three octave range a total of five times as the RSSI reading sweeps through all possible values. For ascending RSSI values, the tone will "roll over" from its highest pitch value to its lowest pitch value whenever the upper limit of tone frequency is reached. Conversely, for descending RSSI values, the tone will "roll under" to the highest tone pitch whenever the lower limit of tone frequency is reached.

This magnified mode of tone operation allows very precise bearing measurements because easily detectable changes of tone pitch will be generated even for sub-decibel changes of RSSI values.

The Strap Settings

Several pads are provided on the backside of the PC board, beneath the PIC chip, to configure the PicoPlot DF for specific operating conditions. The two squeal tone polarity pads (circular pads labeled "ST") should be shorted together to select negative RSSI polarity or left open circuit for positive polarity. The remaining square pads expect either an open circuit or a ground connection. The strap settings are identified in Table 1

Circuit Description

The PicoPlot DF circuit employs a PIC 18F2423 microcomputer controlled by a 14.318 MHz crystal. A simple transistor inverter (Q1) provides the 9600 baud RS232 output to the display computer. Negative voltage for the RS232 link is robbed from the host computer's TXD line, via resistor R19. Squeal tone audio is generated by TMR1 in the PIC code, and drives pin 21 of the PIC. The audio level is set by trimpot VR5, and amplified by an LM386 speaker amplifier, U4. The operating mode of the direction finder is binary selected with two wire straps on pins 5 and 25 (M1 and M0) of the PIC micro.

The ENABLE and HEADING inputs are used to provide information about antenna status. Both are biased high with pull-up resistors and expect switch closures to ground. The ENABLE input is employed in all three direction finder modes as well as the self-test mode. The HEADING input selects the ×1 or ×5 squeal tone range when the SteadyScan mode is selected. In the TriggerScan and TachScan modes, this input expects a momentary switch closure to ground when the direction finder antenna sweeps past the 12 o'clock position on the *WinPlot* display. This input has an RC filter with a time constant of about 5 ms, so the driving pulse should have a duration of at least 10 ms.

Two pins on the micro (TONE INVERT

on the schematic) can be shorted together to invert the "sense" of the squeal tone pitch. Normally, (pins = not shorted) the pitch of the squeal tone ascends with ascending RSSI voltage, but shorting these two pins together will cause the pitch polarity to be reversed so that a descending RSSI voltage will generate an ascending tone pitch.

The RSSI signal is scaled and biased in the op-amps and also passes through an RC LPF (R8 / C1) with a cut frequency of about 340 Hz. After this, it is measured on pin 2 of the PIC micro with 12 bits of precision across a range of 0 to 5 V dc. Resistors R11, R12 and R13 provide an additional two bits of measurement precision, (14 bits total) using a dithering routine in the software. The ratio of R11 to R12 equals 1 to 8200, or about ½ of the value of the least significant bit of the 12 bit ADC. Similarly, the ratio of R11 to R13 equals 1 to 16,400, or ¼ of the ADC's LSB value.

The dithering method is rather clever and works like this: Each measurement of the RSSI value actually consists of 4 consecutive ADC measurements, added together, to yield a 14 bit value. For each of the successive 4 ADC measurements, the outputs on pins 27 and 28 of the PIC micro are switched from low to high in a binary sequence so that the value measured by the ADC increases slightly (by ¼ LSB) with each succeeding measurement. Basically, these three resistors together constitute a two bit digital to analog converter (DAC) with a range equal to one LSB of the ADC. The DAC output is then summed with the RSSI signal, to gain an extra two bits of measurement precision. (14 bits total = four 12-bit measurements added together.)

In the software, the least significant bit is *not* transmitted in the RS232 message; it is examined and used only to round off the

Table 2
PicoPlot DF Parts List

Quantity	*Designation*	*Part*	*Part Number*	*Unit Price*	*Total Price*
1	n/a	DA-15M Conn	A32073	5.30	5.30
1	n/a	D-conn hdwr	7233K-ND	0.87	0.87
1	n/a	Mating DA-15F plug	215FE-ND	2.21	2.21
1	n/a	Scr, capt 4-40 w/clip	2061K-ND	0.68	0.68
1	n/a	Circuit board		10.00	10.00
1	U1	chip, opamp	MCP604-I/SL-ND	1.25	1.25
1	U2	chip, micro SOIC	PIC18F2423-I/SO-ND	5.52	5.52
1	U3	chip, vreg TO92	296-1365-1-ND	0.54	0.54
1	U4	chip, spkr amp	LM386M-1-ND	0.91	0.91
1	Q1	xstr, 2N2907 TO92	PN2907-ND	0.22	0.22
2	D1, D2	diode, LED	67-1064-ND	0.46	0.92
1	DZ1	diode, Zener 4.7 V	1N5230BDICT-ND	0.30	0.30
1	Y1	xtal, 14.318 MHz	X1081-ND	0.81	0.81
1	R27	10 Ω 1/8W	10EBK-ND	0.46/5	0.10
1	R8	100 Ω 1/8W	100EBK-ND	0.46/5	0.10
1	R11	62 Ω 1/8W	62EBK-ND	0.46/5	0.10
2	R15, R16	470 Ω 1/8W	470EBK-ND	0.46/5	0.20
3	R9, R21. R23	1.0 kΩ 1/8W	1.0KEBK-ND	0.46/5	0.30
1	R19	2.2 kΩ 1/8W	2.2KEBK-ND	0.46/5	0.10
12	R3, R4	10 kΩ 1/8W	10KEBK-ND	0.77/10	0.93
	R5, R6. R7, R14, R17, R18, R20, R24, R25, R26				
1	R10	22 kΩ 1/8W	22KEBK-ND	0.46/5	0.10
1	R22	180 kΩ 1/8W	180KEBK-ND	0.46/5	0.10
1	R12	510 kΩ 1/8W	510KEBK-ND	0.46/5	0.10
3	R1, R2, R13	1.0 MΩ 1/8W	1.0MEBK-ND	0.46/5	0.30
2	VR1, VR3	trimpot 10 kΩ 12T	490-2970-ND	2.36	4.72
3	VR2, VR4, VR5	trimpot 500 Ω 12T	490-2982-ND	2.36	7.08
1	C8	0.001 μF 0805 SMT	399-1147-1-ND	0.05	0.05
1	C11	0.033 μF 0805 SMT	399-1165-1-ND	0.10	0.10
1	C12	0.047 μF 0805 SMT	399-1166-1-ND	0.08	0.08
9	C1, C2	4.7 μF 0805 SMT	399-5505-1-ND	0.29	2.61
	C3, C4, C5, C6, C7, C9, C10				
1	C13	100 μF	478-1723-1-ND	1.30	1.30
TOTAL					**47.90**

Part numbers are all from DigiKey except the circuit board, which is from ExpressPCB.

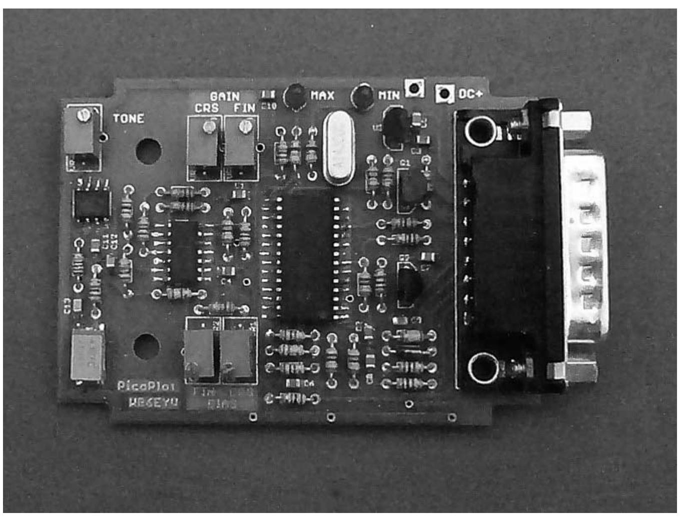


Figure 4 — Here is a top view photo of the completed PicoPlot DF board, showing component placement.

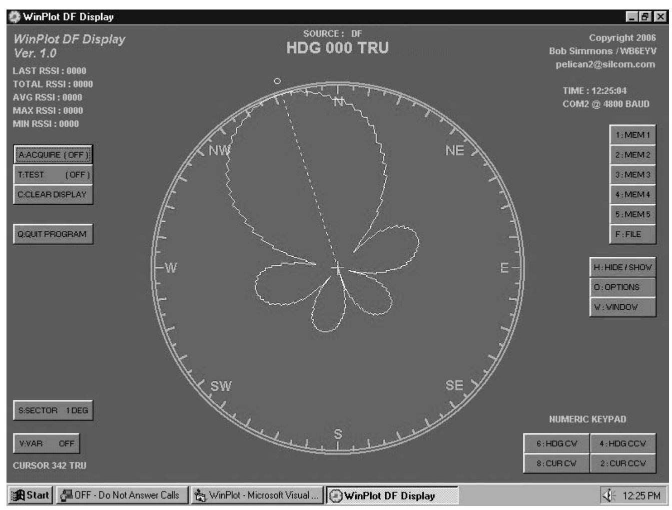


Figure 5 — This screen shot shows the layout and operation of the *WinPlot* program running on a PC. The plot in the center shows the results of running the test plot.

remaining 13 bits. The remaining 13 bits are translated into ASCII digits, yielding a value ranging from 0000 to 8191, sent in each RS232 message. Switch closures for the ENABLE and HEADING inputs are sent to the display computer as separate messages using numbers greater than 8191 to differentiate them from RSSI numbers.

Software Description: The PIC code

The PIC software is written in PIC assembly code for an 18F2423 chip running a 14.318 MHz crystal clock. The software contains about 2500 lines of source code which assembles into about 1400 bytes of machine code. A good fraction of the code is actually lookup table data for the squeal tone and the self-test pattern rather than executable instructions.

The AN0 channel of the ADC is used for RSSI measurements. Various parallel port pins on all three ports (A, B and C) are employed for a variety of digital inputs and outputs, and the HEADING input on pin 5 of PORTB is interrupt driven. Interrupts are also used for TMR0 overflow (TACH input) and TMR1(squeal tone generator.)

The three straps for the TACH RATE and the single strap for squeal tone polarity are only examined when dc power is applied. Other inputs (HEADING, ENABLE, TACH and MODE SELECT) are examined in real time as the program runs. The built-in test pattern data generates an ideal SIN(x)/(x) pattern with one major lobe and four side lobes, with the main lobe pointing to a bearing of 245°.

The *WinPlot* Display Program

The *WinPlot* display program is written in *VisualBasic 6* for use with the PicoPlot DF. In addition to the main function of gathering, analyzing and plotting the RSSI data, several additional features and options enhance the power and utility value of the program.

Numeric readouts in the top left corner indicate how many RSSI messages were used to generate the present display, which is a measure of the angular resolution, as well as the maximum, minimum and average value of all RSSI readings in the sweep. Five temporary memory slots are available on the right side, to hold and recall plots that were previously generated. Plots can also be permanently saved to a file and recalled from the file later if desired. This can be useful if the data will be analyzed later by some kind of external program.

A SECTOR feature is provided to average several adjacent bearings of data before plotting, which has the effect of smoothing out the envelope of the polar plot and reducing any jagged edges in the display. This can be useful if the antenna is rotated too quickly to allow at least one RSSI message for each one degree sector of the display which requires 9 seconds. It can also be useful for mitigating the effects of signals with rapidly fluctuating signal strength during a scan.

A normally hidden OPTIONS screen allows selection of parameters which rarely change including the RS232 COM port, the color scheme for the display, the polarity of the RSSI coefficient, and the direction of antenna rotation. Reversing the RSSI coefficient will turn all peaks into nulls and vice versa, so this feature can also be used by hunters who want to take bearings on antenna nulls rather than antenna peaks.

An adjustable bearing cursor (dotted line on the display) is also provided to get numeric values of the relative bearing to any feature of the polar plot envelope. This bearing cursor is automatically set to point to the most probable relative bearing whenever a new plot is generated. The most probable bearing calculation is *not* based on the bearing to the highest signal peak. Instead, it is based on a rho-theta (calculus) integration of the total area enclosed by the plot envelope, so that all of the plot data is used to calculate its value.

Essentially, the calculation finds the center of mass (the "centroid") for the enclosed polar plot area and then identifies the relative bearing from that centroid to the center of the screen. This method has proven to be very effective at identifying a signal direction, especially in multipath situations where a clean polar plot cannot be obtained. It isn't foolproof, but it does help a good deal with lousy plots. This seems especially true for situations where a clear signal path is present, but the plot is degraded by strong reflections from objects near the direction finder.

No controls are provided in the *WinPlot* program to select the direction finder mode — none are required. The MODE straps on the PicoPlot DF board affect the local operation of the board, but no operational changes for the different modes are required in the display program. *WinPlot* works exactly the same for SteadyScan, TriggerScan and TachScan modes. No provisions are made for scans of less than 360°. There are no "sector scans" allowed, and the antenna rotation direction (CW or CCW) must not change during a scan — no backing up is allowed, or a misleading (false) display will result.

The display program has its own test pattern generator (separate from the one in the PicoPlot DF), which allows the display program to be used alone for evaluation and learning purposes. It generates an ideal SIN(x)/x pattern with one major lobe and four side lobes, with the major lobe pointing to a relative bearing of 330°.

Speculations

The data buffer in the *WinPlot* display program is quite large and is capable of accumulating RSSI messages (at a rate of 40 messages per second) for 15 minutes before overflowing. This means the PicoPlot DF and *WinPlot* combination can also be used with very slow tower rotators at base stations, but it also means that a rigid mounted direction finder antenna affixed to a mobile platform can be used if the mobile platform is rotated through a 360° turn in a reasonable amount of time. For example, an aircraft in flight with a rigid mounted COM antenna can be used to perform direction finder measurements if the aircraft executes a 3 minute coordinated turn.

There is no minimum rotation time for a scan, but the angular resolution of the display will suffer as the rotation time decreases. If it is found when the scan is completed and the data analysis begins that the data set contains less than 360 messages, (one per degree of display) the data is smeared so that the available messages fill a 360 element direction finder bearing array. For example, if a sweep lasts only three seconds (120 messages) then each message will be allocated to three successive direction finder bearings in the display. This leads to a somewhat jagged image in the polar plot envelope, but use of the SECTOR feature can deal with this cosmetic problem.

Although intended primarily for direction finder operations, the PicoPlot DF and *WinPlot* combination has also found favor among a few folks that do antenna work, since it obviously allows experimental changes of antenna geometry to be evaluated almost instantly for performance improvements such as side lobe suppression, F/B ratios, and other parameters.

The PicoPlot DF and *WinPlot* combination can also be used with many workbench spectrum analyzers employed as the direction finder receiver since these analyzers generally provide a dc-coupled video output at a rear panel BNC. Setting the center frequency of the analyzer to a specific frequency and setting the dispersion (frequency span) to zero yields a single channel receiver, and the video output becomes an RSSI signal.

Advanced direction finders

Constant antenna rotation by means of a motor drive is an appealing idea but requires considerable physical complexity and the use of a rotary RF joint. Commercial rotary joints are expensive, but an effective amateur joint can actually be contrived pretty easily by modifying an ordinary coaxial RF connector such as a BNC or type N. Removing the locking mechanism on a BNC by cutting or grinding off the locking mechanism which normally immobilizes the connector yields a high quality RF connection that is capable of constant rotation.

If this is done, some additional tricks will greatly improve the reliability of the joint; packing the interior of the connector with silicone grease will provide lubrication, and also will immobilize any metallic flakes that will wear off the mating surfaces during normal operation. They might otherwise short out the joint. One of the two mating connectors can be rigidly mounted, but if possible, the other should be allowed to free float so that it will self-align with the centerline of the hard-mounted connector to reduce wear caused by centerline misalignment. To maintain constant mating pressure on the surfaces, some sort of spring loading mechanism should be contrived like a light tension spring pressing against a surface on one end that can be slipped over the outer jacket of the coax for the free-floating connector.

Contriving a mechanical drive to rotate the antenna is more complex, and it is complicated by the fact that the centerline of the rotation axis must be "hollow" to allow installation of the rotary RF joint. Even so, the problem is intriguing, and this is where the ingenuity of the reader, if so inclined, really comes into play. Gear drives, worm drives and even belt or capstan drives all spring to mind, using anything from a stepper motor to a cheap variable speed hand drill. Electric towing winches (used on vehicles) might be another prospect; they are inexpensive, abundant, and usually weatherproof.

The Inspiration

I originally created a similar direction finder device decades ago while employed at a marine electronics shop in the Los Angeles harbor, where I found an abandoned radar pedestal in the company junk pile. It was obtained when the radar on a ship was replaced with a newer model, and it was kept on the premises as a source of spare parts for other ships. It proved to be ideal for the task, having a hollow circular waveguide rotary joint and a fully weatherproof enclosure with a heavy duty motor drive already installed. I created a cylindrical brass plug for the waveguide rotary joint on a lathe and provided a centerline hole for the new coax rotary feed. A 6 foot mast was created and bolted to the flange that originally secured the radar dish, and that was it. A type N connector modified as described earlier provided the rotary RF joint.

The display was actually a spectrum analyzer with a storage display that was adjusted to observe a single RF channel as described earlier. Furthermore, the analyzer had an external trigger input for the display sweep, (many bench top analyzers have this feature also) and this was driven by a magnetic switch in the pedestal that sensed when the antenna swept past the 12 o'clock position. The display sweep time was then adjusted with the timebase vernier knob so that one antenna sweep corresponded to one display sweep. As a result, each horizontal division on the display represented 36° of bearing angle, and the vertical scale was already calibrated in dBm.

A four element 2m Yagi was affixed to the mast and tested with excellent results. The main lobe and side lobes painted beautifully, and the bearing of the main lobe could be easily identified visually to perhaps a resolution of 6°. The rotary joint proved to be very solid with no dropouts or noise.

My goal was to investigate the feasibility of creating such direction finders for deployment and use by the Coast Guard for triangulation of VHF distress messages. This was years before GPS, and nautical distress callers (usually recreational boaters) rarely knew their position with any reasonable accuracy. Although the concept worked beautifully, the lack of any ready source for abandoned radar pedestals or anything similar as a substitute was the end of it. The potential was clearly demonstrated, however, and now, many years later, it is partially re-created in this design.

Additional Technologies

Someone will, no doubt, wonder why an electronic compass was not fitted to this design, but the present design is already pretty complex. Compasses also are not as foolproof as most people believe they are — they are vulnerable to field distortions caused by magnetic hardware such as screws, bolts, nuts and so on, which can be compensated to some degree, but not completely.

All compasses exhibit sensitivity to the plane of operation for the compass itself; any tilt of the compass out of the horizontal plane in pitch or roll can induce significant measurement errors. This is the main reason why real compasses are routinely fitted into a fluid-filled sphere — to keep them level by floating them on the surface of the fluid. This would not be a significant problem for mast mounted antennas, but portable antennas are another matter.

Even so, significant additional technologies have been developed for this direction finder (contact the author for details.) The basic direction finder system described here is still a very impressive device in its own right. For those with a keen interest in direction finder technology who have longed for the kind of features offered in this design, I recommend it highly. It really is a very slick little critter, very flexible and adaptable, and it performs very well.

Bob Simmons, WB6EYV, was first licensed as a Novice in 1964 at age 13 and remained licensed (more or less) constantly ever since. He also earned a commercial FCC license in 1967. Bob served Naval Reserve duty as a radar technician with about 6 months of total sea time. He spent several years doing civilian work in nautical and marine electronics in Los Angeles harbor, as well as doing some land mobile radio work. This was followed by five years in flight line avionics, working with business jets. He moved to Santa Barbara, California in 1992 and worked on vacuum deposition systems for five years and held assorted engineering jobs at other times. Presently, Bob is self employed and runs a website, making and selling radio direction finding equipment and modules, with the majority of his latest work spent creating embedded software/hardware and developing technologies to enable Internet-linked remote DF stations. His primary interest is developing and applying new technologies to old problems and pushing the DF art forward.

Notes

[1]The ExpressPCB circuit board files and the program code files for this article are available for download from the ARRL *QEX* files website. Go to **www.arrl.org/qexfiles** and look for the file **1x14_Simmons.zip**.

[2]You can download the *WinPlot* program at: **www.silcom.com/~pelican2/PicoDopp/WPLT_INSTALL.html**.

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More Octave for SWR

In this installment of our Octave *lessons, we learn about line loss due to SWR.*

Many of us are constrained by the layouts of our homes and yards with respect to the locations of our antennas. This means that, although we may have a lot of latitude when we choose a type of high frequency transmission line, we may not have much control over the length of the transmission line that connects the antenna to the shack. We may know, therefore, with reasonable certainty, the loss of the line at each frequency of interest as soon as we get around to thinking about what bands we want to cover and what bandwidth we need to cover within each band.

In "Octave for SWR" we discussed methods for relating SWR to the total loss of the transmission line.[1] We verified a graphical method that has appeared in ARRL publications for decades, the "Additional Loss" graph, for calculating additional loss due to SWR.[2, 3] We discussed various measures of loss and decided that the line loss used by ARRL is the most practical for most radio work involving a transmitter connected to an antenna by a transmission line. Figure 1 reproduces that graph for ready reference.

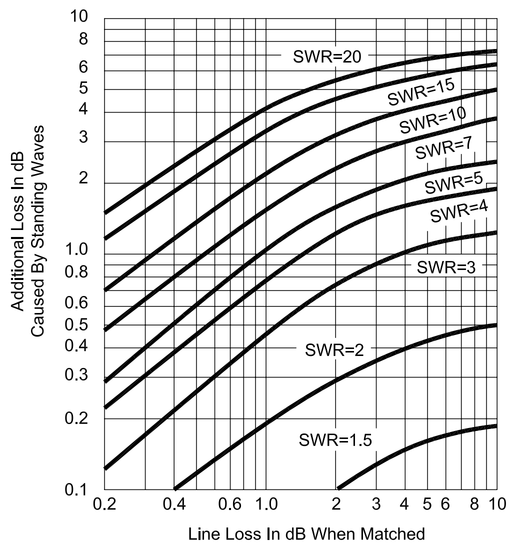

Figure 1 — Additional line loss due to standing waves (SWR, measured at the load).

We can use the "Additional Loss" graph to think about the effects that our particular length of transmission line will have on our antenna choices. If, for example, we build an antenna for 1.8 MHz and the SWR unacceptably increases line loss for frequencies above 1.9 MHz, we may want to choose an antenna type with a broader bandwidth or, alternatively, choose a lower loss transmission line so that we can tolerate the higher SWR. The "Additional Loss" graph can help us as we ponder such decisions.

That graph, though, is a little "busy" if all we want to do is to look at various SWR and total loss values for one particular matched-line loss. Note that each such loss corresponds to values along a vertical line on the "Additional Loss" graph. The graph is made more versatile by displaying only the additional loss, rather than the total loss yielded by Equation 16 on page 23-11of *The ARRL Antenna Book*.[3]

$$\text{Total Loss } (\text{dB}) = 10\log\left(\frac{a^2 - |\rho|^2}{a\left(1-|\rho|^2\right)}\right)$$

[Eq 1]

where:

$a = 10^{0.1\,ML}$

ML = matched-line loss for a particular length of line, in dB.

$|\rho|$ = the magnitude of the reflection coefficient at the load.

This versatility, though, makes it less obvious what's happening to a particular length of transmission line at a constant frequency as we change the SWR at the junction between the line and the antenna.

One of the nice things about *GNU Octave* is that it's quite flexible and the code can be quickly modified to change or extend a particular application.[4] In this case, we might want to produce a graph that displays the values of total line loss with respect to SWR for only one matched-line loss, so that we can quickly determine the total loss of our transmission line for various antenna impedances, and resultant SWRs, as we think about our antenna.

The *Octave* code to take care of this is given in Table 1. The Octave code from this table is available for download from the

[1]Notes appear on page 33.

ARRL *QEX* files website. Go to **www.arrl.org/qexfiles** and look for the file **11x13_Wright.zip**.[5] The code is derived from that in "Octave for SWR," but we've eliminated quite a bit of code that is extraneous to our intent here and we've added a *linspace* command to cause the calculations to be performed over a range of SWR values from 1:1 to 20:1. Since we are going to be performing element-by-element calculations on entries in vectors, we'll add periods preceding each arithmetic operator to tell *Octave* that we're not doing matrix arithmetic here.[6] This was unnecessary in the code used in "Octave for SWR" as the variables there were scalar and there could be no confusion about matrices. In the calculations, we're taking advantage of the fact that the SWR is equal to the ratio of impedances at a discontinuity when both impedances are real (resistive).

We could start directly from reflection coefficients and avoid the translation from the vector of SWR values, but starting with SWRs seems more intuitive and will allow us to easily expand or abbreviate the range of SWR values by changing the upper range limit in the *linspace* command.

The code in Table 1 writes the output to a datafile rather than directly to a plot. Note that in the Table, the datafile is specified to be written to a directory called "/home/mwright/". You may want to change the name of that directory to something more meaningful for you.

The developers of *GNU Octave* are working on providing FLTK/OpenGL capability in *Octave* and are deprecating some of *Octave's* dependencies on *gnuplot*.[7, 8] [FLTK stands for "Fast Light Toolkit." OpenGL is a low level Graphics Library specification. — *Ed.*] In order to make sure this code is usable with various revisions of *Octave*, we'll use *Octave* and *gnuplot* independently with a datafile linking the two. Once we've used our *Octave* code to produce the datafile, we'll use the following commands interactively within *gnuplot* to plot the data in Figures 1 and 2:

```
set title " *** TOTAL LOSS DUE TO SWR FOR 2.0 dB matched-line LOSS ***"
set xlabel "SWR"
set ylabel "TOTAL LOSS"
set grid
plot "/home/mwright/swr_1.txt" w lines
```

If you change the name of that directory in the code of Table 1, you will have to change the last line of the code above to use that same directory name.

Table 1
Octave Code to Calculate and Plot Feed Line Loss

```
# Calculate ARRL Antenna Book Total Loss (Eq. 16)
adB = 0.3;  #  LINE LOSS IN dB
SWR = linspace(1., 20., 300);
refl_coef = (SWR - 1) ./ (SWR + 1);
mllr = 10 ^ (adB ./ 10);
Total_loss = 10 .* log10((mllr .^ 2 .- abs(refl_coef) .^ 2) ./ ...
(mllr .* (1 .- abs(refl_coef) .^ 2)));
# Commands for plotting using gnuplot or FLTK/OpenGL
#plot(SWR, Total_loss);
#title(sprintf("*** TOTAL LOSS DUE TO SWR FOR %g dB MATCHED LINE LOSS ***", adB));
#xlabel "SWR"
#ylabel "TOTAL LOSS"
#grid("on");
#pause;
# Write output to a datafile for external plotting
fp = fopen("/home/mwright/swr_1.txt", "w", "native");
for n = 1:300
  fprintf(fp, "%g, %g\n", SWR(n), Total_loss(n));
endfor
fclose(fp);
```

Figure 2 — Total loss as function of SWR for matched line loss = 2.0 dB.

Figure 3 — Total loss as function of SWR for matched line loss = 0.3 dB

This may seem less convenient than embedding the plotting code within the *Octave* script, but it actually makes the code more versatile, as we can select the tool we'd like to use for the calculations and the plotting program independently.[9] We might, for instance, import the datafile into *MS Excel* or *OpenOffice Calc* and plot from within either of those programs rather than use *gnuplot* or *FLTK/OpenGL*.[10, 11]

If you'd like to plot directly, though, using *gnuplot* or *FLTK/OpenGL* from within *Octave* as we've done previously, uncomment (remove the "#" from the beginning of each line in Table 1) the plotting commands for internal plotting and execute the code. You can switch between the two plotting systems by executing the command graphics_toolkit("gnuplot"); or graphics_toolkit("fltk").

If your *Octave* installation doesn't recognize the *graphics_toolkit* command, you can use only *gnuplot* from within *Octave*.

The function *title()* requires a string input, so we've generated one that includes the proper loss using *sprintf()*. We could return a string variable from *sprintf()* and use it as the argument to *title()*, but embedding *sprintf()* as the argument to *title()* accomplishes the same purpose with one less line.

Note that the "Additional Loss" graph in the ARRL publications contains a lot of useful information over wide ranges of loss and SWR values. Our plots may expedite the selection or evaluation of a particular transmission line but to duplicate all the information in ARRL's graph would require a book full of such plots. The best way, therefore, to take advantage of this different way of presenting the information is to keep the code handy so that we can produce a plot for any particular matched-line loss when needed.

Figure 2 shows an example plot for matched-line loss = 2.0 dB. This is typical of RG-58 for 100 to 200 feet of length on the higher frequency HF bands. We can see that it will require an SWR of greater than 20:1 to increase the matched loss by one S-unit (6 dB). Of course, our transmitter may not be very happy long before we reach such an extreme SWR, and such an SWR is likely to be indicative of severe transmission line or antenna problems. Comparing Figure 2 with the "Additional Loss" graph of *The ARRL Antenna Book* shows good agreement between the two.

Figure 3 shows a plot for matched-line loss = 0.3 dB. This is typical of open wire transmission lines. One advantage of this graph is that we can see that an open wire line with low attenuation doesn't make us immune to the effects of high SWR, although it helps a lot. At SWR = 20:1, we can see that the total loss is around 2.3 dB, considerably higher than the matched loss of the open wire line.

Note that both curves we've drawn might be approximated by a linear expression without very much loss of accuracy if we're not looking for laboratory precision. If we were still using slide rules to plot such curves, we'd probably develop such an approximation to begin with, but with software tools and only a few lines of code in the original expression, there's little or no advantage to using such an approximation.

We can use the techniques presented here to draw simplified graphs of other families of curves for which we have the defining equations.

Maynard Wright, W6PAP, was first licensed in 1957 as WN6PAP. An Amateur Extra Class licensee, he holds an FCC General Radiotelephone Operator's License with Ship Radar Endorsement, is a Registered Professional Electrical Engineer in California. Maynard is an ARRL Member and is a Life Senior Member of IEEE. He has been involved in the telecommunications industry for over 48 years. He has served as technical editor of several telecommunications standards and holds several patents. He is a Past Chairman of the Sacramento Section of IEEE. Maynard is Secretary/Treasurer and Past President of the North Hills Radio Club in Sacramento, California.

Notes

[1]Maynard Wright, W6PAP, "Octave for SWR," *QEX*, Jan/Feb, 2009, pp 37-40.

[2]H. Ward Silver, NØAX, Ed. *The ARRL Handbook for Radio Communications,* 2014 Edition, ARRL, 2013, Figure 20.4, page 20.5, ISBN: 978-1-06259-001-7; ARRL Publication Order No. 0007, $49.95. ARRL publications are available from your local ARRL dealer or from the ARRL Bookstore. Telephone toll free in the US: 888-277-5289, or call 860-594-0355, fax 860-594-0303; **www.arrl.org/shop**; **pubsales@arrl.org**.

[3]H. Ward Silver, NØAX, Ed., *The ARRL Antenna Book,* 22nd Edition, ARRL, 2011, Figure 23.14(A), page 23-12. ISBN: 978-0-87259-694-8; ARRL Publication Order No. 6948, $49.95.

[4]John W. Eaton, *GNU Octave Manual,* Network Theory Limited, 1997 (see **www.octave.org**).

[5]The Octave code from Table 1 is available for download from the ARRL *QEX* files website. Go to **www.arrl.org/qexfiles** and look for the file **11x13_Wright.zip**.

[6]These are single-row matrices, technically termed vectors, but we still often use the phrase "matrix arithmetic" when discussing operations on such vectors.

[7]Learn more about the Fast Light Toolkit at: **www.fltk.org**.

[8]There is more information about gnuplot at: **www.gnuplot.info/**.

[9]Maynard Wright, W6PAP, "Alternatives to Octave," *QEX,* Jul/Aug, 2009, pp 25-27.

[10]Learn more about Microsoft Excel at: **office.microsoft.com/en-us/excel/**.

[11]To learn about Open Office or to dowonload the installation file, go to: **www.openoffice.org**.

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Actual Measured Performance of Short, Loaded Antennas — Part 1

With the help of many friends over many years, the author studied HF monopoles used as verticals, mobile antennas and in pairs as elements of beams and dipoles.

This report contains the real-world measurements for many short, loaded antennas: sizes, shape factors, loading methods, coil and capacity hat placement, coil *Q*, matching, mounting techniques, and more. It documents a long term effort to quantify and compare the effectiveness of shortened, "loaded" antenna elements by making empirical measurements rather than modeling or theoretical calculations. It also compares "conventional wisdom" to these measurements, and identifies differences in published literature on the subject.

Conventional wisdom can be a valuable tool. It may be based on experience, or derived from the works and writings of many researchers. It may also be shaped by myths, the claims of merchants, or misapplications of accepted theory. Usually it isn't quantified. Sometimes it's buried in fathomless calculations. Sometimes it's preached more like a sermon. A misapplication of accepted theory, unconfirmed by actual measurement, often finds its way into popular literature. If left unverified, that misapplication can take on a life of its own, to be repeated in articles, books, on-line articles, and in manuals or even become a part of today's computer modeling programs. That results in design and evaluation errors.

The case at hand is that of shortened, loaded elements often used as vertical monopoles fed against some sort of ground plane, like typical 1.8 to 30 MHz mobile antennas, backyard verticals for the lower frequency Amateur bands, and other medium and low frequency antennas. Such elements are used in pairs in balanced antennas like dipoles and beams. A "shortened element" usually means less than a resonant length, most typically less than a quarter wavelength. "Loaded" means that either an inductance, such as a coil, or a capacitance, perhaps a "capacity hat," or both has been added to the element to achieve resonance on a desired frequency when fed against a conductive plane, a counterpoise, or perhaps a second identical element.

Figure 1 — Typical mobile antenna with multiple resonators .

Conventional wisdom has a lot to say about this subject, like "Bigger is better," "High-Q coils are good," "Low-Q coils are lossy," "One or another position of the coil is best," "Helically wound is best," "Capacity hats are good, but only in certain locations," "Don't use loading coils, only top hat wires," and on and on. If all that is really true, how much better or worse is one or the other, and what are the trade-offs?

There are questions about the effects of multiple resonators on one mast. "That can't work as well, can it?" "What about using mag-mounts for mobile antennas? That won't make any difference, will it?" "Should we match at the feed point or at the transmitter or match at all?" "Why adjust the antenna element to frequency when the auto-tuner at the radio makes the standing wave ratio (SWR) one-to-one?" "Should the mobile antenna be mounted on the bumper or the roof?" "Why do I need radials on my vertical? Even some commercial antenna manuals say ground rods will do the job." And there are a lot more questions.

Figure 1 shows a typical mobile antenna, using multiple resonators. Figure 2 is a short, top loaded vertical for 160 meters, set up on Mellish Reef by Bob Walsh, WA8MOA.

This report is not going to bombard you with formulas and mathematics. That's not my forte. I am a serious student of antennas, plus the theory, formulas, and math involved, but I am not an expert. The important tasks of explaining this subject mathematically or relating it to referenced literature will be left to others more qualified in those fields. What I will do in this report is tell you about my work in one segment of the subject — measurements! I'll tell you what I've done, how I did it, the results I have recorded, and the conclusions I have drawn from those

[1]Notes appear on page 42.

results. Use the data however you choose. If you question any of our methods, I hope that you will set up a measurements program and document your results. I would be interested in reading your report, and I'm sure many others would, too.

One other thing: Let's not overreact. Allow me to explain. I have been an Amateur Radio operator since I was in eighth grade. As a Novice licensee in 1954, while I waited for my General class ticket to arrive, I was "testing" my microphone and modulator on a home brewed pair of 6L6's (tubes!) running 25 W on 160 meters. I was in my basement shop. My dummy load was a light bulb in a socket connected to the transmitter with 4 feet of lamp cord.

At the local club meeting a few days later some of the adults pulled me aside and told me that it would be better if I turned myself in rather than have the FCC come to get me. I had been heard all over town. That's when I realized that when it comes to antennas, everything works!

My point is this: It might be easy to read more into the information in this report than need be. It would be a mistake to interpret my results and conclusions as saying that a particular antenna or technique won't work — or that a particular design is the only one that will work. The numbers involved are degrees of better or worse. As I said, "Everything works!" But, compromises and trade-offs made in the name of achieving your goals can be better made using this kind of information. Okay, let's get started!

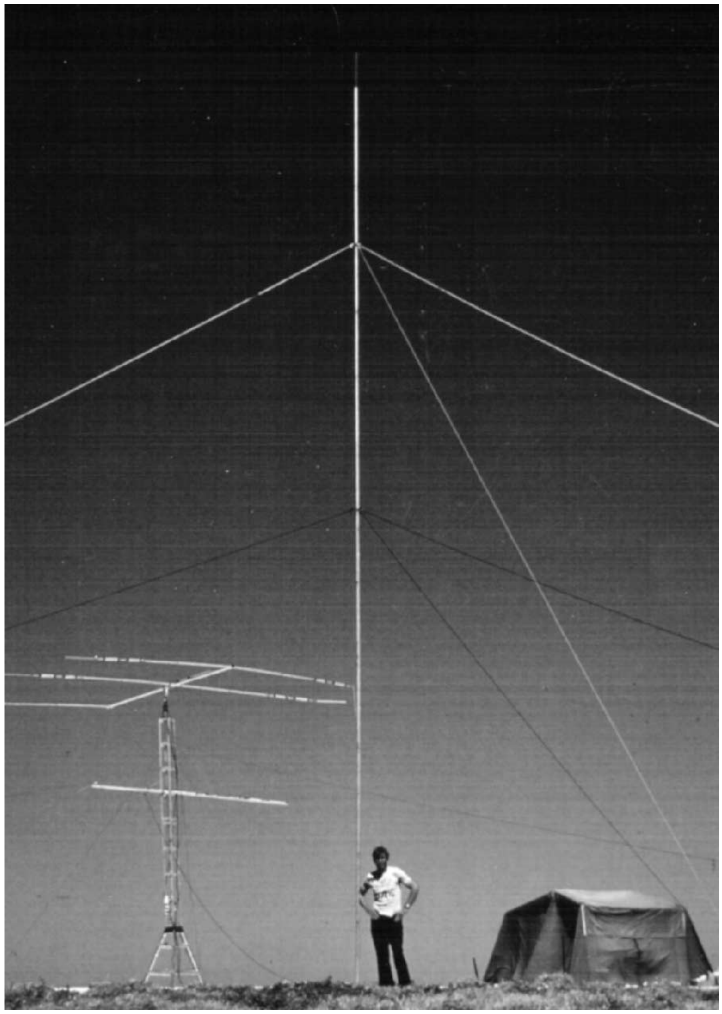

Figure 2 — A short, top-loaded 160 vertical on Mellish Reef set up by Bob, WA8MOA. (Minooka Special)

Thinking About Basics

To make sure we're all on the same page, let's first review a little piece of antenna basics in simple terms. If you know this subject inside-out, skip this segment or your eyes may glaze over. Here we go.

Either the dipole, or its half brother the monopole over a ground plane, is a capacitor-like device we call an antenna, to which we connect the output of an alternating current generator we call a radio transmitter. In order for current to flow, any such device must have two terminals connected to the two output terminals of the generator. The radio frequency (RF) alternating current (AC) creates electromagnetic fields between the two elements of the capacitor/device/antenna. Figure 3 illustrates the basic concept of a vertical monopole.

The energy in those fields is proportional to the RF current in the elements. So, more current in the elements means stronger fields. Energy in those fields is "lost" from the system on each phase reversal of the alternating current. That lost energy is what we call our radiated signal.

As in any circuit, maximum current will flow when resistances are reduced to a minimum. The resistances in a monopole/ground plane include losses in conductors and in the ground plane itself. These are heat losses. Plus, there is "radiation resistance." This figure is the apparent resistance of the antenna that can be attributed to the radiated energy. Therefore, radiation resistance is the only "acceptable" resistance, if you will, and it is determined by the size and configuration of the antenna. Also, if the antenna isn't resonant, there will be either capacitive or inductive reactance present that will act as a resistance to AC and will further "impede" RF current.

Resonance is the condition that exists when the capacitive and inductive reactances are equal, and cancel each other. Therefore, one of the ways to maximize current and radiation is to "resonate" the antenna by adjusting the length and diameter physically and/or electrically. Another way to improve things is to use lower resistance conductors and in the case of a ground plane, make the "plane" part bigger and/or more solidly conductive. That's easier said than done in the case of the vehicle we use for our mobile setup and often the backyard we use to erect a vertical for 1.8 or 3.8 MHz, for example. Nevertheless, to achieve maximum radiation the objective is for the RF energy to "see" only the radiation resistance at the feed point, or as close as we can come to that condition.

Applying these basics to the case in point, the full sized monopole over a ground plane has been sized for resonance. As it turns out, at about a quarter wavelength and multiples thereof, depending on such things as cross sectional area, the inherent capacitive and inductive reactances of the monopole element will be equal and opposite, so they cancel. The monopole is a series-resonant circuit in itself, when fed against an appropriate counterpoise such as a ground plane or an opposing monopole.

The problem is, full size monopoles for the lower Amateur bands are too ungainly for our cars, some of our backyards, and sometimes our pocketbooks, so we often seek to achieve resonance on monopoles much shorter than a quarter wavelength. There are several ways to do this. Since shortening the monopole element reduces both its inherent capacitance and inductance, we can add them back in a more compact form like either "hats" or coils, or maybe both. These may be added anywhere along the monopole, but their positions will determine, to a great extent, the radiation resistance, where in the antenna the current will flow, the size of the fields between elements, and therefore the amount of radiation that occurs. The term "resonator" is often applied to a loading system that has both inductance and capacitance. Figure 4 illustrates the full size quarter wavelength antenna and the shortened, loaded antenna.

What Got This Study Started?

The "*Q*" question, as it relates to loading coils is where it all started for me. *Q*, or quality factor, is most simply expressed as the ratio of reactance to resistance in a component. This was a big issue when I started mobiling on 1.8 and 3.8 MHz in the mid 1950s. Conventional wisdom said that the secret to having a decent mobile signal on the lower frequency bands with an inductively loaded antenna was to use a very large diameter coil, wound with large diameter wire, spaced turns and an air core (no form). In other words, high *Q*. The warning often repeated was that skinny close-wound coils on a form were very lossy and if you use them, you won't be heard as well. They are low *Q*, comparatively speaking.

We were using AM (amplitude modulation) in those days. Most of us had homebrewed rigs, or converted "Command" sets (WW2 surplus) and a few had commercial tube type rigs such as Elmac AF-67s.

Some mobilers used base loading coils on an 8 foot whip. Johnson made a band switching version. A lot of antennas were patterned after Master Mobile, Basset and other commercial products. They used a 3 foot base mast, a 5 foot top whip, and an adjustable large diameter, spaced, air wound coil in between. That way, when the coil was completely shorted, the antenna would resonate on 10 meters. Why the 3 foot/5 foot split? I'd guess it was conventional wisdom.

One of the problems we had with this kind of set-up was extremely narrow bandwidth. We could only cover a few kilohertz on the lower frequency bands with a particular setting of the coil. As you drove down the street, the plate current meter or SWR indicator varied all over the place because of changing proximity to trees, overhead lines, and passing vehicles. A little frost, some rain or a small bug could move the resonant frequency out of the band. Therefore, high *Q* coils had a definite downside. Figure 5 shows a high *Q* coil as part of a mobile antenna.

In the early 1960s I scrounged an old Webster Bandspanner at a Starved Rock, IL Hamfest. This was a commercial mobile antenna for 80 to 10 meters. It consisted of a long, perhaps 5 foot phenolic mast about 1 inch in diameter, with an embedded coil for a good part of its length. A whip protruded from the top of the mast. You could slide the whip into or out of the mast, and a sliding contactor on the bottom of the whip moved up and down the coil inside the mast. This allowed for adjustment of the antenna to any

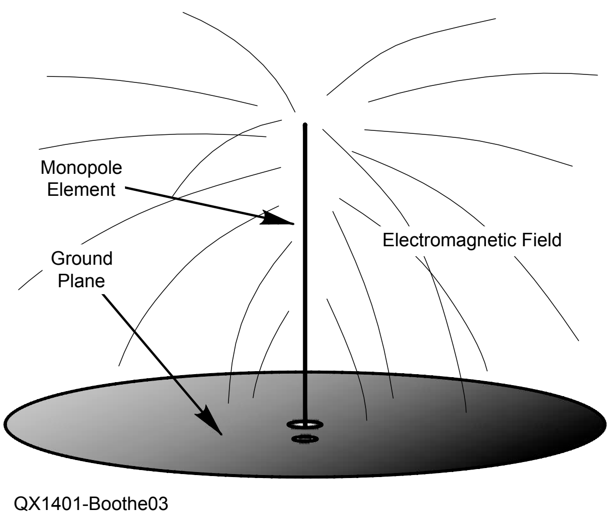

Figure 3 — A Monopole/Ground plane and its fields

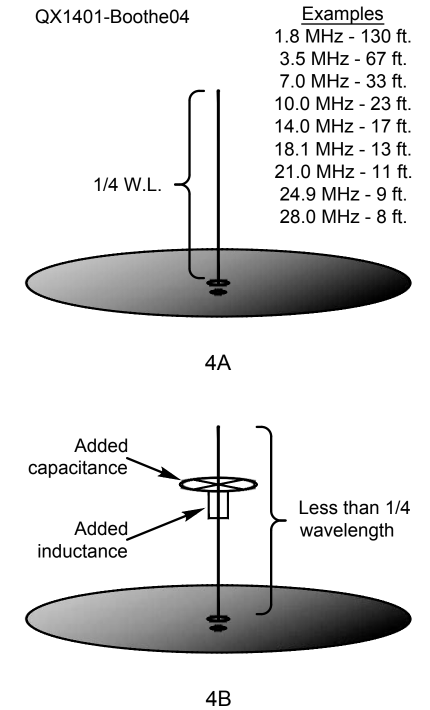

Figure 4 — The "Full Size" monopole and the loaded monopole. (L+C)

Figure 5 — High *Q* coil

frequency from 3.8 to 29 MHz. I tried the Bandspanner on 3.8 MHz. The bandwidth was much greater than with the big air wound coil set-up. Corona and proximity effects were greatly reduced and it stayed on frequency in any weather. Signal reports seemed just as good as with the old antenna, but that wasn't a very scientific evaluation. Besides, it flew in the face of conventional wisdom. This antenna used a relatively low-Q coil, as shown in Figure 6. My next step was to add more inductance and a "lampshade" capacity hat to resonate the Bandspanner on 1.8 MHz.

Results were much the same as on 3.8 MHz. The only logical thing to do was to build a 160 meter antenna from scratch, based on the Bandspanner design. A long, close wound coil of fairly small wire (#20) on a PVC pipe form was mounted as high as possible on a base mast and combined with as much capacitance as possible above the coil. My experiments had shown me that higher ratios of top capacitance to inductance further increased bandwidth. Raising the coil on the mast lowered the SWR at resonance, and that's a good thing, right?

I had no corona problems, I could load the antenna over a bandwidth of 10 to 20 kHz, and almost nothing moved the resonant frequency. It seemed to perform as well if not better than previous antennas as far as signal strength — "seemed to" being the operative phrase. By now, quite a few of us in the area were using similar set-ups. But there was unrest brewing.

This heresy could not be tolerated, so, eventually, I was confronted by an irate mob of "Conventional Wisdomites" who were intent on showing me the error of my ways. A cadre of scientific types, led by my friend George Ostrowski, K9PAW, arranged an antenna signal measurement test at a "160 Meter Reunion" held in Joliet, Illinois in the summer of 1969.

I didn't know much about the test equipment they had set up. Added to that were some fancy attenuators and lengthy calculations. The big deal of the day was the comparison of signal strengths between two otherwise similar antennas for 1.8 MHz. One used a big high-Q coil with a 1:1 length/diameter ratio, 6 inches in diameter, with spaced turns of #10 wire and an air core. The other used my skinny 7/8 inch diameter close wound coil with #20 wire on a piece of PVC pipe and a 20 to 1 length/diameter ratio. And, worse yet, my coil was covered with shrink tubing!

As was expected, the higher Q antenna was better, but by only 0.3 dB. That's right, three tenths of a decibel! That was not expected! Even those of us that thought the lower Q setup was a good deal could not believe it was that close. This was no less a shock to me than it was to the "Wisdomites." We all agreed that the test had to be flawed and George said that modifications were called for. Nevertheless, he and his cohorts were duly impressed with the close outcome, as was I.

Improving and expanding the measurements became an ongoing obsession. Over the next 20 years, sandwiched between life, a job, and a family, I hit the books and the workshop whenever I could. Every time we set up a new measurement program lots of suggestions were implemented that came from interested parties to fix, correct, and improve the measurements. So, we kept modifying and redoing the tests.

New test stands were built, equipment was improved, but time after time, the results were the same — as were doubts about the accuracy of the measurements. After all, we were in violation of conventional wisdom! Meanwhile, my friend Greg Chartrand, WA9EYY (now W7MY), was the first to use my long skinny coil arrangement as a base station top-loaded vertical for 160 meters when he was living in Worth, Illinois. It gave him his first transatlantic reception reports and he dubbed the antenna "The Minooka Special." It was described in *QST* as well as publications in several other countries.[1] Subsequently, it was used by many top band hams as base station verticals as well as mobile antennas in the Chicagoland area and around the world. I put together a number of 43 foot, collapsible, all band versions. They

Figure 7 — Here is my test setup from the early 1980s .

Figure 8 — Late '80s tests with chicken wire fencing for a ground plane

Figure 6 — Low *Q* coil (20 meters)

made a good showing on DXpeditions for many years.

By the way, "Minooka" is the name of a village close to where I lived at the time. I think it's an Indian word that means "wide spot in the road."

During this time, some interesting works on this subject were published by Sevick, Belrose, Lee, Michaels, Brown, Byron, Maxwell, Schulz and many others.[2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12] I devoured all of this material. Over half of what I read differed with the results of my own experiments. I was determined to set up a measurement program that was as flawless as we could make it in order to sort it all out. Meanwhile, I spent a lot of my limited experimentation time working on receiving antennas for my favorite band, 160 meters.[13]

My YL is Joyce, WB9NUL. See Figure 10. She has always helped with my experiments and measurements, plus, she is a diehard county hunter. County hunting is mostly about mobile operation. So it was natural to concentrate on mobile antennas in order to answer the questions concerning shortened, loaded antenna elements.

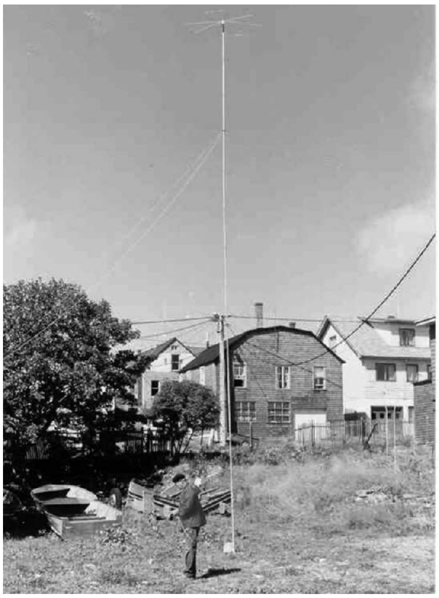

Figure 9 — "Minooka Special" set up on St.Pierre (FP) by Arch Doty, K8CFU (now W7ACD), and John Frey, W3ESU (SK).

Figure 10 — Joyce, WB9NUL helping with a test setup.

We often shared our information with the county hunters at their conventions and also at other clubs and groups. Our efforts were aimed at helping people better evaluate commercial antenna designs as well as to demonstrate ways to "roll your own." I began working on scores of mobile installations to solve problems and improve performance. It was a great learning experience and I collected a treasure trove of tricks and techniques. I designed a complete line of mobile antennas and accessories that was sold under the name of "Custom Enterprises" and eventually by "E-Field Antennas." Neither of those is in business any longer because the owners retired.

How Was it Done?

A plan was hatched. Joyce and I had become involved with the work of our good friend Arch Doty, K8CFU (now W7ACD), and his cohorts, John Frey, W3ESU (SK), and Harry Mills, K4HU (SK). Their work concerned vertical antenna ground systems, elevated radials, folded monopoles and so on.[14, 15, 16, 17, 18, 19] As that work wound down, Arch and I talked about the long suffering subject of shortened monopole loading and my quest for practical data. He was intrigued with the previous test results.

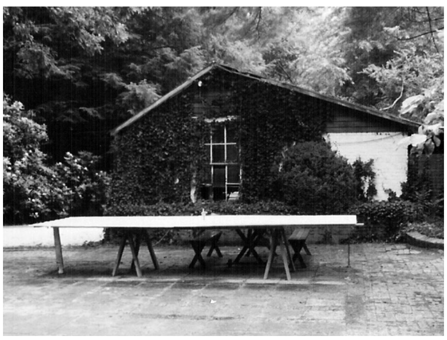

Figure 11 — The test stand over a paved area.

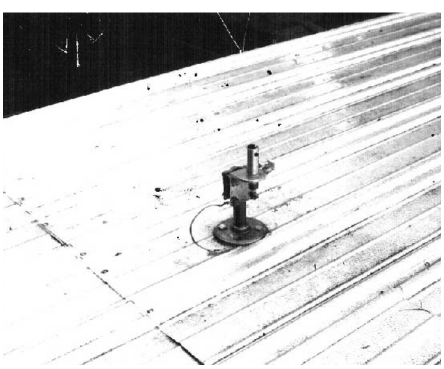

Figure 12 — The test stand antenna mount

We devised a plan to set up a measurement program that would evaluate 1.8 to 30 MHz monopoles empirically, and accurately. We would take into account all the information from Amateur and professional sources that we could gather to design the test set-up. We agreed that measurements would only be accepted as reliable if they were repeated numerous times with the same results. The tests were expanded to include all the parameters mentioned previously plus many more.

The first two or three summer sessions of tests would be conducted in Fletcher, North Carolina at Arch's estate. Then we would continue tests after moving the equipment and operations to the Lower Rio Grande Valley in Texas. We would run the main two series of tests repeatedly each summer for the first few years, noting the differences tied to changes in ground conductivity and looking for "quirks" or anomalies. John Frey, Harry Mills and others expressed their willingness to work on the Fletcher part of the plan. Each year we added parameters that needed to be measured or quantified. These came from participants in the test program, outside suggestions from interested parties, and in an effort to explain unexpected results.

The test stand shown in Figure 11 was designed and built by Arch Doty, K8CFU/W7ACD. He had just been through thousands of measurements regarding ground resistance and return currents in his previous project. He built a test stand that to some extent simulated the characteristics of a vehicle. The ground resistance (R_g) of the test stand varied over the period the tests were run due to changing precipitation, week to week and year to year. The average ground resistance was a little lower than we have measured on several vehicles — about 17 Ω on 14.2 MHz and 38 Ω on 3.8 MHz, for instance. (These measurements were made using the techniques Arch had developed and published. See the references to his many articles in the Notes.) The test stand was a sheet of aluminum "5V" roofing material, 6 feet × 15 feet, elevated 30 inches above a large brick paved area. The antenna mount was in the geometric center. See Figures 11 and 12.

There was a plastic pipe support structure at the side of the test stand with an arm extending over the antenna mount and a rope to allow pulling up and holding various test antennas in position for measurement. This would allow for quick changes of many dozens of configurations without demanding that each be self supporting. I had used a wooden version of this support scheme in earlier tests but was worried about the possible effects of dampness or other contaminants in the wood. See Figure 13.

Pickup points for field intensity were located at different angles and distances from the test stand. The first was only 100 feet away using a 4 foot whip, fed against an iron table as a ground plane, as shown in Figure 14.

The second pickup point was a 10 meter vertical dipole hung about 30 feet above ground in a tree 190 feet away. It was not resonant near any frequency we used in the tests. The third pickup point was an elevated 110 foot folded vertical monopole with 120 elevated radials each 120 feet long about a quarter mile from the test stand. Two GRC ME-61 military field strength meters were used, one modified with a balanced amplifier. The big monopole had a simple detector unit at its base. I am at that detector unit in Figure 15.

For those manning the pickup points, the tests were "blind." That is, a test number was issued via VHF radio and then the personnel at the test stand would apply a calibrated 10 W signal to the test antenna for the field strength measurements. Figures 16 and 17 show me and Arch at the Fletcher test stand. Then, at the test stand, every configuration was measured and documented for bandwidth in kilohertz between 2:1 SWR points, for feed point resistance at resonance, reflected power in watts and two independent SWR readings. Any configuration that showed an SWR of 2:1 or more was measured with and without feed point matching.

The Fletcher Program was where the bulk of the data concerning the Q of coils and the position of the inductor in the mast versus radiated field strength and bandwidth was collected. Two series of test measurements formed the framework of The Fletcher Program, although many additional factors were looked at during those tests. Both series were run repeatedly over a two week period each summer to verify the data. Anomalies were analyzed and the data was averaged to get reportable numbers. Besides our "core" team, many local hams from the Hendersonville, NC area showed up each year to help or observe and to offer suggestions to improve the process. Sometimes they brought their own antennas for evaluation on the test setup.

Other measurements were intermixed with the repetition of Series 1 and Series 2 tests. We measured multiple resonator setups, mounting angle of resonators to masts and alternative types of coils, like pie-wound and toroidal core

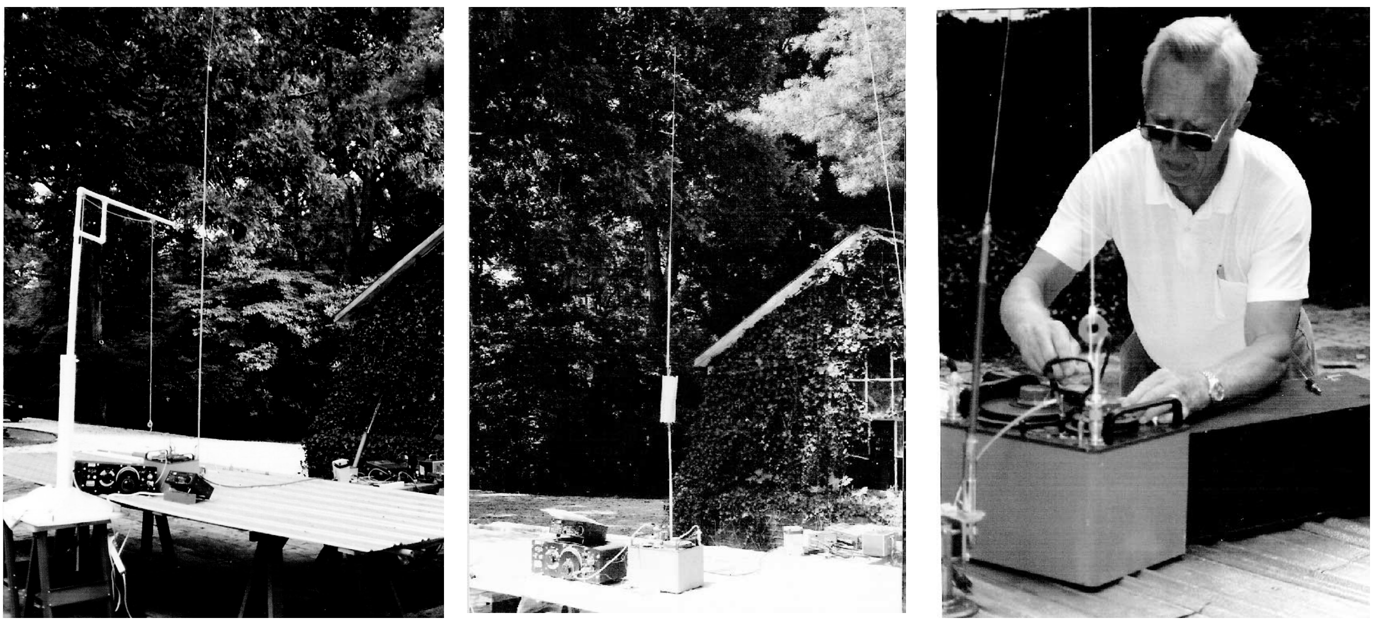

Figure 13 — Antennas on the test on the stand with Arch Doty, K8CFU (now W7ACD), at the equipment.

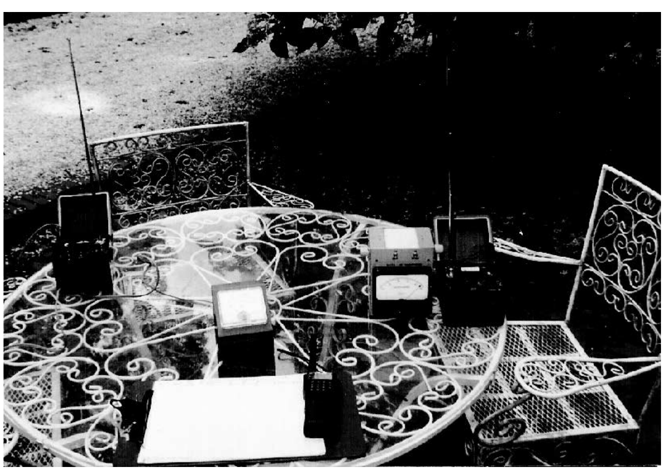

Figure 14 — The closest field strength pick-up point, about 100 feet from the test stand.

Figure 15 — The author at the base of the elevated monopole at Fletcher, North Carolina

Figure 16 — The author at the Fletcher test stand.

Figure 17 — Arch Doty, K8CFU (now W7ACD), at the Fletcher test stand.

Figure 18 — The "Truckstand" used for the "Six Shooter Junction" program.

Figure 19 — Base mount over the radial system.

inductors. As time went on, hams in the area, some of whom helped take readings, brought their pet antennas for evaluation. These were both commercial and homebrewed types. We measured them all, but that data was not included in the "Bottom Line" figures. The pet antennas included no startling breakthroughs. Measurements were consistent with our test antennas. No one had invented "dB paint" or some other secret weapon.

When we were satisfied with the repeatability of what we collected at Fletcher, we packed up the General Radio 1606A impedance bridge and 1330 oscillator, the Bird 43P wattmeter, and the ME61 field strength meters and headed to the Mexican border. Other equipment used in the measurements was more universal and would be supplied locally, or added as we saw the need.

But wait! It's time to figure this out! When we pulled up stakes in Fletcher, we assessed what was left to measure and what we had to resolve. Two things seemed to disagree with a lot of the literature on the subject. One was that after a dozen test programs over 25 years, we had not resolved the almost immeasurable difference in performance between high Q versus low Q loading coils in shortened monopole antennas. Every test so far had reconfirmed the K9PAW tests back in Joliet, Illinois in 1969. That is, that the greatest difference in field intensity (near and far) between long, skinny coils on a form versus big diameter, large wire, spaced turns, air wound coils, all other factors being the same, was 0.3 dB, and that was on 1.8 MHz. The difference could hardly be measured on higher frequency bands.

Also, we could not verify the assertions of authors who put forth formulae locating loading coils at a particular point in the mast to get the best performance. The point indicated was usually close to the center or a bit above. In all of our tests, we found that the field intensity was highest when the coil was moved as close to the top of the mast as possible.

These two items made us pour over the writings to see where we might have gone wrong. In the process of reviewing the literature, we noted a trend that might be important to unraveling the mysteries.

Eureka! We have it —maybe. All of the writings on the subject that predicted big losses in low Q coils in monopoles and also those that located the coil optimally down the mast from the top had one similarity. These authors had made the calculations assuming that the current was constant throughout the loading inductance. About half of the available literature on the subject as well as some modeling programs held that condition as factual. We noted that the other half showed tapering current in loading coils used for making shortened monopoles appear to be resonant quarter waves. Meanwhile, in our experiments, we had seen rather unscientific indications that the current

Figure 20 — Radial system site with a test antenna.

diminished severely as it passed through the coil. For instance, one indicator was the great increase in voltage from the bottom of the coil to the top. When calculations were done using tapering current, the results were very close to those from Fletcher and earlier tests.

It was obvious from this that we needed to verify more scientifically the issue of current taper in loading coils. Even though this was a secondary issue in terms of our original objectives, we wanted to know if this issue could help explain the results we were getting. Inputs from recognized experts told us to compare results using the test stand to those using an extensive radial ground system.

Our first task was to set up the test stand and replicate the Fletcher tests in Texas, so that there was a common reference point, a benchmark. Then we could go on from there.

The Six-Shooter Junction Program was the continuing effort to measure things. Six Shooter Junction was the original name of Harlingen, TX, and that seems appropriate. Harlingen is where we set up our test facilities. Its name is from a town in Holland, pronounced 'har-len-jen.

Our first effort in Texas was a bust. Arch and I became quite frustrated trying to replicate the Fletcher numbers. At first we thought the ground conductivity in the coastal plane was so much greater than Fletcher that the test stand was giving us completely different readings. Eventually we found that the cause was a 50,000 W broadcast station on 1530 kHz, just a few miles north of our location. It had a monster six element antenna array aimed right down our throat toward Mexico. After adding high pass and "suck-out" filters to some equipment and with a little tweaking, it was fixed! A run of Series 1 and Series 2 measurements confirmed the Fletcher data, and we were in business. We had our benchmark.

From that time on, test programs were run periodically in Texas. They included measurements that we had planned when we finished in Fletcher, like;

1) Currents in loading coils
2) Further study of bandwidth factors
3) Alternate resonator design

Over time, and after reporting some of our findings to groups and on the internet, we had the benefit of receiving inputs from many interested persons. This resulted in the addition of quite a few more measurement plans.

4) Ground resistance, band by band, for large and small vehicles versus a "typical" radial system

5) The effects of using magnetic mounts on mobile antenna performance

6) The comparative performance of loaded monopoles with capacity hats located close to or far above the loading coil or with no coil at all.

7) The comparison of monopole matching at the base of the antenna versus in the shack or cabin of a vehicle

8) The comparison of the high Q/low Q results on a vehicle versus over an extensive radial system on the ground.

Besides these, a myriad of antenna design tests were to be conducted. Several configurations of ground mounted monopoles would be built, some as reduced size models.

Methods and equipment changed somewhat. We acquired a big diesel pickup truck. It was a Dodge, extended cab, long bed with a flat cover over the bed. An antenna mount was placed a bit forward of center on the bed cover. See Figure 18.

On the underside of the cover, a "radial" system made of 2 inch wide aluminum roof repair tape was installed. The radials went from the bottom of the antenna mounting plate to the aluminum angle frame that surrounded the cover. The frame was connected to the truck body at all four corners with 1 inch wide braid.

A comparison to the Fletcher test stand showed the truck to have just slightly higher ground resistance on all bands. We decided to use the truck for subsequent tests of mobile antennas on a vehicle. We called it the "truck stand." For those kinds of measurements the truck was placed in a fixed position on a large cement paved area at a citrus grove, two miles from our home, west of Harlingen. The site was generously provided by Cheryl (KJ5PQ) and Mike (KG5UZ) Carver. For "on the ground" tests, there was a grassy space adjacent to the paved area that allowed the installation of an extensive radial system. It consisted of 60 copper radials on the ground, from 40 to 60 feet in length. Figure 19 shows the base mount for the antennas with this radial system and Figure 20 shows an overview of the antenna site.

The field strength pickup point was at our home, two miles to the west. Figure 21 shows the caged folded monopole used at that site.

Every day that tests were run using this site and setup, benchmark readings were taken at the beginning, throughout and at the end of the session. We took note of rainfall and climatic conditions, noting the effect they had on our benchmark readings. Even the change in humidity from morning through midday and to evening hours made a difference in base readings.

Test equipment was also added. Arch, W7ACD provided both the AEA SWR-HF as well as the CIA-HF analyzers, with the plotting software. This provided graphic charts of SWR, resistance, impedance, return loss, and reactance curves plus a Smith chart for every antenna tested. I added the MFJ259 analyzer, an HP 8640A signal generator and a laptop computer for test site plotting. A Yaesu receiver was modified to have calibrated digital field strength readout. It was located 2 miles away at the pickup location.

Helium filled balloons were employed to support ¼ wavelength antennas used in some tests. In order to present the data from both Fletcher and Harlingen in a comprehensive form, and to complete a number of added measurements, we had to use ¼ wavelength resonant elements to determine ground resistance of the "truckstand," other vehicles and the radial system on each band. A wire "reel" was constructed to allow quick infinite adjustment of the balloon supported antennas for perfect resonance.

The elusive "tapering current" question had to be answered. In order to measure RF current in monopole loading coils, Arch obtained four new calibrated RF ammeters. They were mounted together with their thermocouples on small PVC fittings with standard 3/8-24 threads to mate with antenna masts and coils. Measurements were made on test stand antennas, ground mounted antennas, and vehicle mounted antennas. High *Q* and low *Q* coils mounted in various positions from the base to the top of antenna masts were studied on several bands, from 30 meters down to 160 meters. We also measured the current in and out of toroidal wound loading coils. No "heliwhip" or coils considered to be a significant part of a wavelength were used in those tests. Coils with the meters mounted on their ends were always reversible, to allow double checking results for anomalies. Adding the meters to the antennas made very minimal change to the tuning, limited to a slight movement of the resonant frequency downward due to the slight increase in capacitance above the coil. We found no indication that the meters were affected by the RF field. Of course, they were designed for this kind of service.

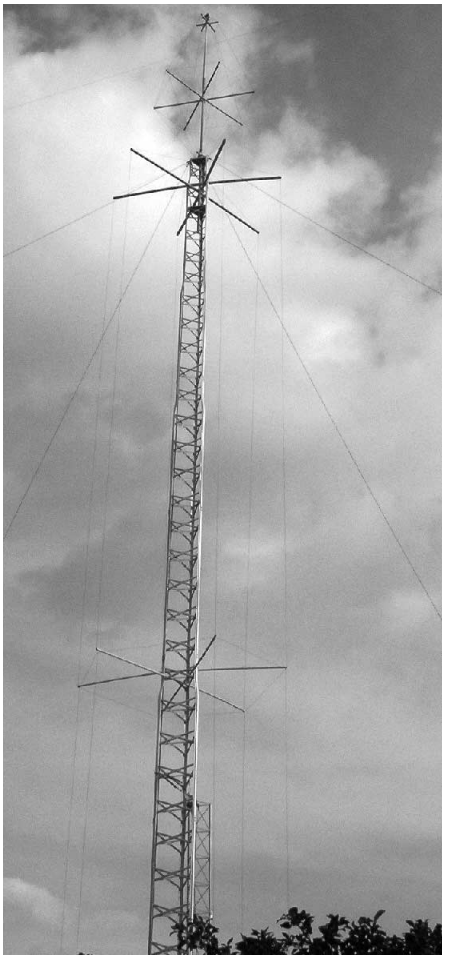

Figure 21 — The pickup antenna was this 80 foot caged, folded monopole for the Texas measurements.

Then, it all had to stop, because we bought a new home. Even though there were more tests on the agenda, we had to abandon the citrus grove site because our new home was about 8 miles northwest of the old place.

In the second part of this article I will present the actual measured results for our Series 1 and Series 2 tests. I will also offer some conclusions that we came to about all of these measurements.

Barry Boothe, W9UCW is an ARRL member and holds an Extra Class license. He has held his call since 1954 after holding WN9UCW for a couple months. He became interested in Amateur Radio at age 13, after experimenting with electricity and electronics during his junior high school years.

Barry was with Caterpillar for 31 years at facilities in the US and Brazil. He was a division manager when he took early retirement. He taught electricity and electronics classes at a community college for six years.

His primary ham radio interests have always been building, antenna research and low-band DXing. He has made 20 trips to Central and South American countries, always involving Amateur Radio to major degree. Barry won two cover plaque awards for QST articles published in the 1970s. Another of his interests is woodworking.

Barry and his wife Joyce, WB9NUL have lived in the Lower Rio Grande Valley for over 23 years. Joyce has held her call for 40 years. She is a county hunter and was president of MARAC, the mobile awards club for 7 years.

Notes

[1]Barry Boothe, W9UCW, "The Minooka Special," *QST*, Dec, 1974, pp 15-19, 28. and *The ARRL Antenna Anthology*, 1978, pp 36-39.

[2]Jerry Sevick, W2FMI, "The Ground-Image Vertical Antenna," *QST*, July, 1971, pp 16-19, 22.

[3]Jerry Sevick, W2FMI, "The W2FMI Ground-Mounted Short Vertical," *QST*, March, 1973, pp 13-18, 41.

[4]John S. Belrose, VE3BLW (now VE2CV), "Short Antennas for Mobile Operation," *QST*, Sep, 1953, pp 30-35, 108.

[5]John S. Belrose, VE2CV, "Short Coil-Loaded HF Mobile Antennas: An Update and Calculated Radiation Patterns." *ARRL Antenna Compendium, Volume 4*, ARRL, 1995, pp 83-91.

[6] P.H. Lee, *The Vertical Antenna Handbook*, New York, Cowan Publishing,1974

[7]Charles J. Michaels, W7XC "Evolution of the Short Top-Loaded Vertical," *QST*, March, 1990, pp 26-30.

[8]Charles J. Michaels, W7XC, "Loading Coils for 160-Meter Antennas," *QST*, April, 1990, pp 28-31.

[9]Bruce F. Brown, W6TWW "Optimum Design of Short, Coil-Loaded High-Frequency Mobile Antennas," *ARRL Antenna Compendium, Volume 1*, ARRL, 1985, pp 109-115.

[10]W.J. Byron, W7DHD, "Short Vertical Antennas for the Low Bands: Part 1 and Part 2," *Ham Radio*, May and June, 1983.

[11]M.Walter Maxwell,W2DU, *Reflections-Transmission Lines and Antennas*, ARRL, 1990

[12]W. Schulz, "Designing a Vertical Antenna," *QST*, Sep, 1978

[13]Barry Boothe, W9UCW, "Weak signal Reception on 160-Some Antenna Notes," *QST*, June 1977

[14]Archibald C. Doty Jr., K8CFU (now W7ACD), John A. Frey, W3ESU, and Harry J. Mills, K4HU, "Efficient Ground Systems for Vertical Antennas," *QST*, Feb, 1983, pp 20-25.

[15]Archibald C. Doty Jr., K8CFU (now W7ACD), John A. Frey, W3ESU, and Harry J. Mills, K4HU, "Vertical Antennas: New Design and Construction Data," *ARRL Antenna Compendium, Volume 2,* ARRL, pp2-9.

[16]Archibald C. Doty Jr., K8CFU (now W7ACD), John A. Frey, W3ESU, and Harry J. Mills, K4HU, "Characteristics of the Counterpoise and Elevated Ground Screen," Professional Program, Session 9, Southcon '83 (IEEE) Atlanta, GA, 1983.

[17]Archibald C. Doty Jr., K8CFU (now W7ACD), "Improving Vertical Antenna Efficiency," *CQ*, April, 1984.

[18]John A. Frey, W3ESU "The Minipoise," *CQ*, 1985

[19]Archibald C. Doty Jr., K8CFU (now W7ACD), Technical Paper Presentation, "Capacitive Bottom Loading and Other Aspects of Vertical Antennas," Technical Symposium, Radio Club of America, New York City, Nov 20, 1987.

Letters to the Editor

Using Time Domain Reflectometry for Transmission Line Impedance Measurement (Jul/Aug 2013)

Hi Larry,

Phil Gaudet, K1IRK, noticed that I made some mistakes in my calculations in the explanation to Figure 5 that begins on page 27 under the heading “Classic TDR Use.” The mistakes are in the times given for the various lengths of line at the top of page 28. The first bump is at 152 ns rather than the second one as I said in the text. The second bump is at about 225 ns, which matches with my results of 74 ns (more or less) for the RG-8X. The total length is 256 ns as shown by the cursors on the oscilloscope trace. That puts the LMR400 at 63 feet, the RG-8X at 29 feet, and LMR-400 Ultraflex at 13 feet for a total of 105 feet. I have no clue how I messed up the numbers in my explanation. My apologies for the confusion.

Of course, I got a really great email on the same day I received my copy of *QEX*. IXYS Colorado has just announced a high speed FET drive IC that would be perfect for a TDR. The IXRFD631 is a Schmidt trigger gate followed by a complementary symmetry pair of FETs. The data sheet lists 4 ns rise and fall times while driving a 1000 pF load. When driving an almost purely resistive load, it should be capable of producing sub 1 ns edges. This part is meant to drive Class D and E power amplifiers in medical service at 13 MHz, as well as other HF power amplifier applications up to 45 MHz. The part should be available through distribution soon, but is also available direct at **www.ixyscolorado.com**.

— 73, Ray Mack, W5IFS, 17060 Conway Springs, Austin, TX 78717; **w5ifs@arrl.net**

An Automated Method for Measuring Quartz Crystals (Nov/Dec 2013)

Dear Readers,

An unfortunate error occurred in this article by Richard Harris, G3TOK. The graph from Figure 6 of Richard’s Jan/Feb 2013 *QEX* article, “The Drive Level Sensitivity of Quartz Crystals” was placed in the Measuring Quartz Crystals article instead of the correct graph for Figure 6.

This is the sample *QEX* article that appears on the “This Month in QEX” section of the ARRL website. The correct Figure 6 is included in the article posted there. (**www.arrl.org/files/file/QEX_Next_Issue/Nov-Dec_2013/Harris_QEX_11_13.pdf**.) In addition, we have printed the correct Figure 6 here for your reference.

— 73, Larry Wolfgang, WR1B, QEX Editor; **lwolfgang@arrl.org**

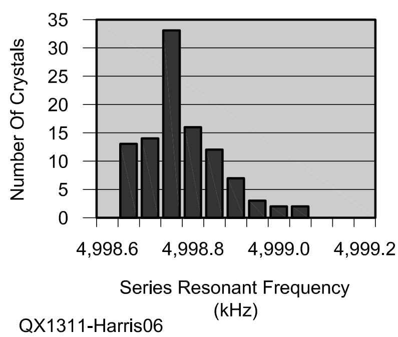

Figure 6 — This graph shows the spread of series resonant frequencies, f_s, for the same 100 crystals.

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