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QEX

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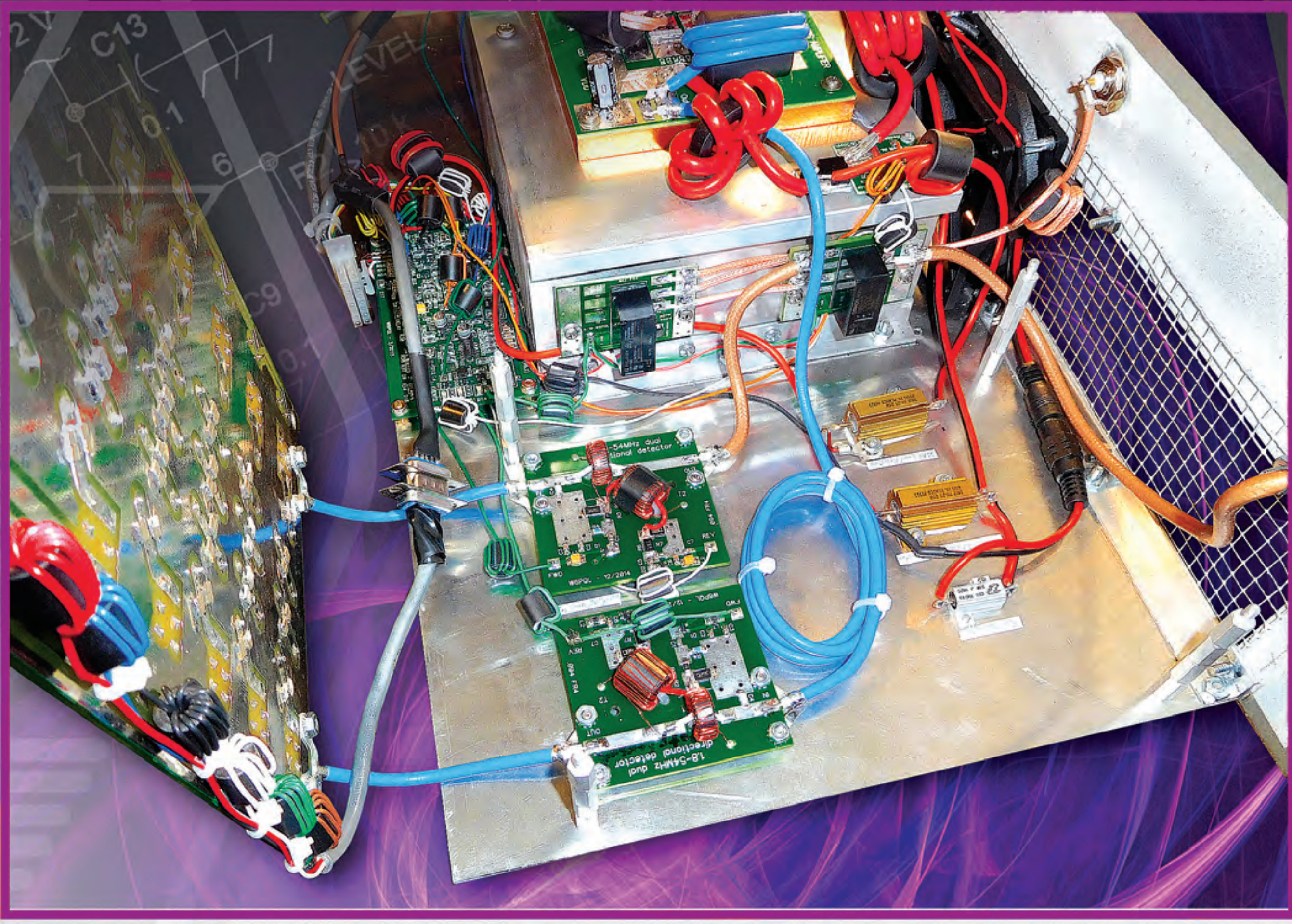

WØIH uses an Arduino to control his 160 m-6 m LDMOS amplifier.

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About the Cover

Michael L. Foerster, WØIH, presents his concepts for building a Laterally Diffused Metal Oxide Semiconductor (LDMOS) 160 m – 6 m amplifier that uses an Arduino controller to orchestrate between the amplifier and two radios. This article is not the “end all” to building amplifiers, but rather just gives a few ideas to build from, or perhaps get the reader to contemplate other solutions for problems that the author faced. The among other features, the Arduino interface powers up the amplifier and monitors many amplifier functions including managing the operating band of the radio to switch the amplifier low pass filter (LPF) band switch.

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The American Radio Relay League

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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.

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

Kazimierz "Kai" Siwiak, KE4PT

Perspectives

QEX Style Changes are in Effect

Reader Jonathan A. Titus, KZ1G, wrote to us about some difficulties in locating references to Figures and Tables in *QEX* articles. He also noted that it is difficult to read "the almost-microscopic superscript numbers that refer to Notes." Thanks Jonathan, we agree that readability should be improved.

You will notice that we are transitioning to some style changes in *QEX* articles as promised in the previous *Perspectives*. **Notes** will no longer use difficult-to-read superscript numbers in the articles or in the list of Notes. Instead, Notes will be identified by sequential numbers surrounded by square brackets, as in "see **[1]**", with the first occurrence in bold typeface. Subsequent mentions of the same Note will be in plain text surrounded by square brackets. The list of Notes at the end of the article will be numbers in square brackets (instead of superscript numbers) followed by a single space.

To help readers locate descriptions of Figures and Tables in the text, the first mention of a Figure or a Table will use a bold typeface, such as **Figure 1** and **Table 1**. Subsequent mentions to the same Figure or Table will use plain text. We hope that you find that these style changes result in improved readability.

We'd like your feedback.

In This Issue

Robert Andre, KEØEXE, supports antennas securely on small tree limbs with his tree branch gadget.

Gary A. Appel, WAØTFB, simulates the performance of cascaded stages in a receiver with his computer based engineering software tool.

Michael L. Foerster, WØIH, discusses concepts for building an Arduino controlled 160 m — 6 m LDMOS amplifier.

Allen Ripingill assembles a versatile set of RF instruments into a single package to test home-built RF projects.

Michael Tortorella, W2IY, characterizes receiver performance using a holistic approach that accounts for many signals in a given frequency interval.

Writing for *QEX*

Keep the full-length *QEX* articles flowing in, or share a **Technical Note** of several hundred words in length plus a figure or two. Let us know that your submission is intended as a **Note**. *QEX* is edited by Kazimierz "Kai" Siwiak, KE4PT, (**ksiwiak@arrl.org**) and is published bimonthly. *QEX* is a forum for the free exchange of ideas among communications experimenters. The content is driven by you, the reader and prospective author. The subscription rate (6 issues per year) in the United States is $29. First Class delivery in the US is available at an annual rate of $40. For international subscribers, including those in Canada and Mexico, *QEX* can be delivered by airmail for $35 annually. Subscribe today at **www.arrl.org/qex**.

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Very best regards,

Kazimierz "Kai" Siwiak, KE4PT

Michael L. Foerster, WØIH

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Building an LDMOS Amplifier with an Arduino Interface

Use these concepts to assemble an Arduino controlled 160 m - 6 m LDMOS amplifier.

We are each given different talents and skills from our parents, schools that we attended, job experiences as well as life experiences. For me, I learned carpentry and construction from my father, electronics in school and a host of technical know-how as a field service technician, even some programming exposure through my jobs as a software test engineer, and a great deal of RF background through my 50+ years in Amateur Radio. From these life experiences, I chose to embark on one of the biggest projects I had ever tried; I built a Laterally Diffused Metal Oxide Semiconductor (LDMOS) amplifier with an Arduino controller (**Figure 1**) to interface between the amplifier and my radios: the Elecraft K3S and KX3.

This article does not present the "end all" to building amplifiers, but rather just gives a few ideas to build from or perhaps get the reader to contemplate other solutions for the problems that I faced. Consider building an amplifier yourself, but if nothing else, enjoy reading the article.

Figure 1 — Front panel of the amplifier.

Desired Functionality

I wanted the Arduino interface to power up the amplifier and monitor the operating band of the radio to switch the amplifier low pass filter (LPF) band switch. I also wanted to configure the radio output power on a per-band basis and have the Arduino load the power setting into the radio for power output and tune power parameters. Monitoring and displaying the band, voltage, forward and reflected transmit power, temperature and input voltage seemed a very natural part of the project as well. Some other functions such as the timeout timer and Bypass/Operate selections were enhancements to the system.

In developing the program in the Arduino, I added a lot of functionality that is not strictly necessary. You can remove these to pare the system down to its functional simplicity.

Amplifier Project Choices

I studied different available LDMOS designs and decided to use a single solid state power amplifier (SSPA) device that provides over 1000 W output with less than 5 W of drive power. I didn't feel the extra 400 to 500 W would be worth the added cost.

I've learned over the years that I tend to forget some details of operating high-powered equipment, and that this can be costly since some of these devices can be very unforgiving! I felt it was very important to build in automatic band switching. There are boards available to read the BCD band outputs from rigs like my K3S, but I also want to use this amplifier with my KX3.

Amplifier Development

I considered the different kits and parts that were available online for the LDMOS amplifiers and settled on the kit parts from Jim Klitzing, W6PQL **[1]**. I purchased most of the boards in kit form, rather than pre-assembled. I ordered the SSPA, LPF, control board, and two of the dual direction detectors (SWR boards) as kits. I also purchased as complete assemblies, the input and output relay boards as well as a dc FET switch that turns on the power to the SSPA with a signal from the control board. The instruction page also lists some of the other required parts for the amplifier that can be purchased from **mouser.com**, **eBay.com** or other suppliers. I purchased the BLF188XR LDMOS chip already soldered in place on the copper heat spreader, as I felt this was a critical process best left to the experienced vendor. I built the rest of the major assembly kits using the instructions provided.

The biggest challenge in the kit building phase was the control board, because it used many small surface-mount parts. This was my first experience in soldering surface-mount devices. I learned to first add a touch of solder to one pad, place the part with tweezers and heat it up, then solder the second side and re-solder the first side. I checked and double-checked my parts placement, especially on the control board. Jim Klitzing, W6PQL, was a great help in getting through a few rough spots on the kit builds. The control board didn't work due to a few poor solder joints on some of the surface mount op-amps. I later learned a touch of liquid flux makes the solder flow much better on these delicate leads. Looking back, I should have purchased the control board pre-assembled.

One of the most valuable tools I have is a jeweler's eyepiece with a side LED light for close inspection of the parts placement and solder joints. A microscope with a USB interface might be very useful for this type of work. My solder station, with interchangeable solder tips and adjustable temperature, proved to work very well throughout this project. It worked for the small surface-mount parts as well as soldering the heavy #10 AWG dc wires to the SSPA assembly.

The design of the case took a lot of thought and time. **Figure 2** shows the completed rear panel. I had a 3U (5 ¼" high) 19" rack-mount cabinet in my junk box that included some great RF-proof finger stock on the top and bottom covers. This proved to be perfect for the case. I purchased an extra piece of 1/8" thick aluminum plate for the bottom of the case to mount the heat sink, resistors and other parts. This bottom aluminum plate was mounted to the back plate to allow removal from the case shell for maintenance. I purchased a 4-40 tap and matching drill, which I used extensively in mounting resistors, boards, standoffs and other parts on this plate and various places within my project.

I also tried to make sure I could mount the boards using connectors to allow for easy removal for future maintenance. This proved to be very useful, especially for the LPF and front panel. I considered putting BNC connectors for the RF input and output lines on the LPF board, but to remove them required unsoldering only the center wire and removing the coax shield connection screws. I built the front panel with a 20-pin connector for the bulk of the connections, along with two 5.5 mm connectors — reversed to prevent incorrect installation — for the two meter connections. Throughout the process

Figure 2 — Amplifier rear panel.

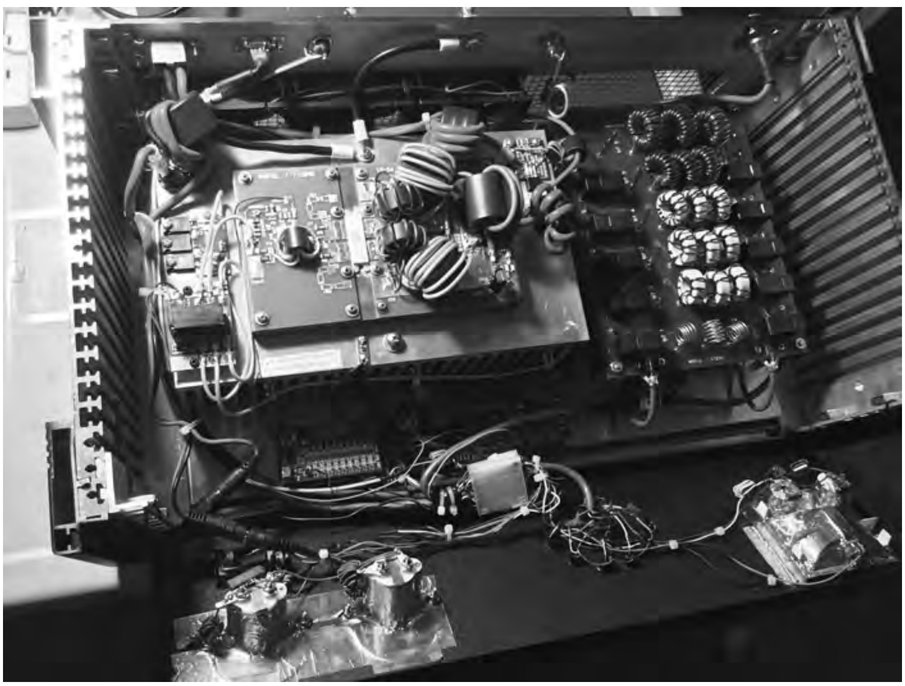

Figure 3 — Amplifier with front panel tilted down.

of building, troubleshooting and modifying, these parts required removal several times. I also needed the ability to check voltages on the front panel, so I bent two pieces of stiff wire to allow the front panel to tilt down at about a 45° angle (see **Figure 3**). Because many of the control board connections were spread throughout the board, I didn't use a connector on it. So far, I've only had to remove the board once. I had to mark each of the colored wires carefully to make sure that I could re-install them correctly.

Most of the wiring was direct point-to-point where I added small ferrite cores wound with about 7 turns of wire. The cable to connect the Arduino to a 15-pin VGA-type connector was made of two shielded 8-conductor cables.

I tried to use color-coded wires throughout the build of the amplifier and subsequent Arduino project. I didn't purchase all of the colored wires separately, but rather used some different cables with 8 or even 12 colored wires that I had in my junk box. I didn't follow any strict color coding, but I did mark the colors used on all my schematics. This will help for future troubleshooting or modifications.

I learned quite a few things from Jim, W6PQL, as I progressed through the amplifier build. For one thing, I had the fans butted up against the heat sink. He helped me to understand that you need to allow at least ¾" of space between the fan and the heat sink, or the fan output will be decreased greatly. He also recommended using conductive tape to cover the meters. I found some fairly inexpensive 2" copper tape that molded over the meters very well. Aluminum tape should work equally well.

Individual ferrite cores should be used on each signal lead at the source and destination board throughout the amplifier to reduce RF pickup. This is very important in an environment where there is a lot of RF signal. I inquired about passing two or more wires through a single core, but Jim told me that two wires make a great transformer. [Wire pairs carrying dc currents should pass through ferrite cores as plus and minus pairs to avoid magnetizing the ferrites. — *Ed.*]

Although I've used inexpensive relays before for high power RF control — specifically for remote antenna switching — Jim's articles detail the testing and use of these relays for high RF power, including compensation for VHF and UHF installations. The relays, seen in **Figure 4**, are used for power switching for the input and output as well as for the LPF.

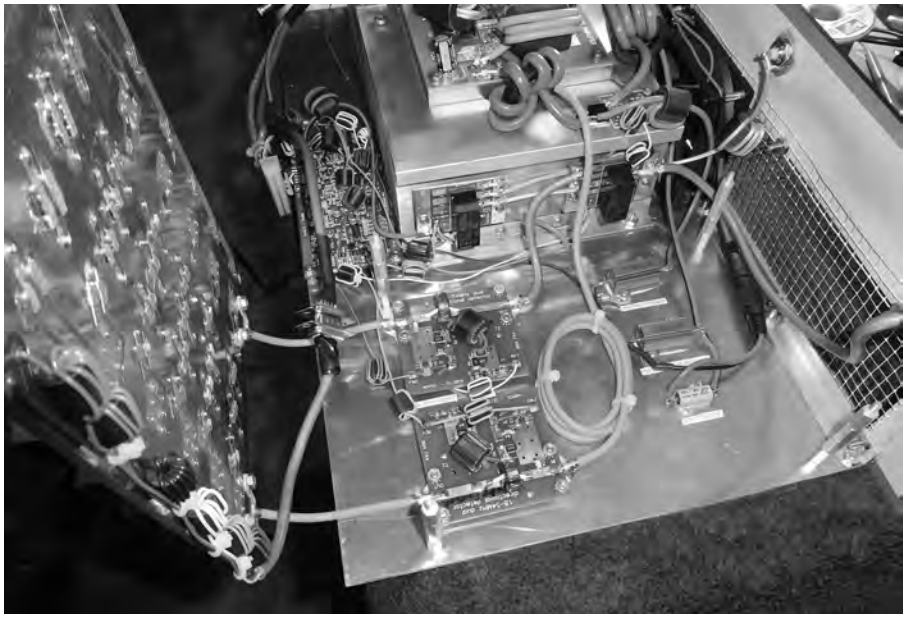

Figure 4 — Relay and SWR boards.

Figure 5 — Layout of the power supply.

Amplifier Power Supply

Many other builders of LDMOS amplifiers favor surplus server-type power supplies that can supply 60 A at 50 to 60 V. These can be very noisy — described as a jet taking off — but the noise can be subdued with modifications. I was aware of these, but decided to build my own supply. I found that four of the 12-V, 40-A supplies designed for LED lighting can be connected in series, and appeared to be a very good fit. The 40-A versions sell for $25 each on eBay and are available up to 60 A. I mounted some large ferrite cores in both the power supply and the amplifier end of the dc supply cable to reduce any possible RFI. I have had no noise issues.

I purchased a large 12" by 12" by 6" plastic electrical box from the local big-box hardware store for about $30. This allowed mounting the four power supplies in a square configuration (**Figure 5**). One was set slightly higher than the rest to allow mounting the ac entrance connector below it. I drilled holes to allow for air flow into the box, as well as for the supply voltage adjust screws and the 120/240 input voltage switches on the bottom. Additionally, I drilled four large 2" holes for the supply exhaust fans and used some thick foam to force the air flow outside the box. The solid state relay (SSR) for the ac switch was mounted in the center along with the soft-start resistor and bypass relay. Five digital voltmeters on top of the case display the voltage across each supply, plus the total voltage. Each supply was setup for 12.5 V to provide a total 50-V output.

The mounting holes were drilled to match the supply mounting pattern. The supplies were wired for ac and dc, then dropped into the box and screwed into place. I can run the power supplies on 120 V ac, but the system runs better on 240 V ac so the shack lights won't flicker.

Initial Amplifier Operation

I discovered in some of my early testing on one band that the amplifier would oscillate; the power output would cycle rapidly from zero to full power. In troubleshooting I found I had the cables behind the amplifier poorly dressed, and somewhat randomly looped around. The amplifier has a great deal of gain, and if the input cable gets too much feedback from the output coax, it can affect the amplifier in drastic ways. I now keep the input cable well separated from the output, and use double-shielded Teflon RG-142U coax for better isolation. I also added a heavy bolt with a wing nut to the back of the case to ground the heat sink and chassis internally for a connection to my station ground.

Nearing completion, I got anxious and started testing the power output of the amplifier into a dummy load, but I had not finished checking out the protection circuits. At one point, I transmitted into the amplifier with the band switch set incorrectly. I immediately noticed the power not coming up and shut down within a half second. This short burst, however, blew out the LDMOS chip. In discussing the loss with Jim, he suggested that to check out the protection circuit, simply set the band switch down one band, key the microphone and snap your fingers. The system should go into protection mode (SWR FAIL) instantly. I requested, and Jim added something to his protection circuit description to help others. He added a test using a 1.5 V battery to the Safety Sensor output line (no transmit required) that must put the amplifier control board into protection mode, shutting down the FET dc power switch and turning on the SWR Fail LED. In troubleshooting, I found I had the SWR Fail LED installed backwards, preventing the circuit from working.

The fan switch circuit control board is designed to turn the fans on during transmit. When the heat sink reaches about 105 °F, the fans are turned on constantly, even during the receive cycle, and turn off at about 100 °F. I found that during a contact, the temperature seemed to stay around 100 °F and didn't go below that, because the fans were off. The fans also seemed to come on and stay on quite frequently. I made a minor modification by adding a 470 Ω resistor across the fan switching FET to ground that turned on the fans all the time, but at a slow quiet speed. During the receiving cycle, the temperature of the heat sink will now continue to drop. During transmit, the added resistor is shorted out by the existing FET switch, and the fans come on at the normal speed.

Solid State Relay Circuit

Rather than run the ac power through the amplifier to the switch that turns on the power supply, I used a 240 V ac solid state relay (SSR) in the power supply. This can be enabled by a 5 V dc signal sourced from the Arduino. Most SSRs are basically ac SPST switches that can be enabled with a dc voltage between 3 and 12 V dc at a few milliamps. I've used SSRs fairly liberally around my shack.

Input Power Attenuator

In experimenting with the communication commands, I discovered I could change the output power from either the K3S or KX3 radio in 1-W increments only, even though manual control allowed the power to be incremented in tenths of a watt. Considering the amplifier required around 2-W of drive, this wasn't enough resolution. A 6 dB attenuator would allow the system to increment the power by 0.25 W and 10 W would provide 2.5 W into the amplifier. The 6-meter band typically requires 5 to 6 W of drive. I therefore set up the 6 dB attenuator with a relay input so when energized from the 6-m LPF switch, it would bypass the attenuator. The attenuator also ensured that I would not overdrive the amplifier input from the KX3. For the K3S, I found the commands to put the internal KPA3 — the 100 W amplifier built into the rig — in bypass mode, ensuring that it could not overdrive the amplifier input.

A note of caution: I have learned that some radios when set for lower power, have been reported to transmit 100 W or more on the first "dit" or transmitted syllable. Transmitting like this, even a short signal can be devastating to a solid state amplifier. Before testing with your specific radio, you might want to investigate and perhaps even test your radio at low power, by using a peak reading wattmeter or an oscilloscope. In investigating this phenomenon, I found an article **[2]** by Phil Salas, AD5X, on using a gas discharge tube to limit the overshoot to the amplifier.

Arduino Development

There are quite a number of different Arduino boards available, each with different capabilities. Because my plans were to use more than one communication port, I settled on the 4-port Arduino MEGA. Initially I am using two communication ports, either of which can connect to the radio. I also started with a 2-line, 16-character display from **Adafruit.com** that includes five push buttons. This shield — a shield is a board connected to an Arduino — requires only two wires using the I2C bus for communicating with the display. There are other similar displays and keyboard combinations available but they require the use of many more pins. I discovered I could mount the Arduino very close to the amplifier and use a longer 4-conductor shielded cable for 5 V power, ground, and SCL and SDA for the I2C wires, to remotely mount the display and keys. I used an old PS2 mouse cable to allow disconnecting the display box. In researching the I2C communications bus, I found that the distance between the Arduino and the display could be lengthened by adding 2.2 kΩ pull-up resistors to the SCL and SDA output lines for the I2C bus.

Power for the Arduino is provided by a small 9-V wall wart supply. I chose 9 V to limit the voltage drop across the Arduino internal voltage regulator. The current draw of about 110 mA does not create a temperature problem. Do not to use the small variable switching power regulators since they generate a considerable amount of RF noise.

Arduino Mounting Cases

Figure 6 shows the case for my display. I cut an opening for the display, and drilled holes centered above the 6 key buttons, and mounted some rubber push buttons cut from an old TV remote control. This gives the keys a very comfortable, tactile feel.

I found a metal case to mount the Arduino MEGA. The case was a bit tight (**Figure 7**) once I mounted the board with the circuitry, beeper, serial interface and internal wiring, but it was quite manageable. The boards are removable for maintenance.

If you decide to use a non-conductive case, make sure you line the inside with copper or aluminum tape and ground it to the system. This helps prevent noise from the Arduino getting into your receiver.

I was concerned about heat buildup in the box that houses the Arduino, so I mounted a very small — about 1" diameter — 5 V fan on the back of the case, and drilled exhaust holes in the top and bottom of the front. I also added a 10 kΩ thermistor to measure the internal case temperature, see **Figure 8**. An analog input measures the voltage across the thermistor for a temperature measurement. I set a pulse width modulation (PWM) output to drive the fan at different speeds. The fan, it turns out, was unnecessary. The only time it has come on was during my testing phase, when I gently warmed up the case with a heat gun.

I also added a line from the thermistor inside the amplifier to another analog input on the Arduino, and put a 20 kΩ resistor in series with the line to the Arduino analog input to keep from loading the thermistor circuit. The added resistor would not affect the readings appreciably, since the input impedance on the Arduino analog input is quite high. I was able to use the same software routines to read the thermistor for the Arduino temperature and the amplifier heat sink because both were setup with the thermistor connected to ground. I used an external digital thermometer to calibrate the thermistor readings.

Figure 6 — The display housing.

Figure 7 — Internal view of the Arduino housing.

Arduino I/O Circuits

Never put more than 5 V on any of the Arduino input or output pins. I used an opto-isolator for each of the LPF band switch relays, along with an NPN transistor to ensure I had enough current to drive the pair of relays on the LPF board, see **Figure 9**. Similarly, I used opto-isolators to drive the 12 V outputs from the amplifier to the Arduino inputs for the *Transmit*, *SWR Failure*, and *Over-Temperature* indications. During my design phase, this seemed like a good safety measure, but after re-evaluating the system, I didn't end up with full isolation between the amplifier and the Arduino. This led me to believe many of these opto-isolators were not necessary. The only exception would be turning on the 12 V to the *Bypass* switch, where the pull-up resistor to the PNP resistor would put 12 V on the Arduino pin when not enabled.

The actual amplifier front panel switches are left in the unpowered positions, the band-switch in the *Auto/160 m*, power switch to *Off* and Operate/Bypass switch in *Bypass* position. This allows the Arduino to control these functions, otherwise the system can also be run manually if the Arduino is disconnected.

There are essentially four different types of circuits used to interface between the amplifier and the Arduino. All of these circuits must limit the voltage to 5 V on any of the Arduino pins.

The LPF circuit board has five 12 V relays to enable the six band filter segments. The 160-meter segment is enabled whenever none of the other segments is enabled. The common side for all relays is tied to +12 V and the negative side of each relay must be switched to ground to enable the band segments. The relay must have a snubber

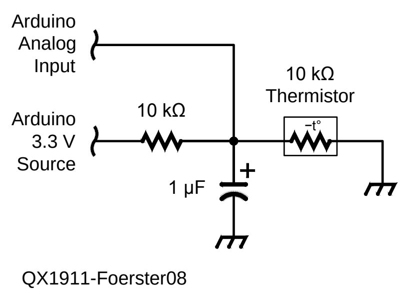

Figure 8 — Thermistor circuit.

diode across it (seen in Figure 9) to prevent damage to the transistor. This is a normal part of the relay circuit on the LPF board for each of the five relays. Because only one relay will be enabled at a time, all five relay driver circuits can share a single pull-up resistor.

Any digital inputs (**Figure 10**) from the amplifier — *Transmit*, *SWR Fail*, and *Over-Temperature* — can be sent to the Arduino through a pair of resistors as a voltage divider to limit the input to less than about 4 V to be safe. The minimum input voltage for an Arduino is about 2.4 V.

A 5 V source (**Figure 11**) to enable the SSR, or enable the *Operate* mode to the amplifier can be accomplished by providing a low signal from the Arduino pin to the base of a PNP transistor, through a 1.5 kΩ

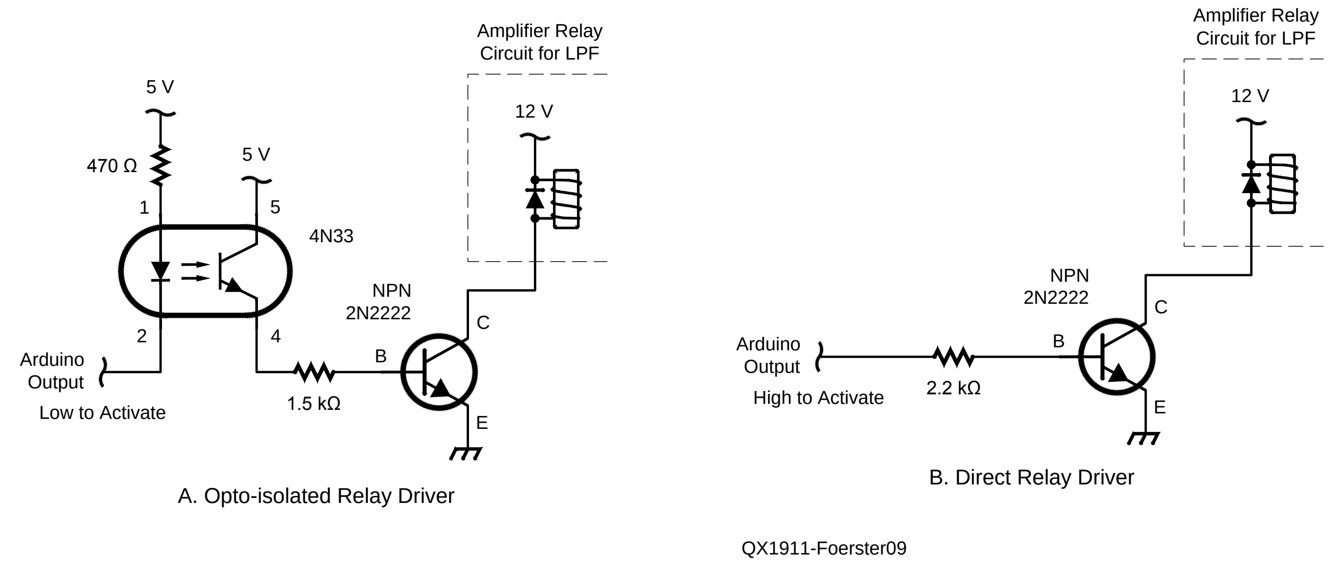

Figure 9 — Connections between the Arduino and relay driver: (A) with opto-isolator, and (B) direct.

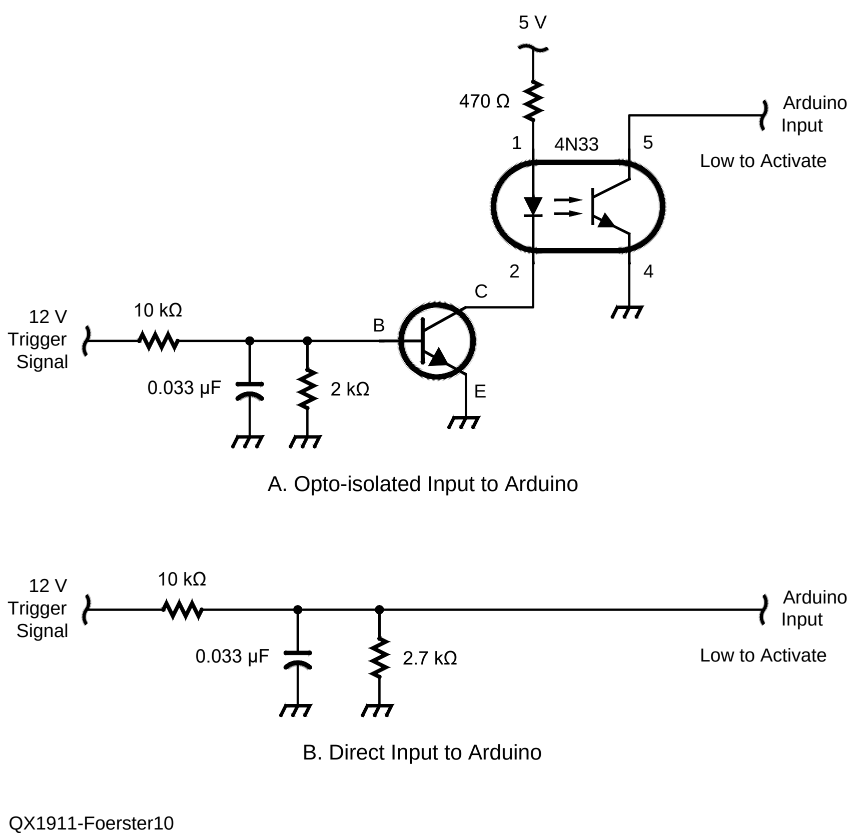

Figure 10 — Arduino digital input circuit: (A) with opto-isolator, and (B) direct connection.

resistor. The emitter of the PNP is tied to the positive voltage, either 5 or 12 V, and brought low to enable a positive voltage to the collector to turn on the output of the circuit. A special circuit may be required to ensure that switching 12 V does not reach the Arduino input.

Figure 12 shows how the 50 V supply voltage is connected from the amplifier to the Arduino to be measured using the analog inputs. To limit this voltage to no more than 5 V, it is prudent to add a Zener diode to limit the voltage to less than 5 V. I used 4.7-V Zener diodes across each input to make sure the voltage cannot go above 5 V. As for the 50 V input, the voltage from the supply should be limited to around 4 V for the 50 V reading. This allows headroom for the voltage to rise above that value, indicating a high voltage failure. Each analog input should also have a small 100 µH choke to limit any RF signal from affecting the inputs.

Serial Communications

The biggest challenge I faced was getting the communication to the radios to work reliably. The lesson I learned was that the inexpensive MAX3232 boards available on eBay are very prone to oscillation, drawing in excessive of 200 mA and with very intermittent behavior. I finally ordered real Maxtor MAX3232 devices from a US online provider and replaced the chips on the small boards. Communications have since worked flawlessly.

While trouble shooting this problem, I used an old trick to measure the current without having to break the circuit. Place a diode capable of supporting the circuit current in series with the positive power input (**Figure 13**). You can then measure the current through the circuit at any time by placing your DVM current meter across the diode. The current meter has a much lower voltage drop than the diode, allowing you to accurately measure the current to the circuit without actually interrupting the current flow to the circuit.

Forward and Reflected Power Indications

I opted for a cross-needle power indication for the forward and reflected power. In retrospect I should have purchased LED metering. Typical SWR boards have negative voltage outputs, but metering and input to the Arduino requires a positive voltage. As it turns out, the LED meters that Jim had available have an op-amp that converts the negative voltage to a positive voltage with no negative supply required. I got boards from Jim with the op-amps but with out the LEDs. Considering that the metering isn't intended to be exact, the LED meters would have been just fine for the amplifier. When using the op-amp driver, make sure that the voltage to the Arduino analog inputs can never exceed 5 V. As with other analog inputs, I added a 4.7 V Zener diode across the op-amp output.

Arduino Code

I won't go into a great deal of detail of coding the Arduino, but there are a few concepts worth pointing out. My project was designed for my Elecraft radios, but the commands for other radios will be very similar. You need just a few basic commands such as reading the operating frequency, reading and setting the radio power output, and turning the radio off.

The Arduino first has a *setup()* routine, which defines all of the input and output pins and executes only once during startup. This is followed by the *loop()* code, which is executed from the top to the bottom, and then

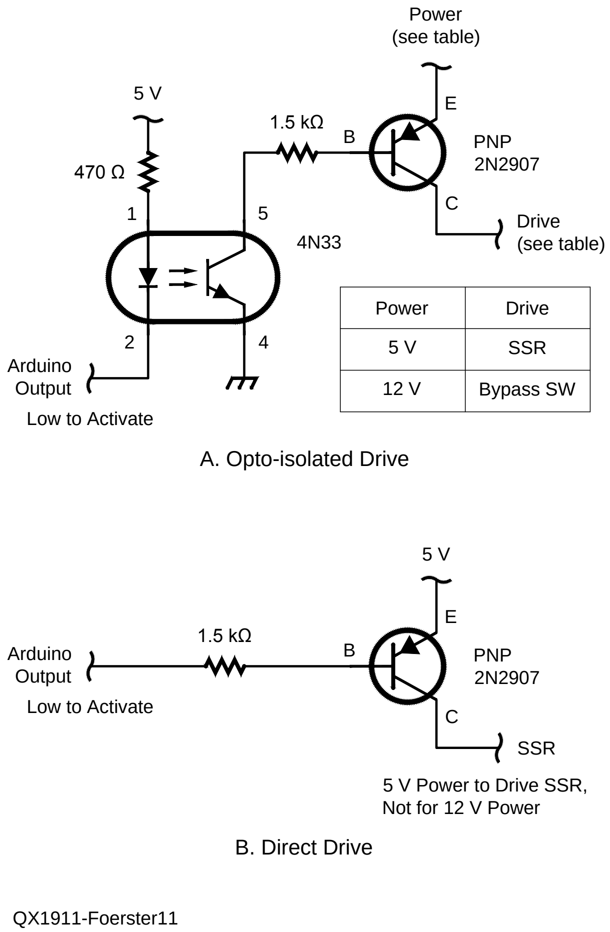

Figure 11 — The 5 V drive to the solid state relay: (A) with opto-isolator, and (B) direct connection.

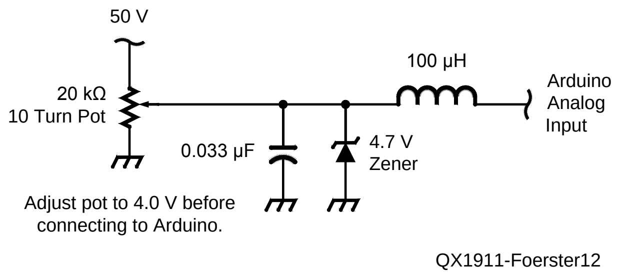

Figure 12 — Reading the 50 V signal without exceeding the Arduino 5 V limit.

repeated constantly. On this project I learned to use the tabs in the Arduino development environment to divide up all of the code into different subject pages. Creating a tab is quite simple. Click on the down arrow button on the upper right side of the Arduino development environment, and click "New Tab". This allowed me to split up the code into different logical files, which makes developing and debugging much easier to understand. All of the declarations, *setup()* and *loop()* are in one file. The other files are: *Analog, Band, Buttons (keys), Display, Eeprom, Morse, PowerUpDown, RigComms, Timeout, Subs* (State Subroutines from main loop).

If you want to view the code I have written, download the Arduino Integrated Development Environment (IDE) **[3]**. Then download my code files from the **www.arrl.org/QEXfiles** web page into a directory named "*LDMOS-Amp-IF*". Double click any of the files in that directory. All of the files should open at once, the main "*LDMOS-Amp-IF*" file starts on the left. The rest are in alphabetical order.

You will also need the Adafruit display driver to compile the project. Download the *Sketch/Include Library/Add.ZIP Libarary* **[4]** and install it in your Arduino environment. You will also need to set the "*Tools/Board*" menu to "*Arduino Mega*".

State Machine Flow

I set up the code flow as a "state machine" (see **www.arrl.org/QEXfiles**), which defines a number of different states, or modes, that are named using easy to understand *NAMES* within the code. Each state is a very clearly defined name. The states change when the user presses the pre-defined keys or from the digital inputs from the amplifier such as "*Transmit*", "*SWR Fail*" or "*High-Temp*". This makes it very easy for the programmer developing the code to keep track of the operations within each state for not only the main loop but also for the key button or the display routines.

The Arduino will execute a loop roughly every 200 ms when running in most modes, other than *ModeOff* and some of the start-up and shut-down routines. As long as you know and understand the modes, it's very easy to figure out the key (button) actions.

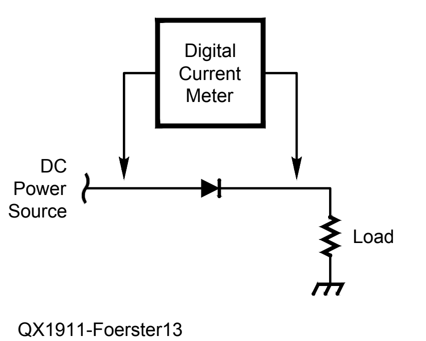

Figure 13 — Current measurement solution that doesn't require breaking a connection.

Key Actions:

- From ModeOff, Press Select key, proceeds to ModePowerTurnedOn
- From ModeReceive, press of Select key cycles to ModeSetupBandPower (Start of Setup Mode)
  – Up Key increases power by 1 W to a 12 W maximum
  – Down Key decreases power by 1 W to a 1 W minimum
  – Right Key changes band up (80 m to 40 m, etc.)
  – Left Key changes band down
- From ModeSetupBandPower, press Select key cycles to ModeSetupTimeout
  – Up Key increases time by 1 hour to a 9 hour maximum
  – Down Key decreases time by 1 hour to a 1 hour minimum
- From the ModeSetupTimeout, press Select key cycles to ModeSetupBypOper
  – Up key sets mode after band change to Operate mode
  – Down key sets mode after band change to Bypass mode
- From ModeSetupBypOper, press Select key cycles back to ModeReceive
- From ModeReceive, pressing the right key will reset the timeout timer
- From ModeReceive, pressing the Left key will repeat the last Morse error code
- From ModeReceive, a 3 second press of the Select Key turns system off and change to ModeOff
- During Power down routine, pressing the Left key will prevent the radio from being powered off.

The display actions are setup similarly, see **Figure 14**. Knowing what state the code is in makes it easy to define what is shown on the display for each mode.

In some of my early code testing, I found that the system would occasionally attempt to change bands while I was transmitting. It didn't take long to figure out that I needed to inhibit any band changes during transmit, when the RF signal could affect the circuits. The routine to check the radio frequency is executed about every two seconds. The fix was to simply keep resetting the timer for this routine constantly during transmit. Therefore, the check for band change was never executed until at least two seconds after the transmit cycle was completed. Anytime a band change is detected, it's always wise to wait a short period of time (100 ms) and then recheck the change, to be certain there was not an invalid change momentarily detected. I felt it was also important to put the amplifier in *Bypass* mode during the band changeover period.

Figure 14 — Display progression.

System Test Procedure

Before I retired I was a software test engineer. I wrote formal test procedures and executed them for the projects on which I worked. Back then, most of the testing was done using test automation software. True to my past experience, I wrote and executed a test procedure, but executed it manually. I've actually executed the tests a number of times as I made changes to the code. I did find bugs in my code and problems with the hardware as a result of the testing, and even found some new enhancements to add to the system. I discovered I wasn't sending an adequate error message, should the system not preset the power in the radio, or disable the K3 internal power amplifier. At this point I also added commands to turn off the radio, as well as the amplifier. The test procedure, see the **QEXfiles** web page, is also nice to execute after making a number of code changes to make sure everything is still operating as intended.

You need to pay very close attention to any failure modes that are possible with the system, things like if the frequency reading is invalid, or if the writes to the rig power or tune output fail. After each write to change the rig power, you should verify that the setting was successfully initiated. Any failure of these functions must cause the system to go into Bypass mode, preventing possible amplifier action that could damage the amplifier by overdriving the input. It is wise to check the loop time for the different modes often. You may find some of your routines take too long to execute, and timing may need to be adjusted to compensate.

Code Reviews

One of the other habits I retain from my professional days is to review my code. Through the reviews, I've added many comments and modifications to the code to make it more readable and cleaner, besides fixing a number of bugs. I have even asked my son, Tony Foerster, KEØPXK, to review my code. It helps to have another eye on the code to keep you from developing bad habits, and spotting things you may take for granted.

Simplified Design Considerations

In this project I've added a lot of functionality that may not be necessary for everyone, such as controlling radio power output, system power timeout, mode change to bypass, turning the rig off, and so on. Other designers may choose to include a 13 dB attenuator to allow a 100 W input, and therefore controlling the power may not be necessary to prevent overdriving the amplifier.

A much simplified version of the controller could be built to read the band data either by the Comms or BCD band outputs (Elecraft or Yaesu) or even reading the analog pin for an Icom radio to select the band for band switching. You could consider adding an Arduino NANO to simply follow your radio band changes to change the band on the amplifier. This could be done without a display.

Another thought would be to mount the display on the front panel of the amplifier itself. A good RF shield would be necessary to prevent the amplifier RF from affecting the Arduino, and to keep noise from the circuits from generating birdies in your receiver.

Future Plans

When I started this project, I had envisioned a touch-screen display to operate the amplifier interface. However, I wasn't comfortable learning to code the graphical display. Since I was quite familiar with the 2-line, 16-character displays, I decided to use it for the initial build. In thinking about this upgrade, I may try using an Arduino NANO internal to the amplifier with just a serial communication line coming out of the amplifier and going to another Arduino, which would drive the touch-screen display. The connection between these two could be a serial communications port to pass the information required between the two. The communications to the rig would be maintained out of the external Arduino device.

Another future project is to allow this amplifier to emulate the KPA500 serial communications commands from the Arduino to allow it to be used with remote control. The challenge is not with the amplifier commands, but rather allowing the radio to communicate with both the Arduino and the remote control access software through a single port on the radio.

ARRL member Michael Foerster, WØIH, holds an Amateur Extra Class license and has been continuously licensed since he received his first license, WNØVNH, in 1968, then several months later as WAØVNH. He has worked as an electronics technician, and moved into software testing about 25 years ago. Michael retired in 2015 and enjoys experimenting with ham radio, remote radio control, Arduinos and antennas. He also spends part of his summers on a 28-foot sailboat. His amateur station includes the Elecraft K3S, P3, KPA500, along with a KX3 portable radio and vintage Heathkit SB-101, HW-101 and SB-221 equipment.

Notes

[1] J. Klitzing, W6PQL, web page: **www.w6pql.com/**

[2] P. Salas, AD5X, "Amplifier Overshoot-Drive Protection", *QEX*, Sep./Oct., 2018, pp. 15-16.

[3] Arduino Development Environment: **https://www.arduino.cc/en/Main/Software**

[4] Adafruit Display/Keyboard Driver available at: **https://github.com/adafruit/Adafruit-RGB-LCD-Shield-Library**

Robert Andre, KEØEXE

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Tree Branch Gadget

Hang light-weight antennas securely on small tree limbs with this gadget.

I'm an avid climber of trees. "Pruning work" provides a handy excuse to hang antenna anchors and generally satisfy my inner-boy. Still, one branch on an ash in my backyard had been eluding my pulley-lanyard conquest. At 40 feet, it forms a ceiling with nothing below. It's a good site for a vertical tow-line — otherwise known as an "antenna test site" — but the branch is too small to climb, too high for my ladder, and crowded by offshoots that would interfere with a thrown or "shot-up" line. The only practical technique was to climb what I could on the main limb, and secure myself in a mammoth Y, at a mere 17 feet above the ground. With both hands free, I could then use a 26-foot extension pole to reach the branch. I would raise and drop over it some manner of rigid hook.

Designing the Hook

I set about designing both the pole and the hook. The extra-long pole terminated in an elaborate, string-controlled, hand clamp. Truth be told, it was barely adequate for the job, so I'll skip its details! Suffice to say that I managed to use the pole effectively, via sufficient perspiration.

The U-hook, however, was quite a rewarding invention. I imagined that some sort of lock feature could be designed into the device, to prevent its dislodgement in high winds. It also must be non-metallic, strong, and lightweight for lifting and to cause minimal damage to the tree branch over time. I chose straight, ½-inch PVC electrical con-

Figure 1 — The tree branch gadget in the unlocked position.

Figure 2 — The tree branch gadget in the locked position.

Figure 3 — The tree branch gadget in place and locked, ready for hoisting an antenna with the cords.

Figure 4 — The tree branch gadget locked in place and supporting a 2-m band quarter-wavelength vertical antenna.

duit, which is elastic, UV-resistant, and can be reformed upon heating. Such a device eliminates the need for a metal pulley, because the tow-line is simply fed through the full length of the conduit, right around the branch.

Construction

Figure 1 shows the tree-branch gadget in the unlocked position, and **Figure 2** shows it in the locked position. Forming the bends in a 5-foot piece of PVC conduit involved several steps. First, I table-sawed a lengthwise slit into a same-length piece of polyethylene water pipe. This allowed the pipe diameter to be compressed slightly, so it could be slid completely inside the PVC conduit. This extra inner support would prevent the softened conduit wall from collapsing as it was being heated and reformed into the two curves seen in Figure 1. I cut this inner pipe into two sections, so I could rotate the slits to align along the outer radius of each curve. This prevents the cord, once installed, from being pulled into a slit. I used a heat gun to thoroughly warm the PVC conduit along the arc regions.

A T-style junction box, a gently-curved elbow, and three end caps complete the list of parts to be cemented together. Small drilled holes allowed the paracord to pass through two of the end caps. The cord was easily vacuum-sucked through the entire gadget, after all the cement had cured.

The splicing knot in the two 50-foot $\frac{3}{16}$"-diameter cords at the junction-box end prevents accidental pull-through, but in one direction only. When not in use, I keep the free lines tied-off, for obvious reasons!

Installing the Gadget

After a fun day of building, I successfully installed the device on the noted branch with help from a neighbor. The locking mechanism worked beautifully. I pulled on one cord from my position in the tree, while my friend pulled on the other, at a considerable angle, from his own backyard. We quickly achieved the satisfying "click" as the springy pipe snapped around the elbow piece into its cradle.

Figure 3 shows the gadget locked in place on a tree branch with the cords ready to hoist a vertical antenna. **Figure 4** shows the gadget in place supporting a quarter-wavelength copper vertical antenna.

Unlocking is accomplished by similar creative pulling on the cords. When raising my first antenna, I noticed considerable drag, unlike a pulley, so I hoisted it slowly. Patience is a small price to pay for success!

Robert Andre, KEØEXE, earned his BSEE degree, and has 20 years experience developing computer power, storage, and operating sub-systems. A life-long interest in radio electronics encouraged early-on by two hams — one an uncle and the other a brother of a boyhood friend — propelled him to achieve the General Class license in 2015 and Amateur Extra class license in 2019. Current special interests include developing his skill with Morse Code (often writing and using novel computer programs), assembling a proper station and antennas, and eventually building and operating vacuum-tube low-power rigs powered by batteries made from a great many "rescued" partially-spent AA cells.

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RF Work Bench

Test home-built projects with this versatile set of instruments.

RF integrated circuits have come a long way in recent years, adding frequency response unheard of 5 to 10 years ago. Advances in analog and digital technology have made it possible to achieve frequency responses from 50 MHz to 6 GHz in a single integrated circuit. Simple circuit boards incorporating these ICs are now available that can perform all of the functions found in older complete instruments. The RF Work Bench presented here incorporates some of these circuit boards and is a very useful instrument for stimulus response testing of home built RF projects, commercial equipment or instruments.

Figure 1 — RF Work Bench.

Description

In this RF Work Bench you will find some of the most useful RF instruments packaged into a single relatively small box costing about $250, see **Figure 1**. It contains a VCO, RF Power Meter, two 20 dB RF Amplifiers, two Digital Attenuators and a Directional Coupler. All RF inputs and outputs use SMA connectors. Before these integrated circuits became available, each one of them would have been a separate instrument, as big as or bigger than the box shown here. This unit is battery operated using rechargeable Lithium batteries. The box also contains a battery management circuit that tells you when it needs to be charged and when the charge is complete. The battery life should be about 3 hours before requiring a recharge.

VCO

This VCO uses an ADF4351 integrated circuit to provide an RF Sweep Generator with a touch screen LCD. The output frequency range is 35 MHz to 4.4 GHz. See **Figure 2**. It has an adjustable output level of +5 dBm, +2 dBm, -1 dBm, and -4 dBm. Since this frequency range is digitally synthesized, the output is a pseudo square

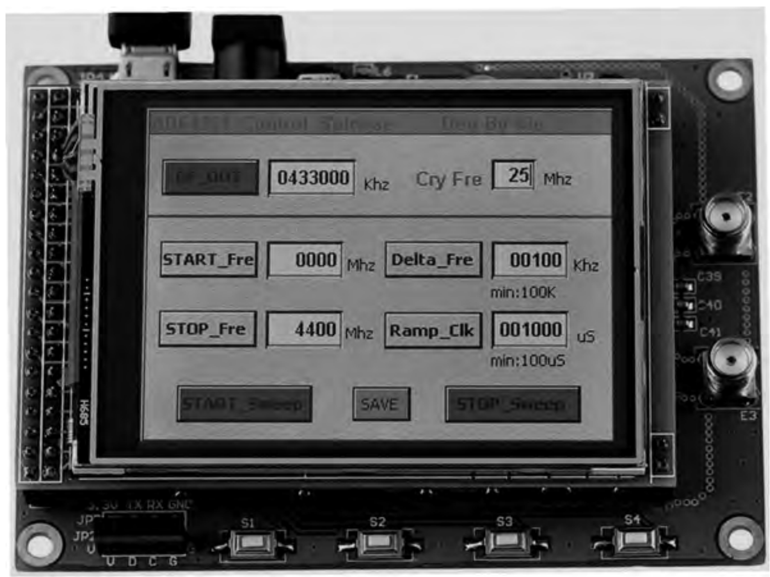


Figure 2 — RF Sweep Signal Generator.

wave. This yields a fundamental with a high 2nd harmonic. The VCO core in the ADF4351 consists of three separate VCOs. Each VCO uses 16 overlapping bands, shown in **Figure 3**, VTUNE vs. frequency, to allow a wide frequency range without a large VCO sensitivity (KV), which would have resulted in poor phase noise and spurious performance. The correct VCO and band (1 of 16), are selected automatically by the ADF4351 and band select logic.

The sweep function does not have a synchronized start sweep output or a dc sweep output, which makes the sweep function nearly useless, unless you have a spectrum analyzer. However, it does sweep up and then down in frequency. It does not use a dc voltage sweep on the VCO. It uses a frequency hopping technique, where a microcontroller sends each new frequency to the ADF4351 through the serial digital interface. The user can set the minimum frequency, maximum frequency, step (Delta) frequency and the step time (Ramp Clock). There are four Key functions: {1} FSK (fastest processing signal 10 ms); {2} Switch RF output; {3} Keyed sweep (single sweep); {4} Sweep control (cyclic sweep). I have not had much luck with some of these controls, except for the function {2} RF switch, which works great.

RF Power Meter

The core of the Power Meter is an AD8318, which is a demodulating logarithmic amplifier capable of accurately converting an RF input signal to a corresponding decibel-scaled output voltage. It employs the progressive compression technique over a cascaded amplifier chain; each amplifier stage is equipped with a detector cell. The AD8318 maintains accurate log conformance for signals from 1 MHz to 6 GHz and provides useful operation to 8 GHz. The input dynamic range is typically 60 dB (referenced to 50 Ω) with error less than ±1 dB. The AD8318 has a 10 ns response time that enables RF burst detection to beyond 45 MHz. The AD8318 RF Power Meter is shown in **Figure 4**.

For linearity correction, the user can set the frequency under test of the Power Meter. When using the RF Power Meter, be careful not to exceed 0 dBm at the input or a slight distortion in power level will occur. Damage will occur above +12 dBm.

The power meter amplifier uses the other half of an LMC6482 op amp. This amplifier

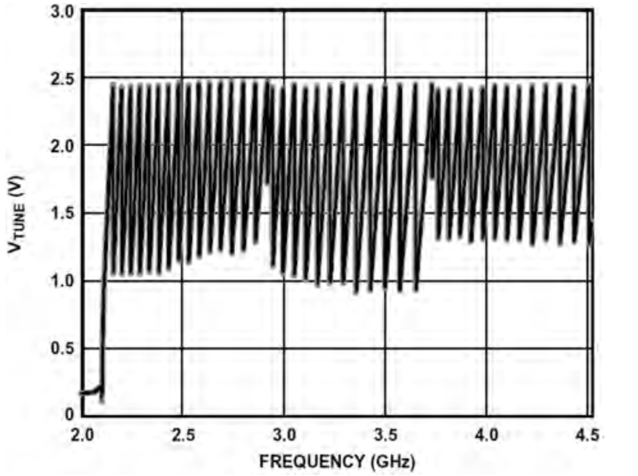


Figure 3 — VTUNE vs. frequency.

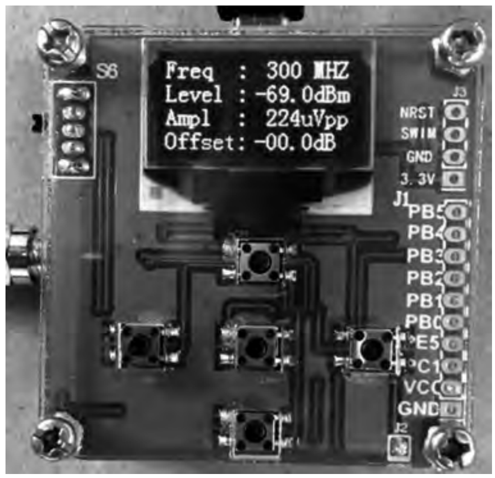


Figure 4 — AD8318 RF power meter.

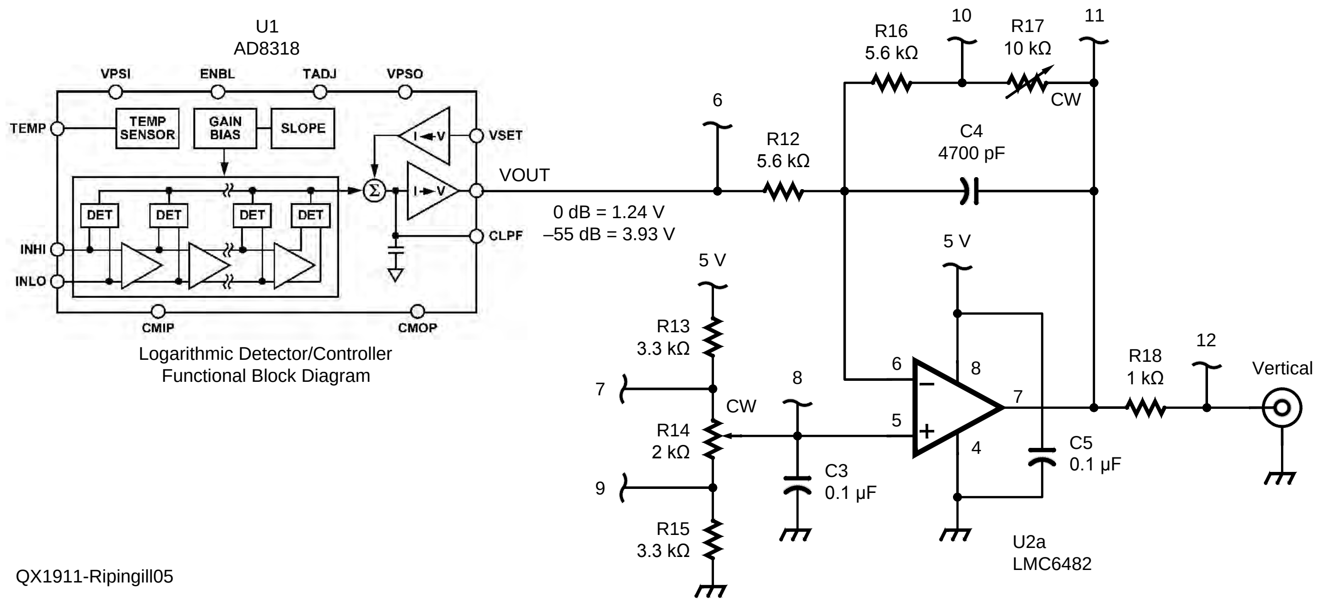


Figure 5 — AD8318 RF power meter amplifier.

allows the user to observe a changing dc voltage representation of the power level. The peak-to-peak level and offset voltage is adjustable. The dynamic range of the dc output voltage for the Power Meter is upside down. So the op amp inverts the signal and provides gain and offset to improve the resolution of the measured voltage coming out of the AD8318, see **Figure 5**. Components list is in **Table 1**.

RF Amplifier

The RF Amplifier uses a SBB5089Z high performance InGaP HBT MMIC amplifier utilizing a Darlington configuration with an

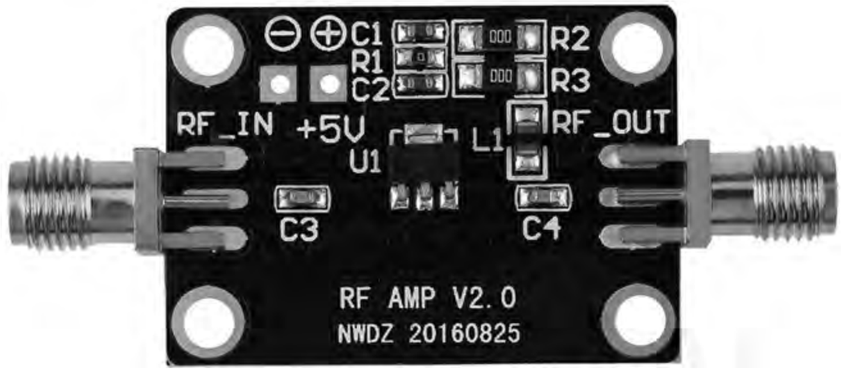


Figure 6 — RF amplifier SBB5089Z.

Table 1. RF Work Bench Components.

Most components available from Amazon or eBay.

B1	Two 3.7 V cells, #18650, 1100 mAh
C1 - 3, C5	Capacitor, 0.1 µF
C4	Capacitor, 4700 pF
D1	Diode, 1N4001
D2, D3	Diode, 1N4148
D4	Diode, MBD701
D5	Blue LED
D6	Red LED
Q1, Q3	Transistor 2N4124
Q2	Transistor 2N4126
R1, R6, R10	Resistor 1/4W 4.7 kΩ
R2, R7, R11	Resistor 1/4W 20 kΩ
R3	Resistor 1/4W 2 MΩ
R4, R5	Resistor 1/4W 1 MΩ
R8, R9	Resistor 1/4W 2 kΩ
R12, R16	Resistor 1/4W 5.6 kΩ
R13, R15	Resistor 1/4W 3.3 kΩ
R14	variable resistor, 2 kΩ
R17	variable resistor 10 kΩ
R18	Resistor 1/4W 1 kΩ
R19-R22	Resistors 100 Ω
S1-S12	SPDT, 2 Position On-On Toggle Switch
S13	SPST switch
U1	AD8318, 1-8000 MHz OLED RF Power Meter
U2	LMC6482IM CMOS Dual Rail-To-Rail Op AMP
U3-U6	AMS1117-5.0, 5.0 v Linear Regulator Module
U7-U10	AMS1117-3.3, 3.3 v Linear Regulator Module
U11	DC-DC Buck Step-down Regulator Converter
Z1	ADF4351, RF Sweep Signal Source Generator Module 35M-4.4G
Z2, Z3	PE4302 Numerical Control RF Attenuator Module 1 MHz-4 GHz
Z4, Z5	SBB5089Z RF Amplifier Board, LNA, DC5V 0.05-6 GHz 20 dB
Z6	RF SWR Reflection Bridge 0.1-3000 MHz, transverters-store.com/rf_bridge/rf_bridge.html
misc.	(14) Adapter SMA Female to Jack Nut Panel Mount Straight Connector
misc.	Electronic Project Box Waterproof, 230 x 150 x 85 mm/9 x 5.9 x 3.3 inch
misc.	(2) SMA RF Coaxial Termination 50 Ω, 2W, 6.0 GHz
misc.	(14) 6.5” SMA Male to SMA Male Cable
misc.	(6) 12” SMA Male to SMA Male Cable
misc.	18650 2x, 3.7 V Battery Holder w/wire leads
misc.	Power connector 5.5 mm X 2.1 mm Jack Socket, Panel Mount
misc.	12 V dc Output ac Adapter Power Supply 1 A Wall Wart Center-positive, female plug
misc.	5.5 mm x 2.1 mm
misc.	14 Socket/Plug
misc.	(12) Fair-Rite impedance beads #2661000101, 61 Material

active bias network. The active bias network provides stable current over temperature and process variations, see **Figure 6**. The SBB5089Z product was designed for high linearity 5 V gain block applications that require small size and minimum external components. It is internally matched to 50 Ω with a gain of 20 dB and a frequency range of 50 MHz to 6 GHz.

Digital Attenuator

The Digital Attenuator uses a PE4302 for a high linearity 6-bit RF Digital Step Attenuator (DSA) covering a 31.5 dB attenuation range in 0.5 dB steps (**Figure 7**), PE4302 Digital Attenuator. This 50 Ω RF DSA provides a parallel control interface, operates on a single 3 V supply and maintains high attenuation accuracy over frequency and temperature. The PE4302 has an insertion loss of 1.5 dB with low power consumption. It has a maximum input of 34 dBm from 1 MHz to 4 GHz. The PE4302 will operate from dc to 4 GHz but the circuit board is capacitively coupled, which limits the minimum frequency to 1 MHz.

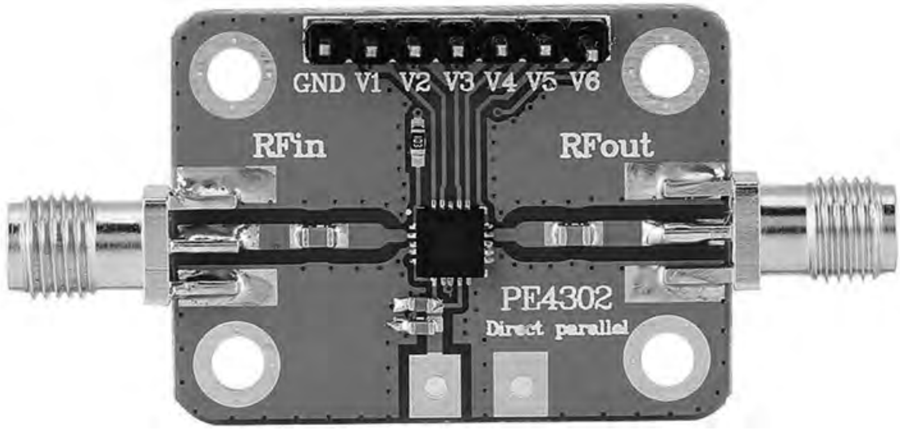


Figure 7 — PE4302 digital attenuator.

Directional Coupler

With this RF directional coupler board, you can measure through-mode filters, amplifiers, reflective mode antennas, impedances, inductance, capacitance and impedance matching and much more, see **Figure 8**. This RF directional coupler bridge is used for measuring the match of devices up to 1 GHz. The bridge can be used for reliable measurements up to 3 GHz.

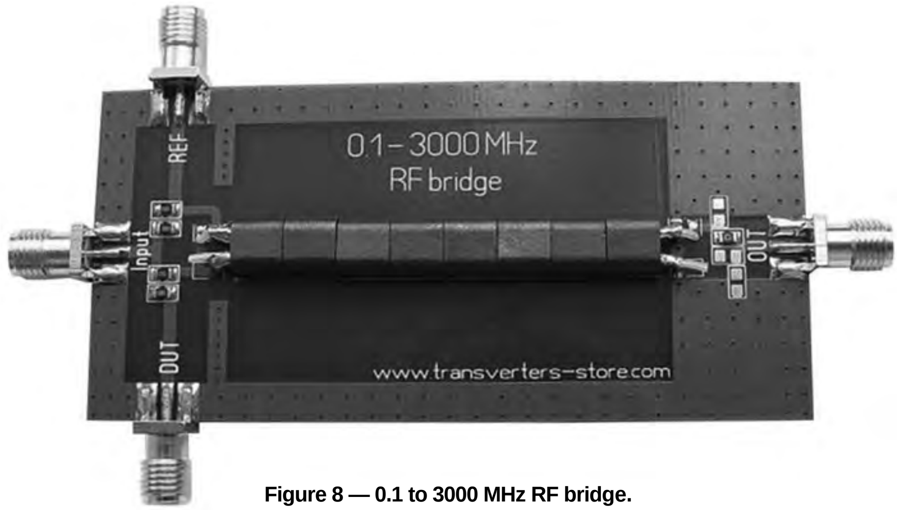


Figure 8 — 0.1 to 3000 MHz RF bridge.

Battery Management (Amplifier Board)

The battery monitor (**Figure 9** see components list in Table 1) uses half of a dual LMC6482 op amp to detect battery voltage when it is below 6.6 V (Recharge) and above 8.4 V (Charge Full). The battery monitor uses three regulators: {1} dc-to-dc converter with output set at 8.4 V, the maximum charge voltage for the two Li-Ion 18650 batteries connected in series; {2} A 5 V AMS1117-5.0 linear regulator is used to power the amplifier board; {3} a 3.3 V AMS1117-3.3 linear regulator is used to set the reference voltage for threshold detection.

Block Diagram

The block diagram (**Figure 10**, components list is in Table 1) shows the power and ground distribution system and how all of the RF connectors are isolated from one another. Each device is connected to its own linear regulator and isolated with series resistors and ferrite beads (Fair-Rite type 61 material), with which suppresses approximately 250 MHz to 1 GHz. This helps isolate the ground system and makes sure the lowest impedance paths between RF devices are the SMA interconnecting cables. The linear regulators prevent crosstalk from one device to another.

Front Panel

Download the front panel artwork jpg file (**Figure 11**) from the **www.arrl.org/QEXfiles** web page and print it on good quality paper; I like to use parchment paper. Be sure to print actual size, do not "adjust to fit" print area.

First, apply one side of the Silhouette America Media Double Sided Adhesive 8.5" by 11" to the rear of the front panel artwork. Trim the edges to fit the front panel. Peel the backing off the back side of the front panel artwork and align over the box. I like to shine LED lights up through the holes to help in the alignment. At this point, I like to use Avery Clear Full-Sheet Labels #8665 and overlap the clear cover sheet over the artwork, so it goes over the sides of the box.

Then, using an X-Acto knife, cut out all of the holes and the squares for the displays.

Construction

First, print the RF work Bench Front Panel on regular paper, cut it down and tape it to the front of your plastic box. Using a sharp center punch, punch the center of each "circle x" and the inside of the corners of each window.

Next, drill small pilot holes at each punch mark. Measure the requirements for each hole and drill the appropriate holes with the correct drill size. Scribe the two window holes and use a coping saw to cut out the window holes. File the edges to smooth out the saw marks. Mount the front panel as shown in the front panel section above.

Next, mount the SMA bulkhead connectors (**Figure 12**) with the nuts on the inside of the box. Mount the SPST switches, BNC connectors and potentiometers. The "Recharge" and "Charge Full" LEDs will be hot-melt glued to the underside of the box.

The ADF4351 SMA connectors must be changed. "E2" is removed and a 51 Ω resistor is soldered from the center pin to one of the ground pins. The "E3" connector is mounted sidewise so as to not interfere with the front panel, as shown in **Figure 13**.

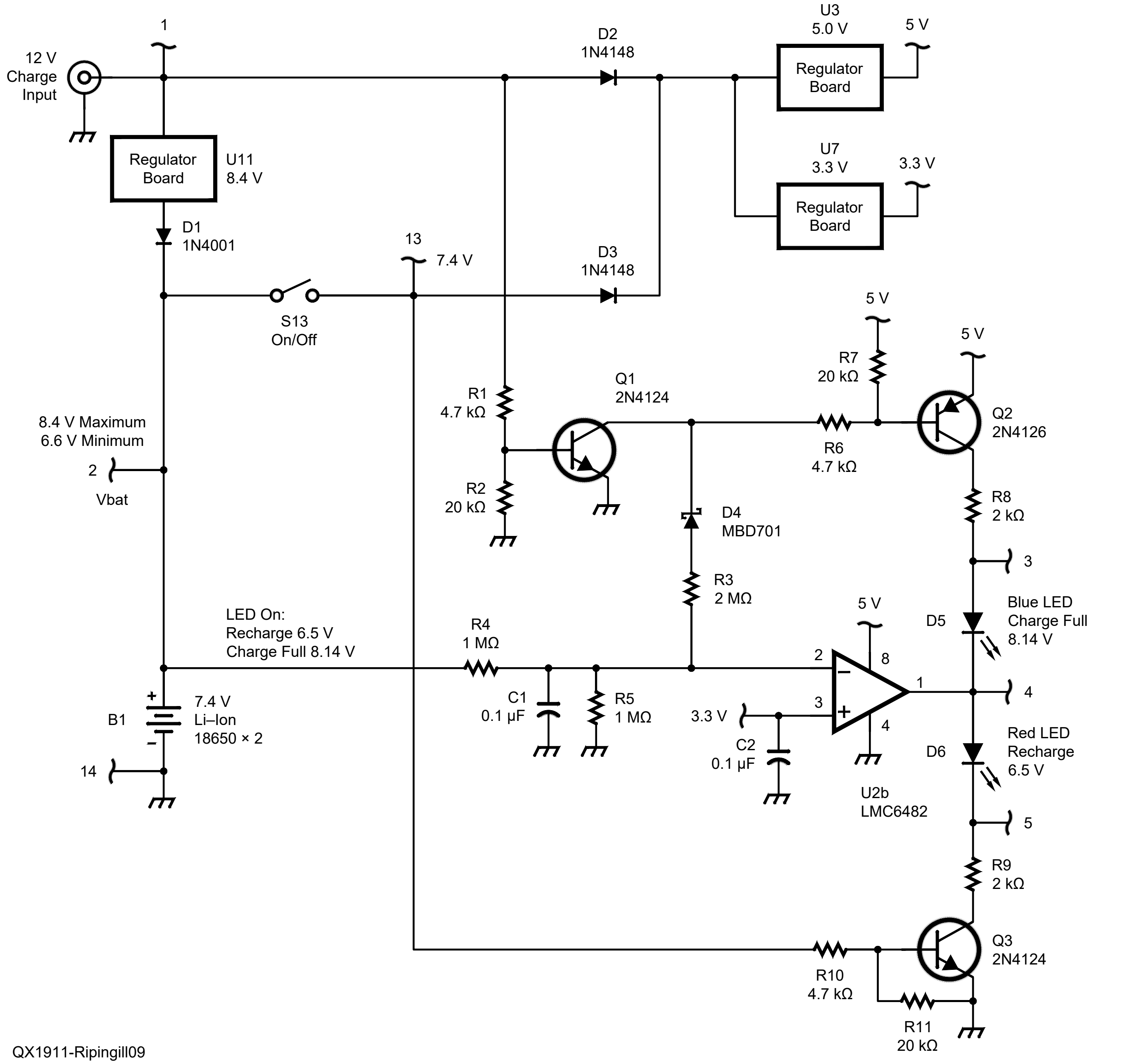


Figure 9 — Battery monitor.

Before mounting the ADF4351 circuit board, the pushbutton switch extensions must be fabricated, see **Figure 14**. These comprise a plastic dowel with a nut and washer glued on the lower end. The washer prevents the plastic dowel from popping out when the box is turned upside down. After placing the four switch extensions in the front panel, the ADF 4351 can be mounted to the front panel.

The AD8318 Power Meter must have a terminal soldered to J5, see **Figure 15**. It is connected to a wire that goes from the AD8318 to the Amplifier Board. This is used as the "Output in Volts" for the RF Power Meter. With this in place, the AD8318 Power Meter can be mounted to the front panel.

You are now ready to wire the front panel. I added two linear +5 V regulators to the front panel, one near the VCO and one near the Power Meter. Note the power leads from the regulator board to the device circuit board have ferrite beads on the ends. I used ribbon cable to connect from the front panel to the amplifier board, as shown on the right side in **Figure 16**. As you can see, I used liberal amounts of hot-melt glue to hold things in place and terminate the wires.

Do you want your masterpiece to last? Broken wires are a major cause of infant to middle age mortality of your home built circuit. To prevent these wires from breaking add a little hot-melt glue over both ends of the wire covering the insulation to the bare solder joint, as shown in Figure 16.

The Amplifier Board contains three regulators, thru hole components and an LMC6482 op amp along with three transistors. I used a 14-pin plug and socket to connect to the front panel. The construction is shown in **Figure 17**.

Mount the Amplifier Board in the box with the charge input connector and the Li-Ion 18650 batteries in the battery holder. I scored the box anywhere the hot-melt glue was used to mount the components, see **Figure 18**.

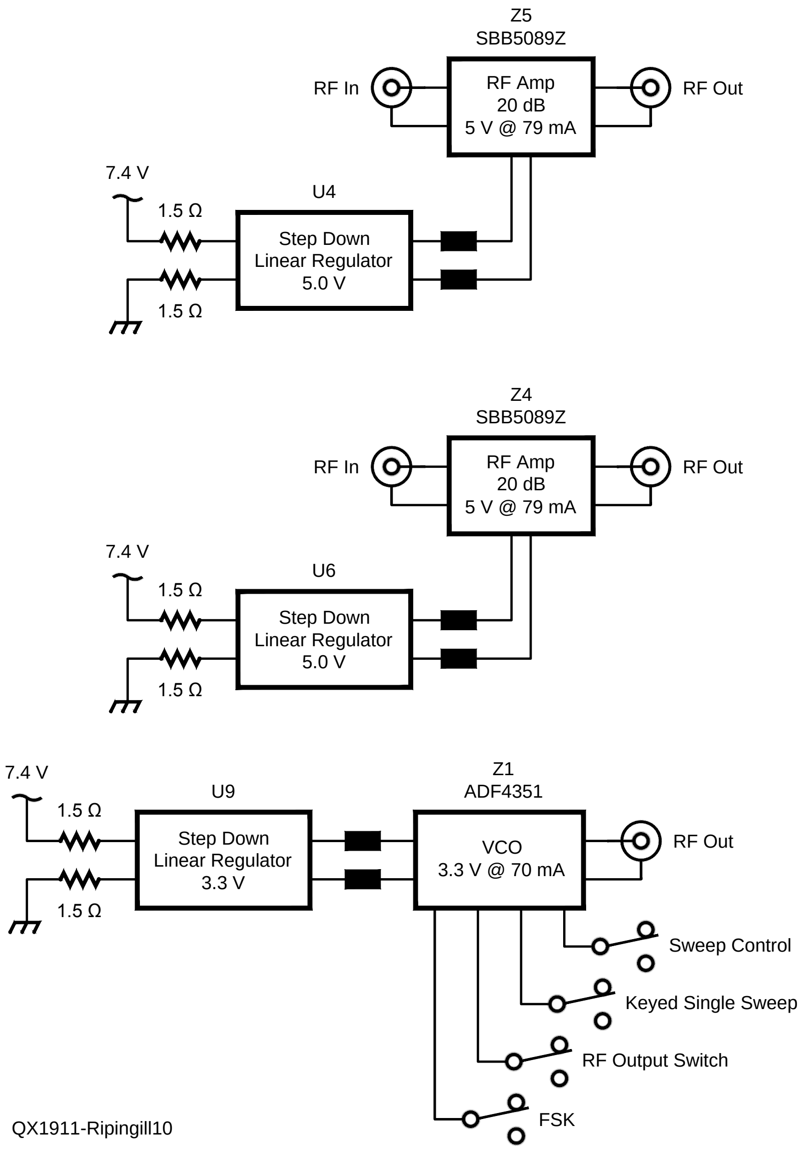
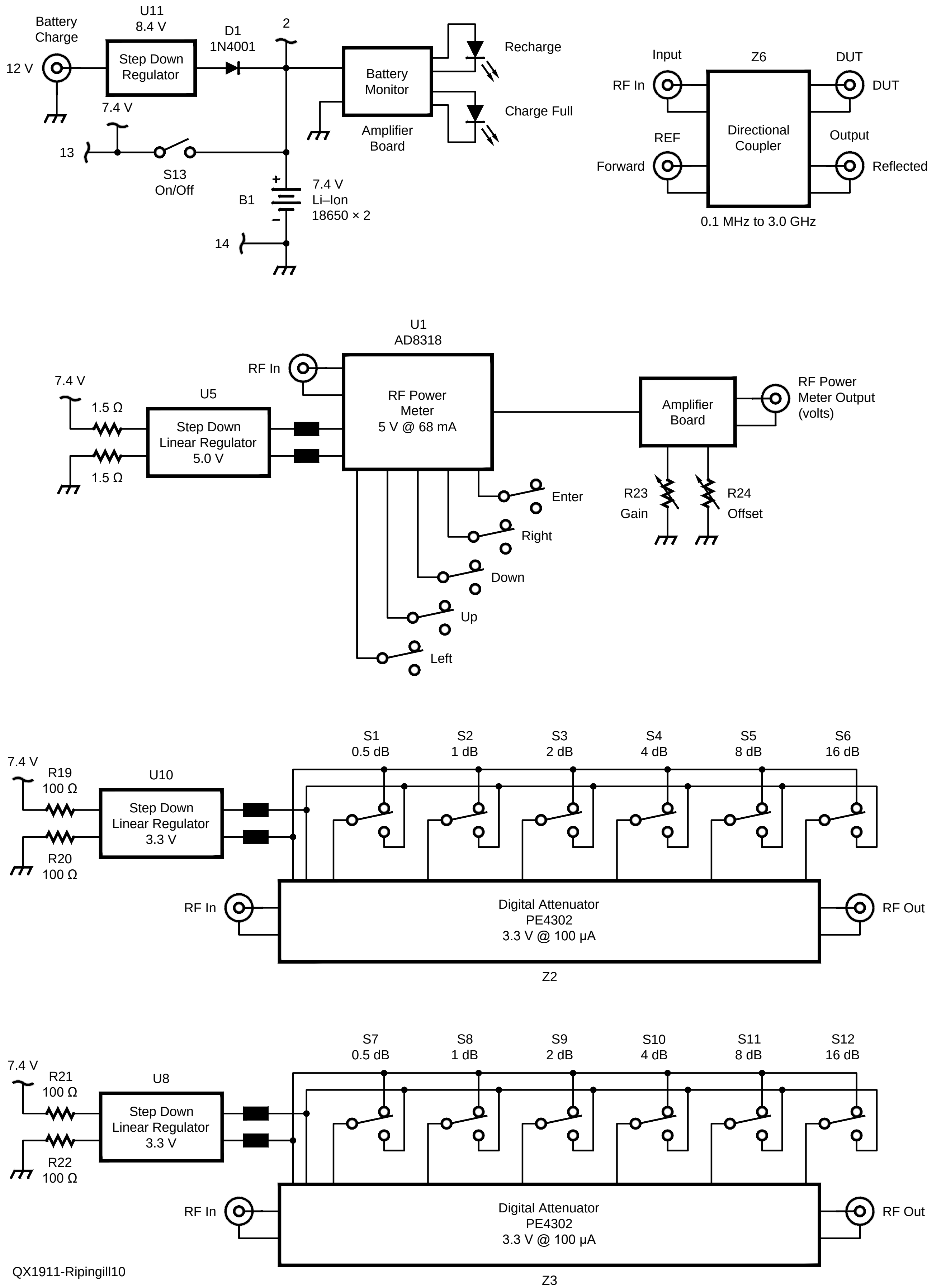


Figure 10 — RF Work Bench block diagram. The switches shown connected to Z1 represent push-buttons visible in Figure 15.



QX1911-Ripingill10

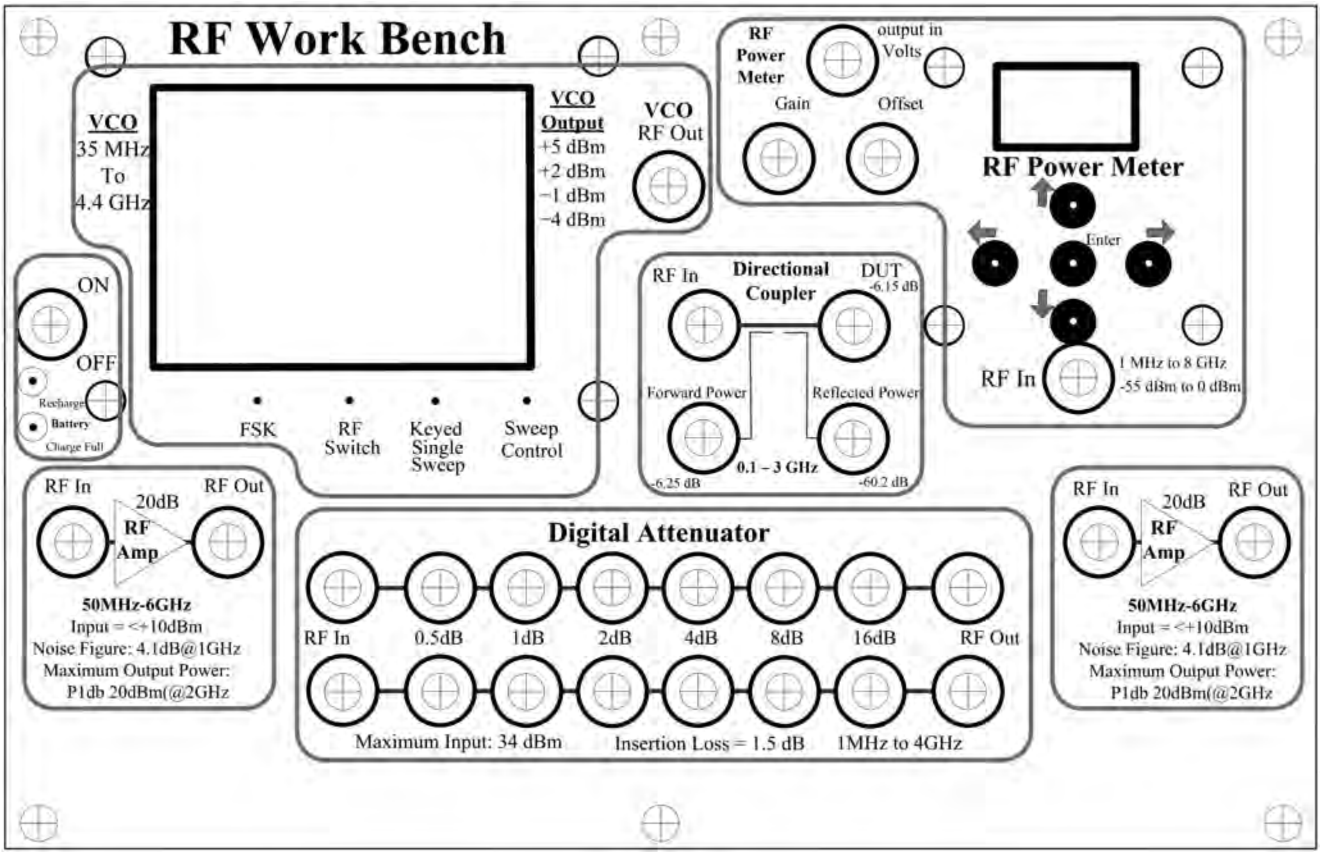


Figure 11 — RF Work Bench front panel.

Figure 12 — SMA bulkhead connector.

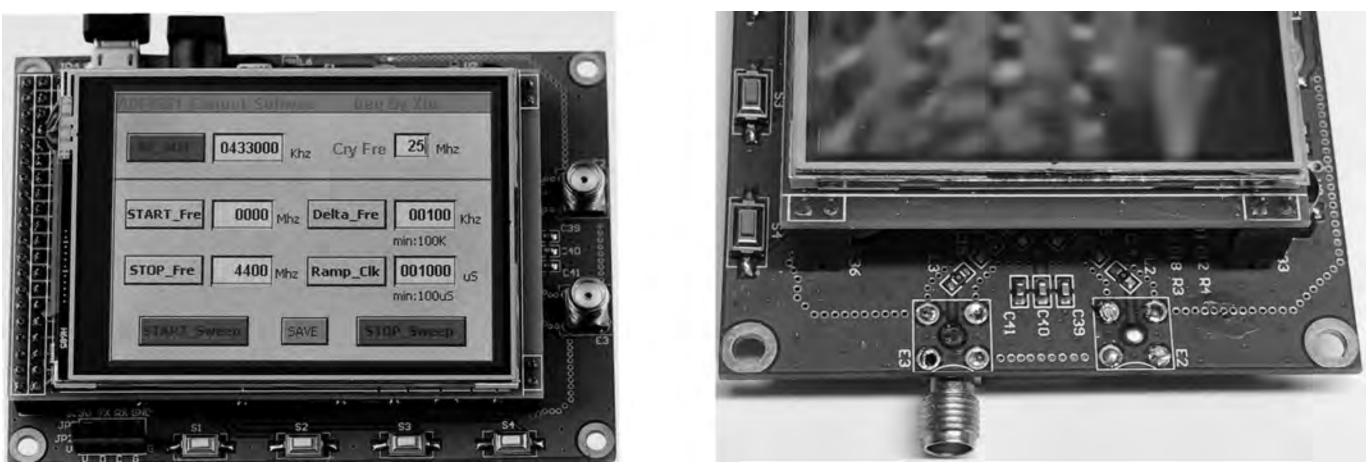


Figure 13 — SMA ADF4351 connector "E2" on right side of left image, and 'E2 connector" shown removed on bottom right side of the rotated board.

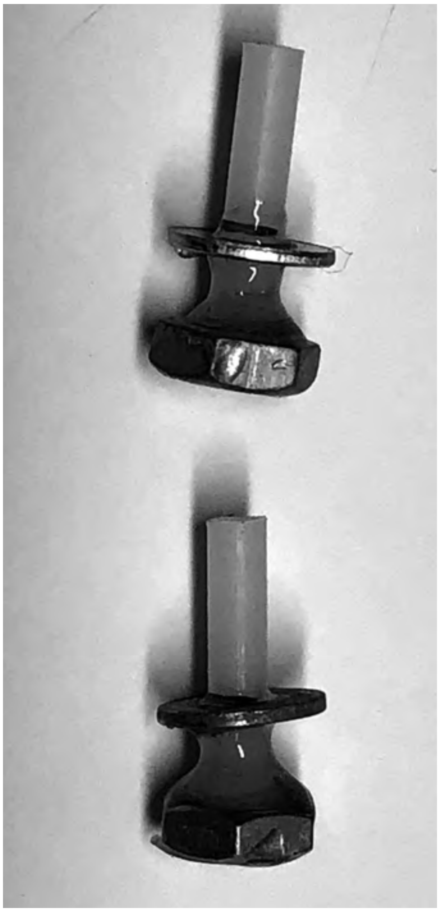


Figure 14 — Switch extensions.

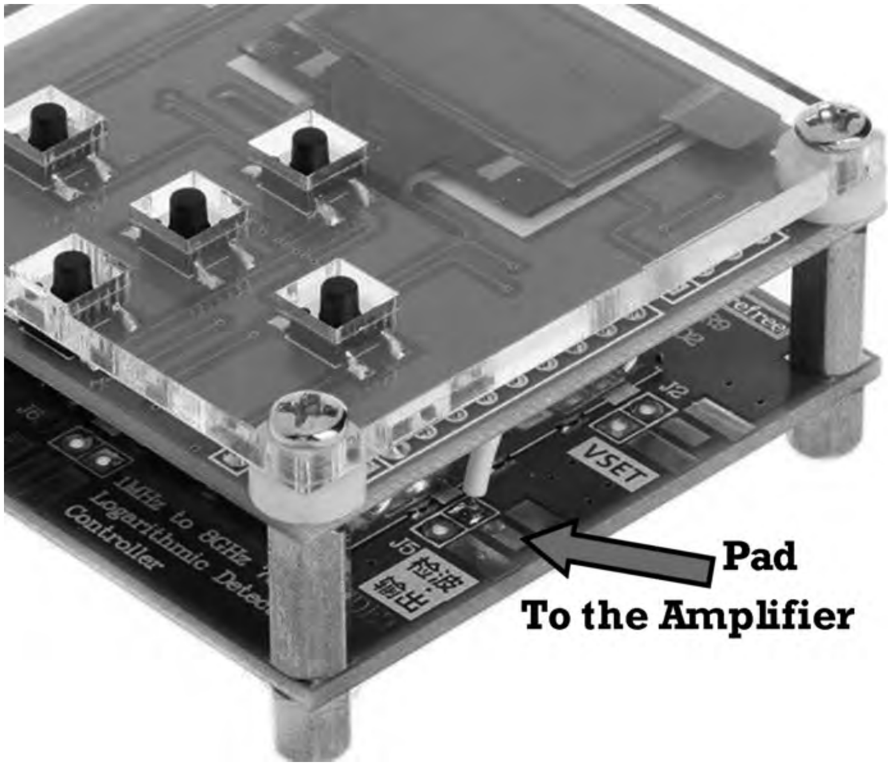


Figure 15 — J5 output "Pad to the amplifier" connection.

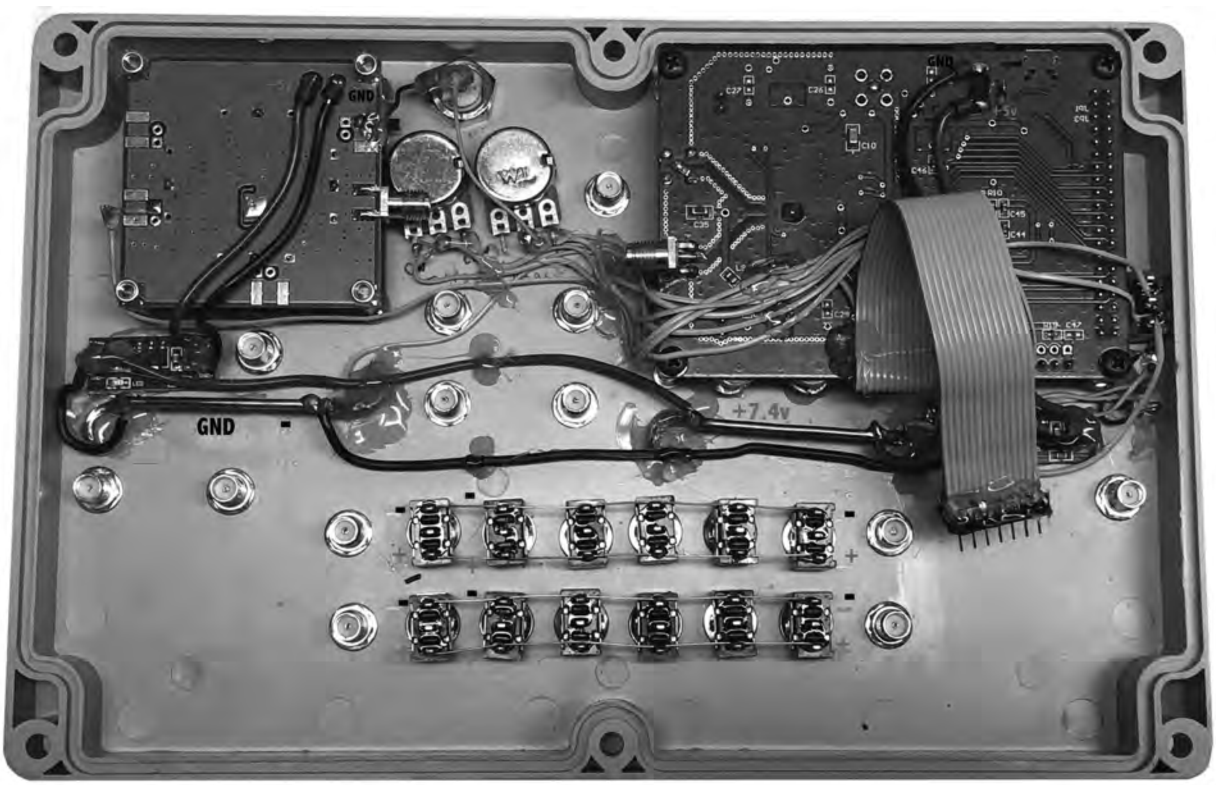


Figure 16 — Underside of the front panel.

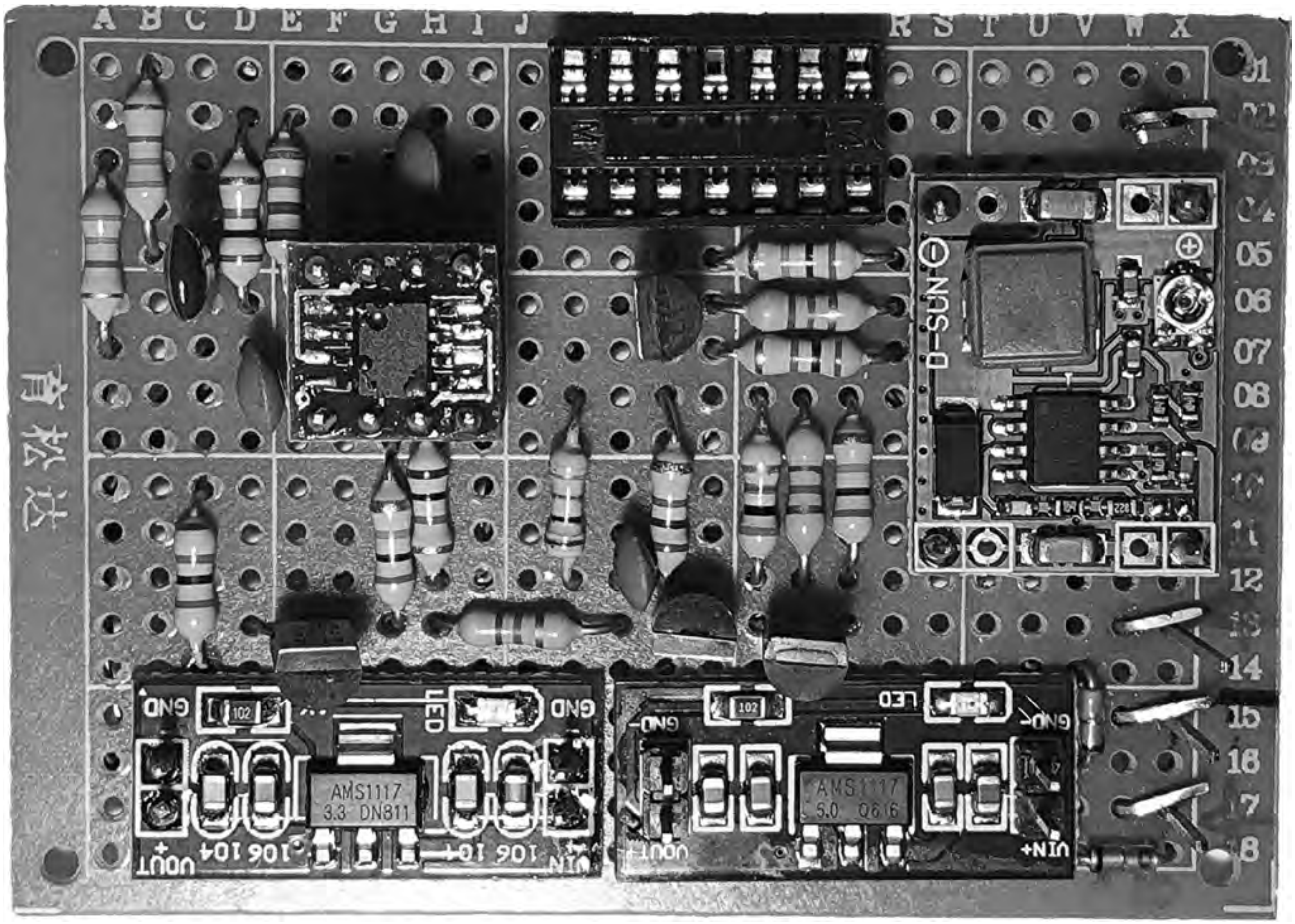


Figure 17 — Construction of the Amplifier Board. A 14-pin plug and socket, seen near the top, is used to connect to the front panel.

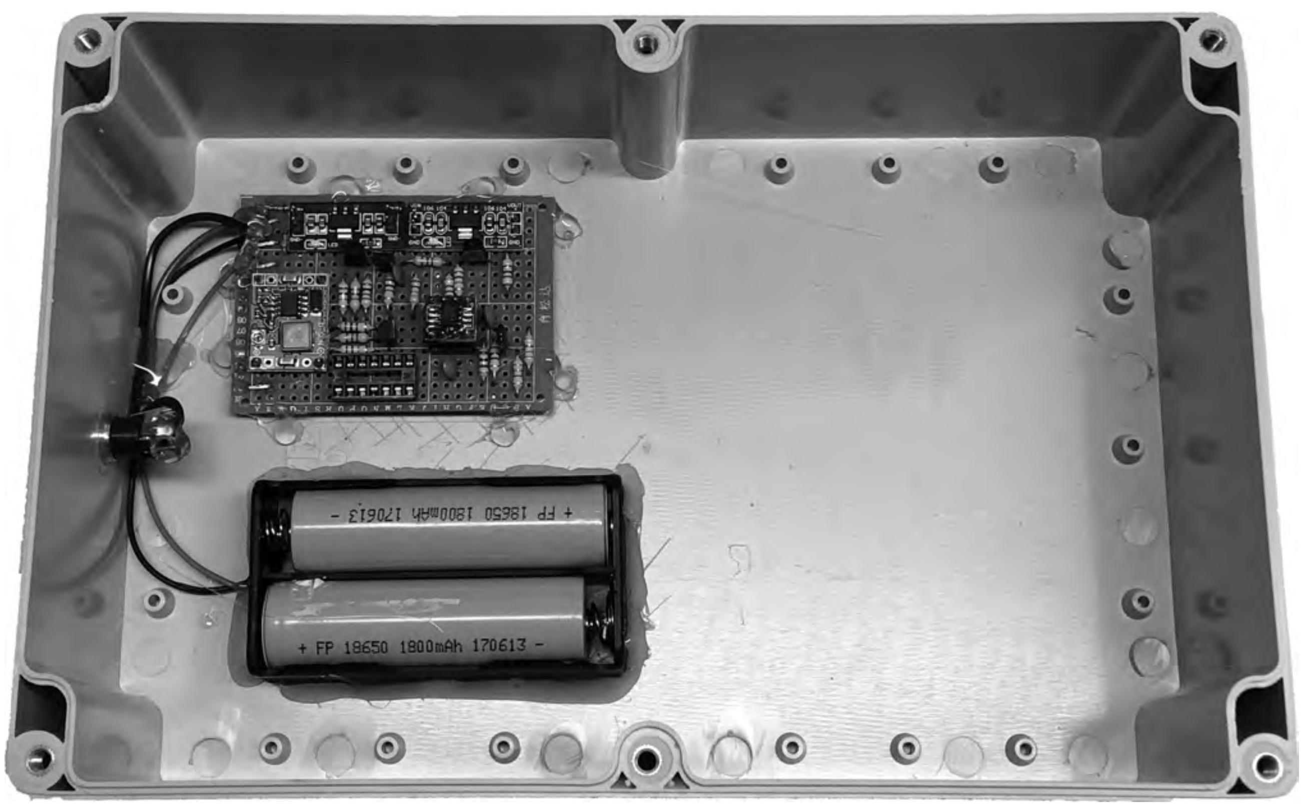


Figure 18 — Amplifier board inside box.

Most of the RF components require a regulator board. There are two types used here: the AMS1117-3.3, shown in **Figure 19**, and the AMS1117-5.0. A 3.3 V linear regulator board is attached to the PE4302 using hot-melt glue. The *Vout* of the linear regulator is connected to the PE4302 with ferrite beads on the end of the wire near the PE4302. Resistors (100 Ω) and red and black wires are connected to the *Vin* with airborne connections. A ribbon cable is connected to the +3.3 V, GND and the six V1 - V6 control wires. The assembly (**Figure 20 – left image**) is then hot-melt glued to provide stress relief (**Figure 20 – right image**). The PE4302 and ribbon cable can now be connected to the front panel, power and switches.

A 5.0 V linear regulator board (**Figure 21 – left image**) is attached to the RF Amp using hot-melt glue (**Figure 21 – right image**). The *Vout* of the linear regulator is connected to the RF Amp with ferrite beads on the end of the wire near the RF Amp. The 1.5 Ω resistors, and red and black wires are connected to the *Vin* with airborne connections. The assembly is then hot-melt glued to provide stress relief. The RF Amp can now be connected to the front panel. The RF components can now be assembled to the front panel using the 6” SMA cables and the power supply wires.

Next, tidy up the components to prevent things from shorting together, and fit it into the box (**Figure 22**). I used tie wraps and tape to make things fit in the box. Be careful not to

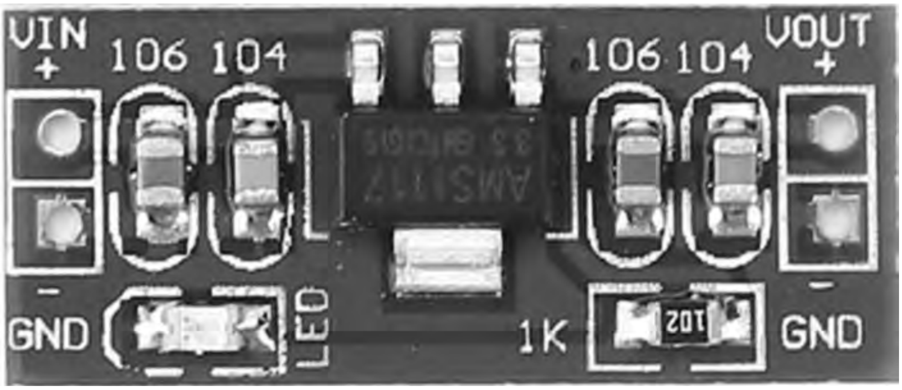


Figure 19 — AMS1117 linear regulator.

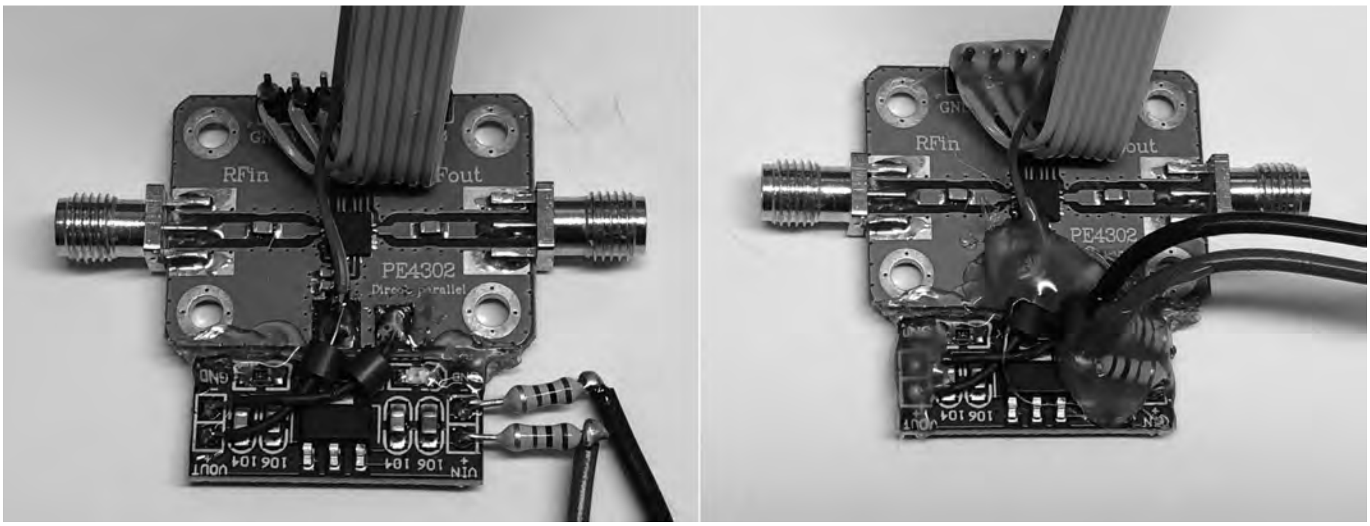


Figure 20 — PE4302 digital attenuator, with connections (left) to the voltage regulator and ribbon cable, and (right) after application of hot-melt glue.

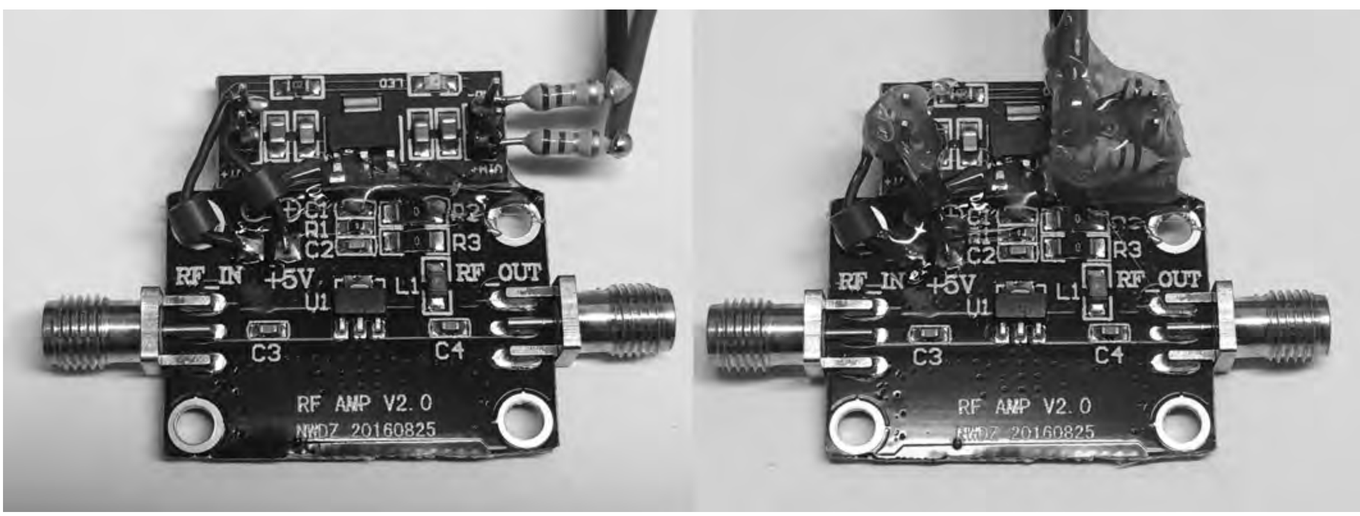


Figure 21 — RF amplifier before (left) and after (right) application of hot-melt glue.

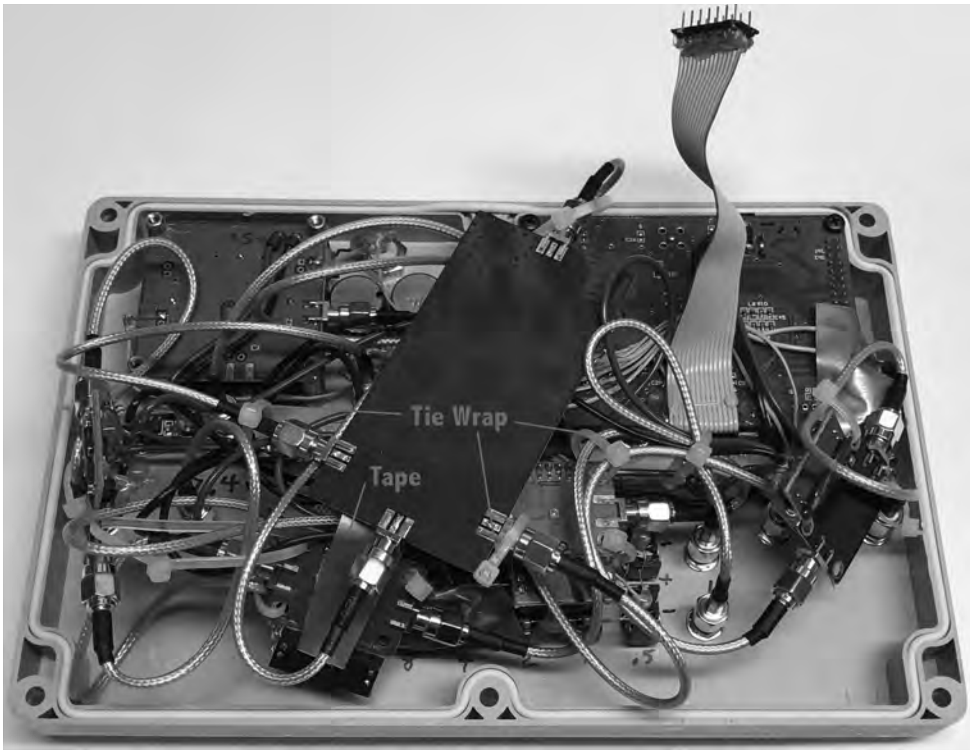


Figure 22 — Front panel rear.

let any conductive surface contact any other, even the RF connectors. If this happens, use tape such as duct tape for insulation. If the RF connectors touch, they could cause a ground loop.

The Front Panel can now be assembled onto the Battery Box. Be careful when plugging in the ribbon cable.

Test the RF Work Bench

Everything you will need for testing is built in. Set the VCO output to -1 dB, “RF Out” ON, press RF_Fre1 (Figure 1). If you press the frequency box, a "keyboard" box will pop up and you can enter your desired frequency. Using an SMA Cable, connect its output to the RF input of the RF Power Meter, which should read about -1 dBm.

Next, connect the VCO to the input of the Digital Attenuator with its output connected to the RF Power Meter. Set the VCO to +2 dBm and the power meter should read about 0 dBm with all attenuator switches set to OFF. Next switch the attenuator switches on one at a time and observe the corresponding drop in the reading on the power meter. It should match the attenuator switch setting. Repeat for the second Digital Attenuator. Set the attenuators for -20 dBm. Connect the output of the attenuator to the input of an RF Amp and its output to the Power Meter. The reading will be about 0 dBm, that’s a gain of about 20 dB for the RF Amplifier for that frequency. Repeat for the second RF Amplifier. You’re done, all of the components of the RF Work Bench have been tested.

Operation

Use the built-in Directional Coupler to measure Return Loss (RL), and derive Standing Wave Ratio (SWR) via calculation or from the conversion chart available on the **QEXfiles** web page (or other online sources). This could be an antenna, or in this case, a simulated “perfect” antenna using a 50 Ω load. Due to mismatches in impedance, some signal is reflected. The ratio of the forward to the reflected power expressed in decibels is called Return Loss (RL).

To begin, select a frequency and connect the VCO RF Out to the Directional Coupler RF Input. Terminate the “Forward Power” with a 50 Ω load. Connect the Directional Coupler “Reflected Power” to the RF Power Meter. Leave the DUT open, representing a maximum mismatch. Record the reading on the power meter, in my case -8.7 dBm. This is the input power plus the sum total of all loses including the Reflected Power. Connect another 50 Ω load to the DUT (Device Under Test). This represents a perfect antenna. Record the reading on the power meter, in my case -52 dBm. Subtract the second reading from the first reading. I get 43.3 dB, and then look up the SWR corresponding to a return loss of 43.3 dB on the SWR Conversion Chart, which in this case is 1.014:1. An SWR value under 2:1 is considered suitable for most antenna applications. At less than 2:1 the antenna can be described as having a good match.

Allen E. Ripingill, Jr. was a Senior Principal Systems Engineering Manager(retired) at Cubic Defense Applications, San Diego CA, and has over 40 years of new product development experience. He has overseen a group of system engineers that designed and developed tactical data links and training systems for the military. Prior to joining Cubic in 1995, Allen was a Senior Member of the Technical Staff at Ball Aerospace, where he designed electronic control and sensor systems for scientific research and military surveillance satellites. Allen has also started several small companies and holds over 32 foreign and US patents. Allen has been a Senior Member of the IEEE, Old Crow’s Association, and the Louisville CO Optimist Club. He is a member of the Montague Elks, a Mason with a 32 degree MSA in the Scottish Rite and is a lifetime member of the Disabled American Veterans.

Errata

In K. Siwiak, KE4PT and U. L. Rohde, N1UL, “Tuning Short Antennas for Portable Operations”, *QEX* Sep./Oct. 2019, the caption for Figure 5 is incorrect. It should be,

Figure 5 — Measured impedance of a 35 ft whip antenna used on a ship.

Also the company name should be spelled **Rohde & Schwarz**.

Gary A. Appel, WAØTFB

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An Engineering Tool for Simulating Receiver Performance

Analyze multiple cascaded stages in a receiver with this computer based tool.

Back in the dark ages when computers were running DOS, engineers took advantage of the availability of spreadsheets on their computers to perform the analysis of the cascaded stages in a receiver. The engineer would write the appropriate equations in the cells of the spread sheet to calculate the cascaded performance of multiple stages. It was a bit awkward, and fraught with danger as cutting and pasting might well break the cascaded calculations, but it was much easier than performing all the calculations by hand. A better tool would be an application written specifically for the purpose of analyzing receiver performance. This article introduces a Windows application written to supply this need. It was developed over a number of years in response to our need for analyzing receiver performance for a number of clients. After retiring, I decided to transfer this application to a more current environment. In the process the application has been cleaned up a bit, and some of the less useful features removed, leaving the more basic analyses intact. It has been my desire to make this application available to others.

A Simple FM Broadcast Receiver.

Let's take a quick look at a simple FM broadcast receiver. We'll not attempt a tutorial on the use of this application, but instead take a quick look at some of the capabilities of the application. **Figure 1** displays a simple diagram of an example receiver. For convenience, the receiver has been partitioned into two modules. They are labeled the "Front End", which includes a mixer, converting the

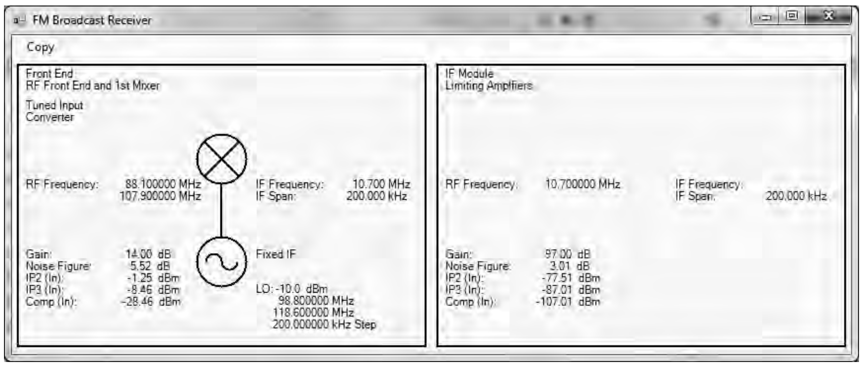


Figure 1 — The receiver performance can be visualized in a display of the characteristics of the cascaded modules.

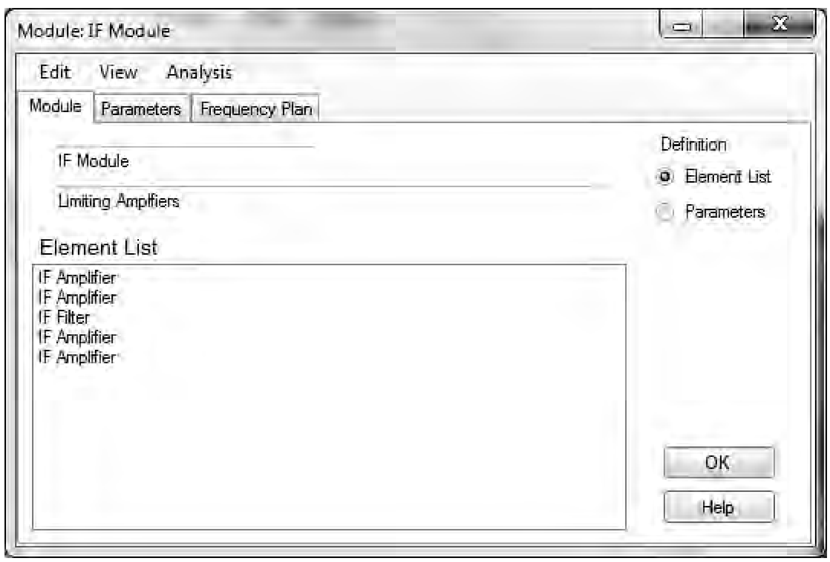


Figure 2 — The performance of a module can be defined by cascading a number of stages, or elements.

RF input signal to an IF frequency of 10.7 MHz, and the "IF Module", the primary gain and limiting for the receiver. Each module displays the frequency characteristics of that module, along with the gain, noise figure, and intercept and compression characteristics, calculated from the various stages in each module. The Front End module performs a frequency conversion, and also displays the basic characteristics of the local oscillator (LO), the tuning range, step size, and level. Theses modules may be actual sub-assemblies, or they may just be logical groupings within the receiver. Let's continue by taking a closer look at the IF Module.

Figure 2 displays a form defining the IF Module. On the Module tab it displays the five stages cascaded in the IF module; four limiting amplifiers and an IF filter. The characteristics of the IF Module displayed in Figure 1 were the result of calculating the cascaded performance of these five stages. On the Module tab we also see two edit boxes, the first assigns a name to the module, and the second includes a short description of the Module. The Parameters tab allows the user to define the module by a set of parameters, rather than by a cascade of elements, useful during the early phase of the design when the required performance from each module is being defined. We'll not consider the Parameters tab in any further detail. The Frequency Plan tab applies only to a module containing a frequency conversion. We'll look at that later.

Figure 3 displays the Module tab for the Front End module. The front end selectivity is provided by two tunable preselelectors, with an amplifier between, followed by a mixer and the first IF filter. Because this module performs a conversion, the Frequency Plan tab shown in **Figure 4**, must define the conversion characteristics. We see here the standard conversion characteristics for a conventional FM broadcast receiver, tuning from 88.1 to 107.9 MHz, in 200 kHz steps. On the upper right hand of the form we have defined the conversion as a fixed IF – that is, the LO tunes to convert the RF input range to a fixed IF frequency of 10.7 MHz. Another option is fixed LO, where an RF range is converted to an equal span at the IF frequency by a fixed LO frequency, also known as block conversion. The final choice applies to a conversion of a fixed IF frequency to a fixed IF frequency, as would be present in the second conversion in a dual conversion receiver where all the tuning is accomplished in the first conversion. The injection side is selected as high here, indicating that the LO frequency is equal to the sum of the RF and IF frequencies. The other option is low, where the LO frequency is equal to the difference between the RF and IF frequencies. The terms high and low side are used because this was a common designation when most receivers performed their first conversion to a lower IF frequency.

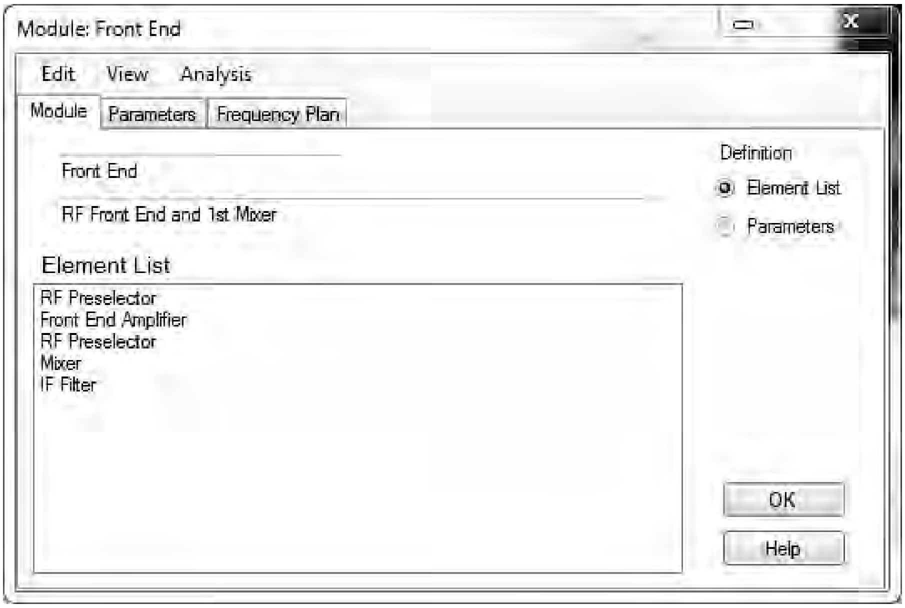


Figure 3 — The Front end contains gain, filtering, and a mixer.

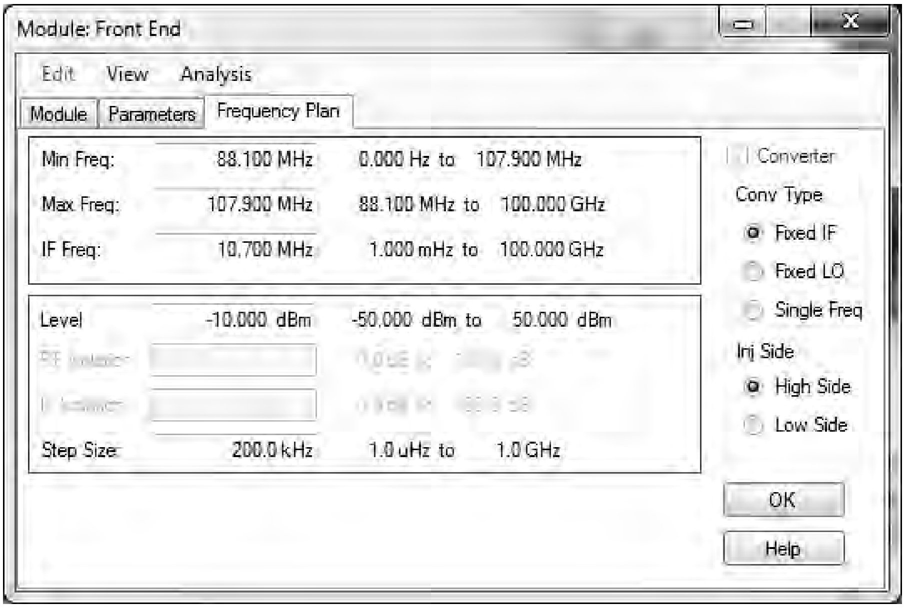


Figure 4 — The 'Frequency Plan' tab defines the conversion characteristics of a module.

The Element Building Blocks.

Figure 5 displays the element library for this receiver, a list of elements that have been defined for inclusion into this receiver. Included in this library are the front end and IF amplifiers, the 10.7 MHz IF band-pass filter, the mixer, and the tunable RF preselector. Available elements are amplifier, gain controlled (AGC) amplifier, mixer, attenuator, transformer, switch, high-pass filter, low-pass filter, band-pass filter, and preselector – a simple tunable band-pass filter. Once an element has been defined it can be included into the receiver chain as many times as desired. As an example of an element definition, the form defining the IF Amplifier is shown in **Figure 6**. The fundamental parameters for the amplifier are shown on the Characteristics tab of the form. The gain controlled amplifier is defined by the same characteristics, but most of these characteristics are defined as a function of the gain control voltage.

The supplied parameters depend on the element. For example, the attenuator is defined entirely by its attenuation. The band-pass filter is defined by center frequency, bandwidth, passband ripple, loss, and number of resonators. The low-pass and high-pass filters are defined by cutoff frequency, ripple, loss, and number of elements. The preselector filter is a simple tracking filter defined by percentage bandwidth, loss, number of resonators, and distortion characteristics. These filter characteristics allow the application to calculate image rejection and LO leakage. During the analysis, the characteristics of each element are converted into the normal block parameters, roughly equivalent to these amplifier parameters as defined in Figure 6. Additional details of the element definitions are available in the manual associated with the application.

While not actually required for a block analysis of a receiver chain, each element is also defined by the impedance characteristics, as shown in **Figure 7** for an amplifier. These impedance characteristics allow the application to calculate system signal levels in volts, along with the power levels. As a convenience, the voltage gain can be defined here. Changes in the voltage gain will be reflected in the power gain specified on the Characteristics tab. Some elements, like the filters, must be defined with equal impedances at the input and output. The Power tab allows the user to define which power supplies provide power to the element, at what current level, so the program can keep track of the supplies and total current drawn by the receiver.

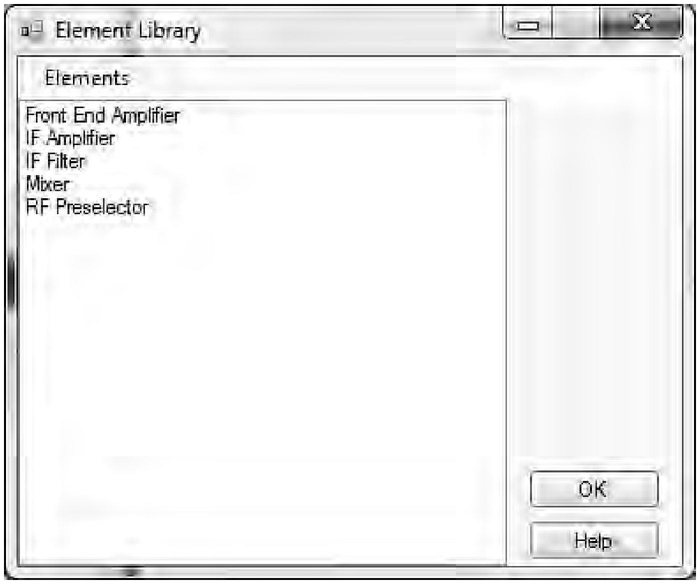


Figure 5 — User defined elements are added to the Element Library, for incorporation into the receiver chain.

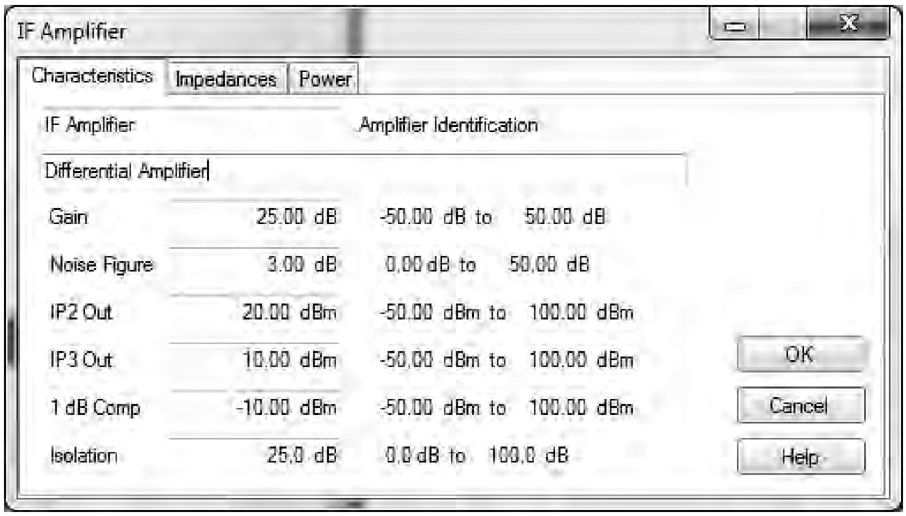


Figure 6 — The IF amplifier is defined by gain, noise, distortion characteristics, and reverse isolation.

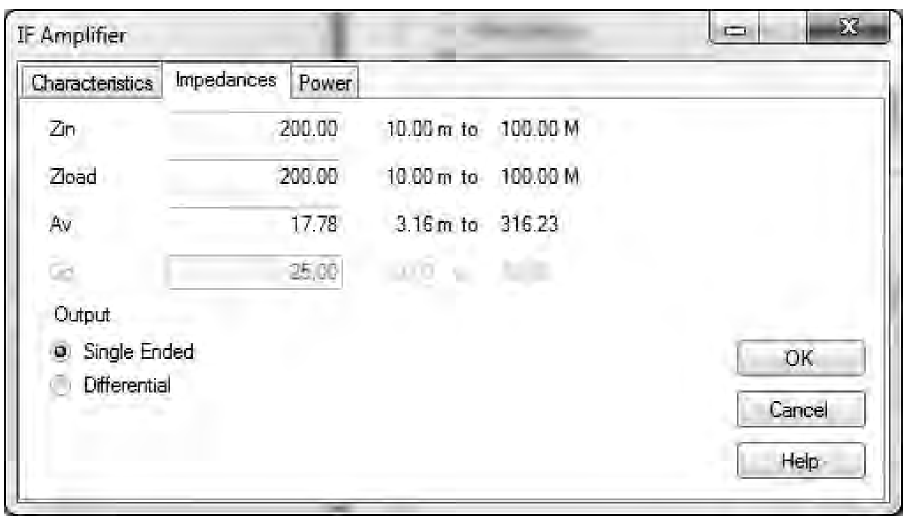
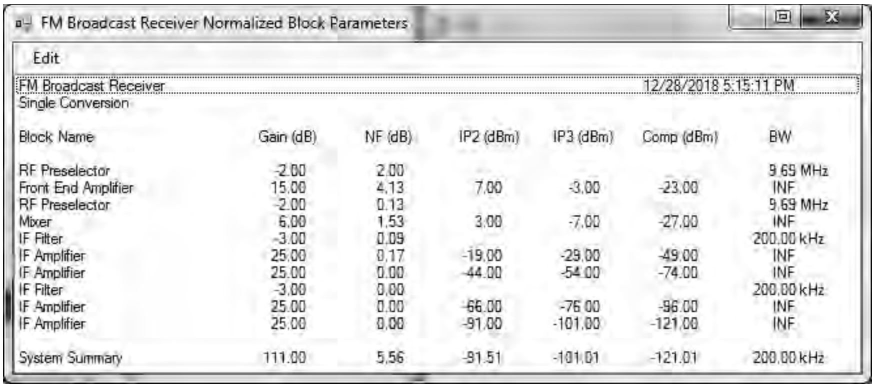


Figure 7 — Impedance characteristics are required to enable voltage level calculations.

Some System Calculations

This application can calculate and display the characteristics of each stage within a module or within the entire receiver, displaying a summary of the characteristics of each stage, along with the cascaded performance of all stages. Another option is to display the cumulative performance at the output of each stage. A third option is to display the normalized performance of each stage, along with the performance of the cascade of elements. The normalized parameters display the contribution of each element to the total, if no other elements contributed to the total for that parameter. **Figure 8** shows the normalized parameters for the entire receiver. Note that the biggest hit to noise figure is the Front End Amplifier. If no other elements contributed to the receiver noise, the receiver noise figure would be 4.13 dB. Similarly, the intercept point parameters, and compression parameter will display which elements cause the greatest degradation in these parameters. In this case the Mixer causes more degradation than the Front End



Block Name	Gain (dB)	NF (dB)	IP2 (dBm)	IP3 (dBm)	Comp (dBm)	BW
RF Preselector	-2.00	2.00				9.69 MHz
Front End Amplifier	15.00	4.13	7.00	-3.00	-23.00	INF
RF Preselector	-2.00	0.13				9.69 MHz
Mixer	6.00	1.53	3.00	-7.00	-27.00	INF
IF Filter	-3.00	0.09				200.00 kHz
IF Amplifier	25.00	0.17	-19.00	-29.00	-49.00	INF
IF Amplifier	25.00	0.00	-44.00	-54.00	-74.00	INF
IF Filter	-3.00	0.00				200.00 kHz
IF Amplifier	25.00	0.00	-66.00	-76.00	-96.00	INF
IF Amplifier	25.00	0.00	-91.00	-101.00	-121.00	INF
System Summary	111.00	5.56	-91.51	-101.01	-121.01	200.00 kHz

Figure 8 — The normalized characteristics allow the user to identify the contribution of each element to the cascade.

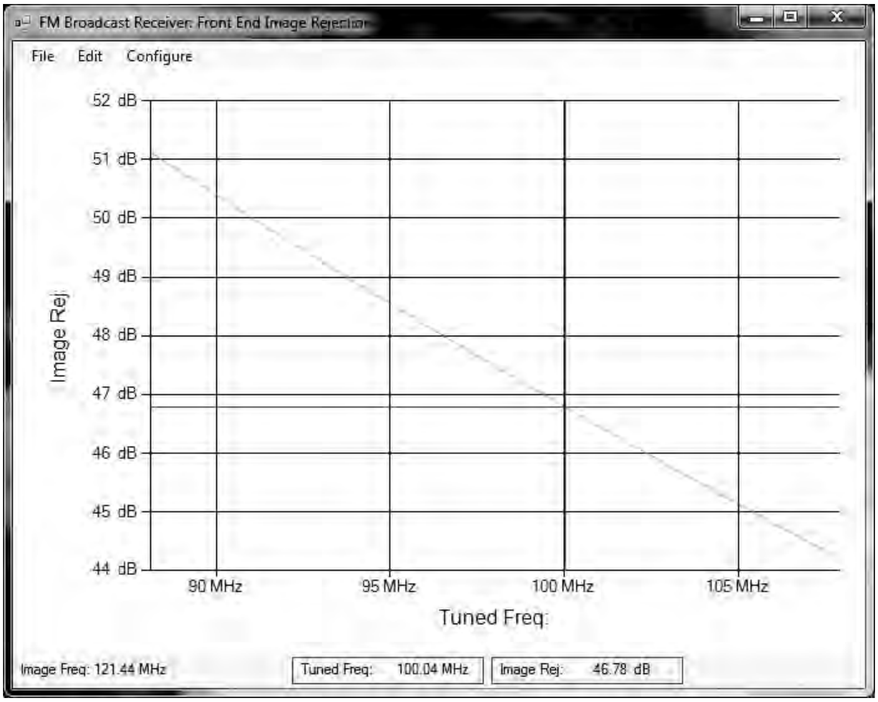


Figure 9 — The image rejection degrades with frequency because the preselector bandwidth increases as the tuned frequency increases.

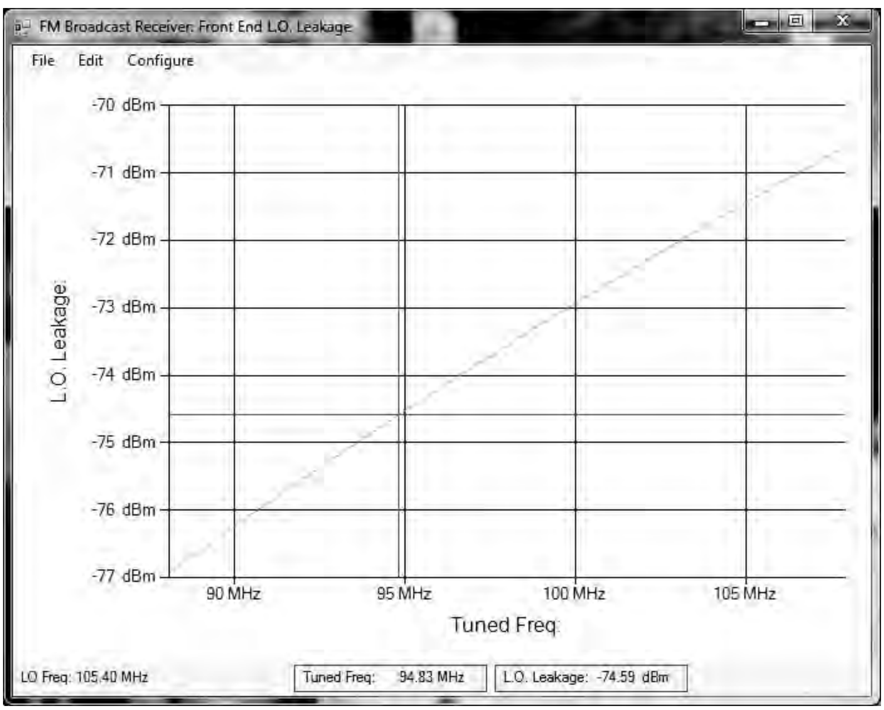


Figure 10 — The LO leakage increases with tuned frequency, as the preselector filter bandwidths increase.

Amplifier to the intercept and compression characteristics (lower intercept points and compression point). The compression and intercept performance of the preselector have not been defined, and so the contribution of the two preselector stages is not calculated in this analysis. Stages beyond the first IF filter will not contribute significantly to the intercept or compression performance, as the receiver is responding to a single signal after this IF filter. This block analysis can also be displayed for a single module.

The primary purpose of the two preselectors in the Front End module is to provide rejection to the image of the desired signal. The characteristics of the preselectors, along with the frequency characteristics of the conversion, will allow us to calculate the image rejection for the module. If, in addition, we have defined the LO to RF isolation of the mixer, the reverse isolation of the amplifier, and the level of the LO specified for the module, we will have all we need to calculate the LO leakage at the front end of the module — assuming there are no indirect leakage paths. **Figure 9** displays the image rejection calculation for the Front End module. As the tuned frequency increases, the preselectors are retuned, resulting in a greater bandwidth, and lesser rejection at the image frequency. **Figure 10** displays the calculated LO leakage at the input to the Front End module as the tuned frequency varies across the FM broadcast band. The accuracy of the image calculation and LO leakage calculations are limited by the simple algorithms used to determine the rejection characteristics of the filters, but should provide a reasonable first approximation.

Another plot available for the conversion in a module is a plot of the single signal spurious susceptibility frequencies present in the conversion. These are frequencies where an undesired signal will be converted to the IF frequency by some combinations of the fundamental or harmonic of the signal, and the fundamental or harmonic of the LO. **Figure 11** displays a plot of some of the single signal spurious responses for the Front End module. The dashed lines correspond to the desired signal frequency and its image, resulting from the 1st harmonic (fundamental) for both the RF and LO signals, as shown in the lower left corner of the plot. The two lines (second and third from the top) between the desired signal and its image are the two responses due to the second harmonic of the signal and the second harmonic of the LO. A solid line (second from the bottom) of the plot represents IF leakage at 10.7 MHz. As the user selects a larger range of the harmonics in the calculation, the number of spurious lines will increase.

Figure 12 displays a calculation of the signal to noise ratio in dB for the receiver.

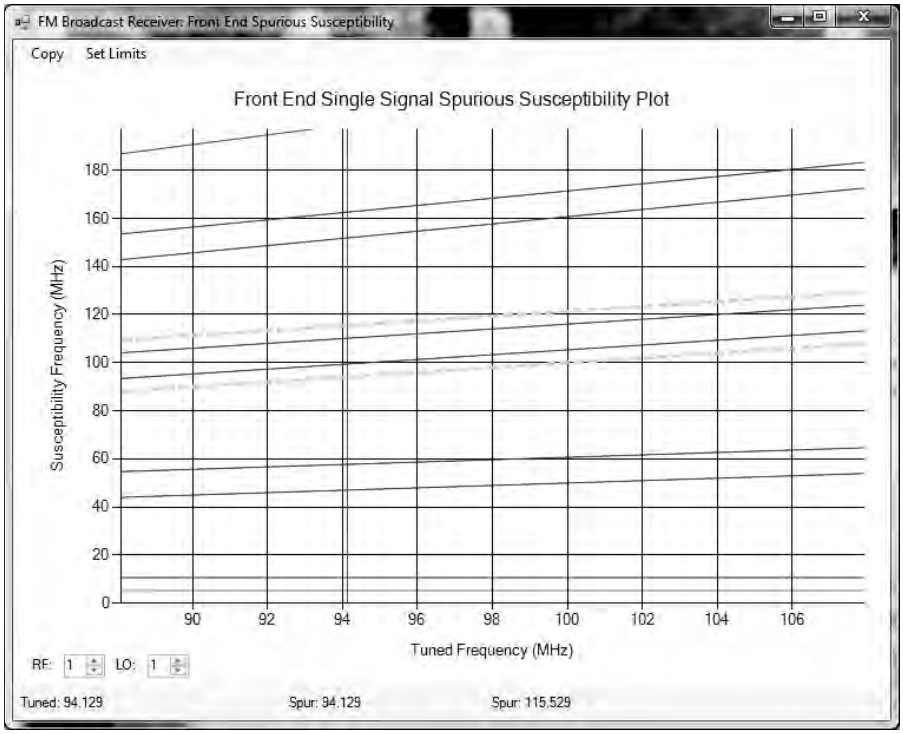


Figure 11 — A variety of signal frequencies will convert to the IF frequency of 10.7 MHz.

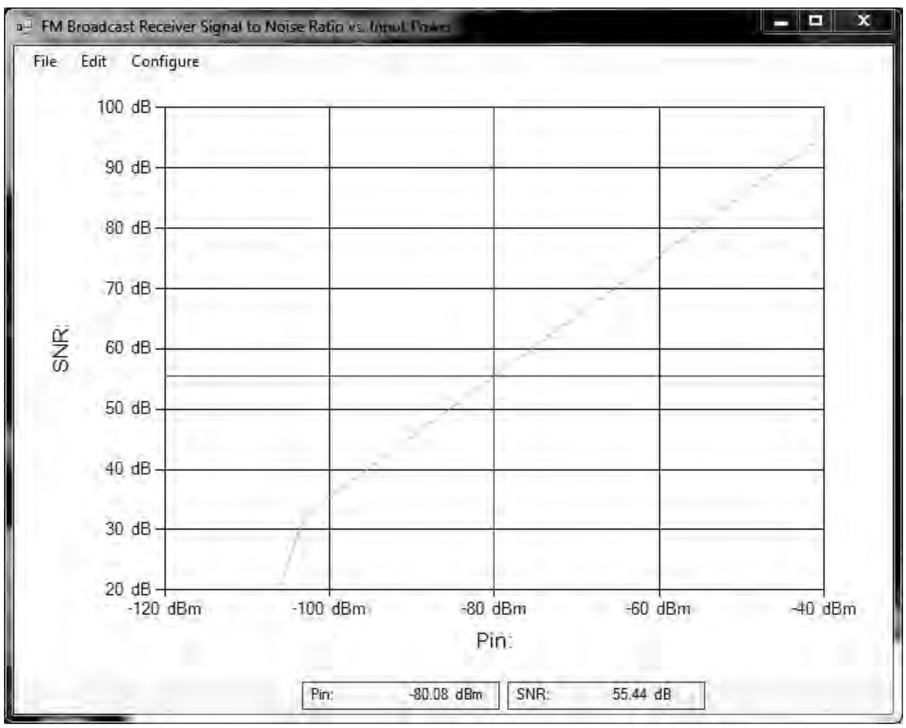


Figure 12 — The FM signal to noise ratio displays a threshold near -103 dBm.

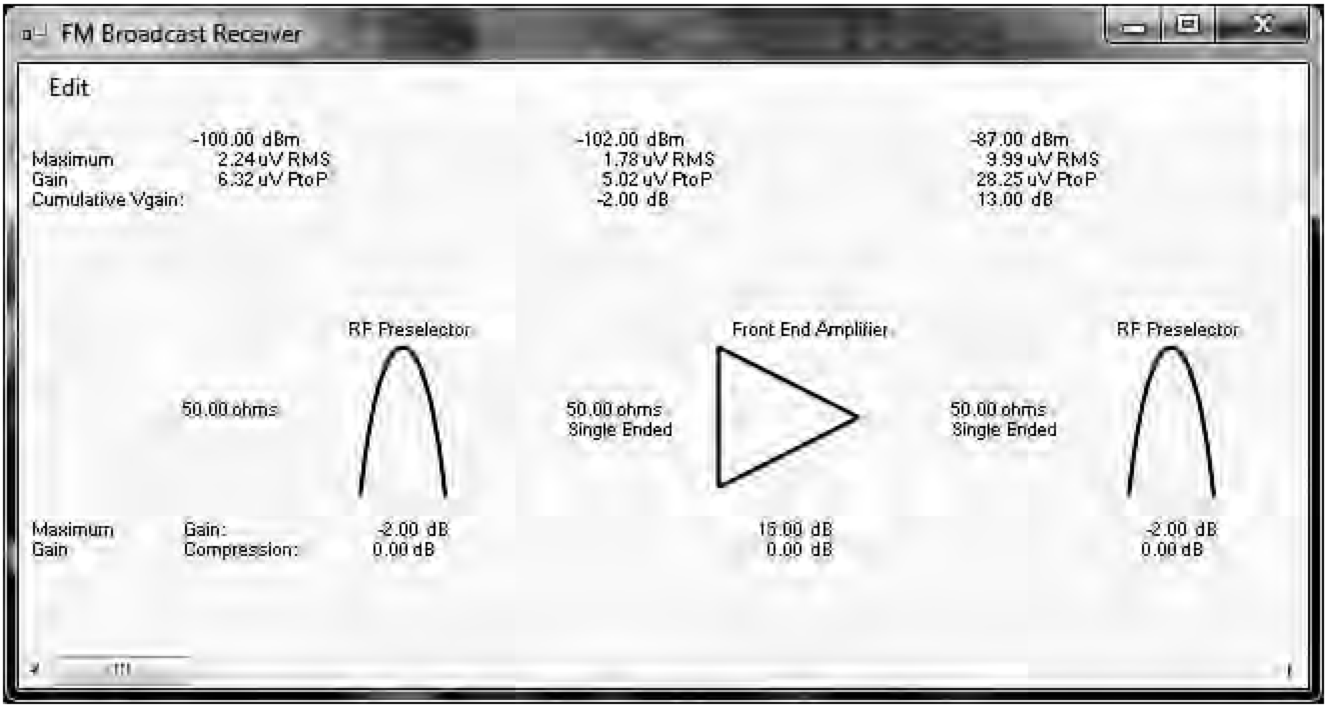


Figure 13 — Signal levels can be tracked through the receiver chain as a tool for verifying the gain performance of the receiver.

The FM threshold is visible here near an input level of -103 dBm, about 1.5 µV rms in a 50-Ω system. The application can also calculate the bit error rate for several digital modulation formats.

Two block diagrams are available for the receiver, or an individual module. One displays the characteristics for each stage, along with the cumulative characteristics at the output of that stage, along with the signal level at the input, output, and between stages. The other, shown in **Figure 13**, displays signal levels throughout the block diagram, taking into account the impedance level at each interface between stages. This has proven especially useful when measuring signal levels down the receiver chain to verify performance against the predicted signal levels. Note that both block diagrams will usually scroll because of the number of elements required. Figure 13 displays just the first three elements in the receiver.

The application also allows the user to define characteristics of the input signal, demodulator, and AGC detector. A control panel is available for setting the tuned frequency and the AGC range for a receiver with AGC capability. The AGC amplifier element is available for inclusion in a receiver with AGC capabilities. The gain, noise figure, intercept points, and compression characteristics can be defined as a function of the AGC voltage for AGC amplifiers, allowing the user to analyze the receiver performance as a function of AGC voltage, and in turn, the input signal level.

Conclusion

This application, in an earlier form, has proven useful in designing and verifying the performance of various receivers for a number of clients. This application has been revised and rewritten in *C#* for execution under Microsoft Windows 7. It should run as well on later versions of Windows. This short description is intended to suggest the usefulness of this application. Additional information and examples can be found in the manual by downloading the application from the **www.arrl.org/QEXfiles** web page. We hope that the application proves useful for those interested in receiver design.

Gary A. Appel, WAØTFB, has been involved in the design of radiofrequency equipment for over 30 years, most recently as an RF design consultant in the Silicon Valley. Gary has been fascinated with radios since his first crystal set, and was first licensed as WNØTFB in November of 1967 at age 14. He is a member of the ARRL and holds a BSEE degree from Washington University in St. Louis. Gary has been retired since 2008 and enjoys the opportunities that his retirement has provided for working on homebrew projects and pursuing other technical areas of interest.

Dr. Ulrich L. Rohde, N1UL, Awarded The 'Honorary Fellowship' of The IETE (India)

The Governing Council of The Institution of Electronics and Telecommunication Engineers (IETE) of India, is India's leading professional society in the field of Electronics, Telecommunication Computer Science/Engineering, Broadcasting, Information Technology and related areas, has honored Dr. Ulrich L. Rohde with 'The Honorary Fellowship' of the Institution of Electronics and Telecommunication Engineers.

The 'Honorary Fellowship' of the Institution is accorded to an eminent person in the field of Science, Technology, Education and Industry. IETE is privileged to have eminent dignitaries, a Nobel Laureate, Technocrats, Administrators, Industrialists, National and International leaders on its Honorary Fellowship rolls.

The conferment ceremony of Honorary Fellowship will be held during the Inaugural Session on 28th September 2019 during 62nd Annual IETE Convention (AIC) on 28-29 Sep 2019 at Dr Ram Manohar Lohia Avadh University, Ayodhya, Uttar Pradesh (UP).

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A Holistic Approach To Receiver Performance Characterization

Accounting for many signals in a given frequency interval provides a more realistic picture of the receiver response.

Good receiver performance in crowded, strong-signal environments is important to many Amateur Radio endeavors, including contesting and DXing on HF. The art of receiver performance characterization has been developed over some decades from simple measurements of MDS and blocking dynamic range to now include intermodulation distortion, third-order intercept, and other advanced concepts. These have proven useful in comparing receivers against one another. However, for reckoning receiver performance on an absolute scale, a more holistic approach may be beneficial. This paper suggests another receiver performance characterization method that tries to take into account the presence of many signals in a given interval of frequencies so that a more realistic picture of the response of the receiver to many, rather than only two, potentially interfering signals may be obtained. The method focuses on what is perceived by the receiver user and is based on a mathematical comparison of the spectral densities of a chosen interval of frequencies before and after processing by the receiver.

Scope

This paper discusses primarily the mathematical construction of metrics or figures of merit to support the proposed method. The idea of comparing the output of the receiver to its input is not a novel one; the primary contribution of this paper is the definition of several associated metrics or figures of merit that would be needed to make good use of such testing. There may be significant engineering challenges in implementing the proposed method and readers are invited to discuss possible implementations and improvements in subsequent articles. While the discussion here is in the context of direct conversion and superheterodyne HF receivers, in principle, any receiver that outputs audio may be considered.

The proposed method is a generalization of Noise Power Ratio (NPR) testing that uses white noise as input to a microwave receiver as a means of determining receiver linearity **[1]**. However, the method discussed here does not necessarily rely on white noise as an input, but rather allows the experimenter to control the spectral density of the input, so that many possible input spectra (including the two-tone tests in common use as well as the white noise input used in NPR testing) may be accommodated.

Background

I have been interested in receiver performance characterization ever since some of my colleagues at Bell Laboratories in Holmdel, NJ, cobbled together in the late 1970s a measurement system to determine the minimum distinguishable signal (MDS) and blocking dynamic range of various receivers owned by members of the Holmdel Amateur Radio Club (K2DR). Some results that were obtained are summarized in **Table 1**.

I don't recall all the specific details of the tests (in particular, the spacing of the two signals used), but they were conducted according to protocols in common use at the time **[2]**. You can see that there is quite a bit of variation across receivers.

Other authors offered additional development and variations on Hayward's

Table 1.
Some Performance Measurements on Older Receivers.

Receiver	*Bandwidth (Hz)*	*MDS (dBm)*	*Blocking Dynamic Range (dB)*
Drake R4A	400	–139	108
Drake R4B	400	–132.5	113
Drake R4C	400	–141	113
Drake R4C	2400	–133	113
Drake TR-7	300	–123	103
Kenwood TS-520	500	–131	85
Kenwood TS-820S	2400	–134	104
Yaesu FT-101B	600	–139	96
Yaesu FT-101B	2400	–131.5	86
Yaesu FT-101EX	600	–137.5	94
Collins 75A-4	3100	–129	82
Collins 75S-3B	500	–138.5	111
Icom IC-701	500	–130	107

ideas in references **[3 – 8]**. The very important stream of work devoted to improving the performance of receivers in the presence of strong signals owes much to references **[9, 10]**. Sherwood and Heidelman **[11]** published a seminal paper in 1977, which stimulated a great deal of further work on measurement and improvement.

There has been much additional development of these ideas over the past few decades but the work remains largely within the framework outlined by these early endeavors: two-tone testing with two or three spacings. In this paper, we propose a generalization that may help receiver producers and users acquire a more comprehensive picture of receiver behavior in diverse real-world environments.

Synopsis

The proposed method is based on two simple ideas:

- A receiver is a machine for converting RF into audio. This observation is inspired by the mathematician Paul Erdös who famously stated that "A mathematician is a machine for converting coffee into theorems."
- The purpose of receiver performance characterization is to provide a potential receiver user with a clear representation, or summary, of the receiver's audio output under a variety of conditions. That is, the ultimate judge of receiver performance is what the user hears.

Accordingly, we take as the basis for the proposed method a comparison of the spectral density of a range of radio frequencies (for example, a 15 kHz segment of some amateur HF band) with the spectral density of the 15 kHz wide interval of audio frequencies that results from the operations in the receiver (local oscillators, mixing, etc.) on that 15 kHz range of RF frequencies. Differences of less than 1 dB are not discernible to the ear and are ignored in the comparison.

Method

Consider a receiver that operates over the frequency range $[L, U]$. That is, the lowest frequency the receiver can receive is L (MHz) and the highest frequency it can receive is U (MHz). Posit the existence of a spectral density φ over the interval $[L, U]$. The receiver operator is interested in reception of a stated range of frequencies $[f_0, f_1] \subset [L, U]$. Here $f_1 = f_0 + \delta$ where δ is at the discretion of the experimenter and could be 0.0021 (2100 Hz) for SSB operation, 0.0005 (500 Hz) for CW operation, or other user-specified bandwidth. The user will hear a range of audio frequencies $[f_0 - H, f_1 - H]$ where H represents the net effect of all the heterodyning needed to turn the RF input into audio. H will vary depending on the specific frequency the receiver is tuned to in the interval $[f_0, f_1]$ and the desired audio output. For instance, if the receiver is tuned to $f^* \in [f_0, f_1]$ and the desired audio output is 800 Hz when the receiver is tuned to f^*, then $H = f^* - 0.0008$ (in MHz). Local oscillators and mixers in the receiver are configured to produce the needed H.

Let φ_H represent the spectral density of the audio output range $[f_0 - H, f_1 - H]$, measured in dB. In a perfect receiver, there is a constant $\alpha > 0$ for which,

$$\varphi_H(f - H) = \alpha\varphi(f), \quad f \in [f_0, f_1]$$

for every $[f_0, f_1] \subset [L, U]$. We may arrange the units so that $\alpha = 1$. This equation represents that, in an ideal receiver, what the receiver user hears is a faithful audio representation of the range of signals appearing at the receiver's input. That is, the audio output of the receiver is a perfect reproduction of the input signal, frequency-shifted down into the audio range by the heterodyning in the receiver. Any discernible deviations from this ideal representation are undesirable. Those that are caused by spurious responses generated inside the receiver are the subject of receiver performance characterization.

For example, in the two-tone test commonly used, we may be interested in the range of frequencies [14.0095, 14.0105] MHz. In two-tone testing, the input spectral density φ may consist of two spikes (delta-functions), one at 14.010 MHz and the other at 14.012 MHz (2 kHz spacing). The first signal is in the center of the passband of interest while the second is outside. Then, assuming the audio passband is centered at 800 Hz and is 400 Hz wide, the spectral density of the audio passband should (in an ideal receiver) contain a single tone at 800 Hz and nothing else. In a real receiver, there may be other discernible audio in the passband because of mixer nonlinearities, reciprocal mixing, intermodulation distortion, or other undesirable receiver properties.

The two-tone test is simple to administer and allows for relatively straightforward analysis of sources of irregularities in the receiver. However, it gives a somewhat oversimplified picture of receiver performance in the real world in which there may be many potentially interfering signals both within and outside the desired RF passband. One purpose of the method proposed here is to provide a more realistic picture of receiver performance in the presence of a complex array of signals, more representative of what may be encountered in practice. To that end, we allow a wider range of possible input RF spectral densities. In practical applications, one may wish to run the test with, say, three different input RF spectral densities, one characterizing a "quiet band" with few signals present, another characterizing a "normal" band such as might be encountered on a weekday without any special stimulus for operating, and a third characterizing a "busy" band such as might be encountered during a contest or DXpedition pileup.

For the performance characterization described here, the experimenter specifies a spectral density φ of the RF input to the receiver. It is advisable to specify φ over all of $[L, U]$ (or a sufficiently large subinterval). It is not enough to control only the portion of the input spectral density over the interval $[f_0, f_1]$ because one important reason for receiver performance characterization is that strong signals outside the desired passband may generate spurious responses in the receiver (see previous paragraph) and appear as undesired signals in the audio passband. So for purposes of the test, we will specify an input spectral density φ_0 over some sufficiently large subinterval of $[L, U]$ that contains $[f_0, f_1]$. Ideally, this subinterval should be chosen so that any frequencies outside it have no chance of discernibly affecting the receiver output. An ideal receiver will produce a faithful audio representation of the input RF passband (by "faithful" we mean following the spectral density equation above). The characterization method seeks deviations from this faithful representation to the extent that they can be perceived by the operator. We adopt 1 dB — 1 dB is the "just noticeable difference" (JND) in psychoacoustics — as the minimum distinguishable difference in audio signals.

In generalizing receiver performance characterization in this fashion, one of the key problems that arises is the need to summarize the results of the test in a compact form that allows for comparison from one receiver to another. The main contribution of this paper is to suggest a few (scalar) metrics to help with this task.

Metrics

Several receiver performance characterizations, or metrics, may be defined. The first receiver performance characteristic $P_1 = P_1(f_0, \delta, \varphi)$ we consider is given by

$$P_1(f_0, \delta, \varphi_0) = \frac{1}{\delta}\int_{f_0}^{f_0+\delta} I_{\{|\varphi_H(f-H)-\varphi_0(f)|\geq 1\}}(f)\,df$$
$$= \frac{1}{\delta} m\left\{f \in [f_0, f_0 + \delta] : \left|\varphi_H(f - H) - \varphi_0(f)\right| \geq 1\right\},$$

where m is the ordinary set-theoretic (Lebesgue) measure of the stated set and I_A is the indicator function $I_A(f) = 1$ if $f \in A$ and $I_A(f) = 0$ if $f \notin A$. P_1, which depends on the RF passband $[f_0, f_1]$ over which the characterization is desired and the spectral density φ_0 applied by the test operator, measures the proportion of the represented audio passband where the audio heard differs from what it should be by more than 1 dB. Note that $0 \le P_1 \le 1$, and smaller is better. Also, even though φ_0 is defined over a larger interval than $[f_0, f_1]$, P_1 records information on what the receiver does only within $[f_0, f_1]$. The characterization range $[f_0, f_1]$ may be varied to suit various evaluation needs (engineering, marketing, etc.).

P_1 describes how much of the passband that the receiver user is listening to contains signals that are discernibly different from what the user should be hearing but it does not indicate how strong any such undesired signals may be. A second performance characterization that does respond to signal strength could be defined as follows:

$$P_2(f_0, \delta, \varphi_0) = \max\left\{ \begin{array}{l} \left|\varphi_H(f-H) - \varphi_0(f)\right| : \\ f \in [f_0, f_0+\delta], \left|\varphi_H(f-H) - \varphi_0(f)\right| \ge 1 \end{array} \right\}$$

If the set

$$\left\{ f \in [f_0, f_0+\delta] : \left|\varphi_H(f-H) - \varphi(f)\right| \ge 1 \right\}$$

is empty, then P_1 is zero, that is, no signals louder than 1 dB above what should be there can be heard. P_2 tells the loudness of the loudest undesired signal in the listening passband $[f_0, f_0 + \delta]$. We have $P_2 \ge 0$ and smaller is better.

Other characterizations in the same spirit as these, but that respond to different perceptions, may be devised. For instance, $P_3 = P_3(f_0, \delta, \varphi_0)$ tells the total audio power of all the undesirable signals that can be heard:

$$P_3(f_0, \delta, \varphi_0) = \left[\frac{1}{\delta} \int_{f_0}^{f_0+\delta} \left|\varphi_H(f-H) - \varphi_0(f)\right|^2 I_{\{|\varphi_H(f-H)-\varphi_0(f)| \ge 1\}}(f)\, df \right]^{1/2}$$

Discussion

The major advantage of metrics like those suggested above is that they provide a more realistic representation of the behavior of the receiver under conditions more approaching those seen in actual use. Specifically, their focus on what the user is able to perceive (hear) directly makes them easy to interpret.

Certainly, it is fair to recognize that these may have some drawbacks as well. The drawbacks include:

- It may be a significant engineering challenge to assemble instrumentation enabling the creation of arbitrary spectral densities and the associated computations.
- It is difficult to capture in a single number the complicated pattern of audio signals, desired and undesired, in the receiver's audio passband.
- It may be desirable for a complete characterization to allow incorporating sensible ranges of f_0, δ, and φ into a single resulting figure. These parameters would be chosen to represent typical ranges of interest to the receiver user. Computation of a portmanteau metric incorporating many ranges would need to balance the expense of running the test for many different values of f_0, δ, and φ against the value of a more comprehensive characterization to receiver producers and users.

As suggested by Paul Newland, AD7I, a possible test platform for developing a variety of spectral densities for use as input for the test could be arranged by combining a number of RF generators, some USB and some LSB, each modulated by some speech, Morse, or digital waveform. Another approach might be to use a "recording" off the air of some band segment. This would be most realistic, but problems of repeatability are introduced unless some means of standardization were agreed to.

In practical use, the spectral density over $[L, U]$ at the input of the receiver will vary with time, so what we really have is a $\varphi(t)$. Each of the metrics discussed above could be augmented by incorporating a time variable and then taking the maximum, average, etc., over time. This is a mathematically straightforward extension, but the added complexity in implementation is probably not justified because anything the user hears over an interval of time is simply a composite of what the user hears at individual moments during that interval, and if those individual moments are satisfactory (or not, as indicated by the snapshot characterizations discussed in the **Method** section above), then not much value is added by complicating the issue with time intervals.

Finally, because we are using user perception as a foundation for the performance characterizations, we could contemplate incorporating a factor that reflects the user's hearing frequency response. For instance, P_2 could be modified as follows,

$$P_2(f_0, \delta, \varphi) = \max\left\{ \begin{array}{l} \left|\sigma(f)\varphi_H(f-H) - \varphi_0(f)\right| : \\ f \in [f_0, f_0+\delta],\ \left|\sigma(f)\varphi_H(f-H) - \varphi_0(f)\right| \ge 1 \end{array} \right\}$$

where $\sigma(f)$ represents the user's hearing frequency response, $f \in [f_0, f_0 + \delta]$. This would allow different characterizations perceptible by, *e. g.*, younger users — whose $\sigma(f)$ may be relatively flat — versus older users whose $\sigma(f)$ is likely to roll off at higher frequencies. [In another physiological example, the effective rectangular bandwidth (*ERB*) of the ear is $(0.108F + 24.7)$ Hz, F is the center frequency in Hz, according to B. C. J. Moore and B. R. Glasberg, "A revision of Zwicker's loudness model," Acta Acustica, vol. 82, pp. 335-345, 1996; thus for a 700 Hz Morse side-tone frequency the *ERB* is about 100 Hz regardless of the actual considered frequency interval.— *Ed.*]. However, while these may be of some academic interest, it is unlikely to be useful to the receiver manufacturer's engineering or marketing staff unless they are actively pursuing a mass customization and micro-targeting advertising strategy. In a similar vein, another constituency that a receiver manufacturer might wish to satisfy includes modem demodulators. These would be more demanding of signal purity than human ears; the more complex a signal the modem is trying to decode, the more problematic "junk signals" in the passband would be.

Example

We may analyze a two-tone IMD test using this framework. This test comprises part of the standard *QST* product review for HF receivers. An example is found in Kutzko **[12]**.

Consider the two-tone blocking dynamic range test performed with 2 kHz spacing at 14 MHz in a receiver with a 400-Hz pass band. While the receiver may have $L = 3$ MHz and $U = 30$ MHz, we are interested in the range $f_0 = 14.000$ MHz and $\delta = 15$ kHz $= 0.015$ MHz — δ is chosen to include the range of hearing of most humans with unimpaired hearing. The input spectral density consists of a spike (Dirac delta-function) at 14.010 MHz and another spike at 14.012 MHz. Centering the 14.010 MHz signal in the 400-Hz passband makes the passband [14.0108, 14.0112] MHz. If the operator wants

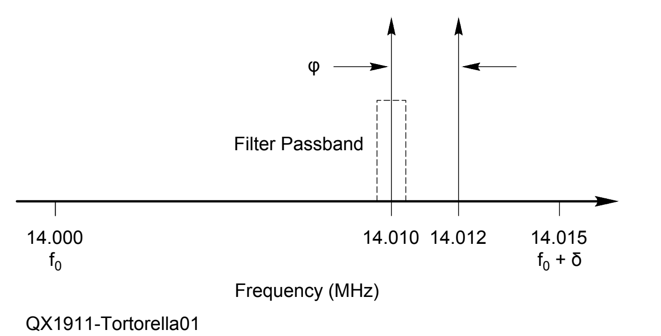

Figure 1 — Example showing a two-tone test.

to hear the desired signal as a 1000-Hz audio tone, then H = 14.009 MHz. The diagram of **Figure 1** may help clarify the situation. For purposes of the mathematics in this example, all quantities are idealized. The tones are pure delta-functions, the filter skirts are perfectly rectangular, etc. Of course, this does not faithfully represent real receivers and real spectra, where all single tones have some non-zero width, filter skirts are rounded, etc. It is these effects, among others, that shape the receiver response and that must therefore be incorporated in any real computation of performance characterizations.

If the receiver were ideal and tuned to 14.010 MHz, then φ_H would consist of a spike (Dirac delta-function) at 1000 Hz and another spike at 3000 Hz. In a real receiver, other audio signals would appear — hopefully, at lower volume — in the filter passband because of nonlinearities in mixers and amplifiers in the receiver. For example, the mixing product 2(14.012) – 14.010 = 14.014 MHz should be outside the filter passband, but because a real filter will not have perfectly vertical skirts, the signal at 14.014 MHz may be audible, especially if a wider filter is used.

Summary and Conclusions

Attempting to generalize standard, conventional receiver performance characterizations (2-tone testing, etc.) to a more full-spectrum approach requires new metrics to capture the complicated properties of an audio spectrum containing more than two tones. This note proposes some new receiver performance metrics based on the difference between the spectral density over a range of frequencies presented at the receiver input and that same spectral density shifted by heterodyning and conversion to a range of audio frequencies. The metrics place primacy on what is perceived (heard) by the receiver user. We have chosen to define metrics that reflect the receiver user's acoustic perception while attempting to summarize a complicated, multi-dimensional situation in a scalar value. While these metrics are mathematically straightforward, there may be significant challenges in practical implementation and suitable choice of parameters (lower end of frequency range f_0, frequency increment δ, and input spectral density φ_0) to provide characterizations that are practically useful for receiver designers and users. I hope that these ideas may prove fruitful in stimulating additional discussion.

Acknowledgments

I am grateful to Paul Newland, AD7I, and Jeff Sanders, W5QR, for helpful discussions. Any errors that may be present are mine alone.

Amateur Extra class licensee and ARRL Life Member Michael Tortorella, W2IY, has been a radio amateur for 58 years. He holds the PhD degree in mathematics from Purdue University and a BA in mathematics and philosophy from Fordham University. He is currently retired from a career as a Distinguished Member of Technical Staff at Bell Laboratories and an adjunct professor at Rutgers University and Stevens Institute of Technology. Michael has written over three dozen research and scholarly articles in mathematics and the book Reliability, Maintainability, and Supportability Best Practices for Systems Engineers. He is a member of the Garden State ARC, FISTS, and the True Blue DXers Club. His Amateur Radio interests include DXing and contesting on CW and curating a small collection of Morse keys and bugs.

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