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Receiver Step Attenuator

This step attenuator is an easy way to improve a receiver's handling of strong signals and to add signal diagnostic capability.

Having been bitten by the software defined receiver (SDR) bug and experimenting with simple SDR 'dongles' and an HF converter, it didn't take long for me to start thinking of ways to improve this simple receiver. It was readily apparent that an HF receiver like this was wide open to strong signal overload from commercial broadcast signals and even from the ham across town. One way to deal with strong signal overload is to add a broadband attenuator between the receiver and the antenna. This article describes an HF step attenuator and control circuit that you can build for about US$80.

My goal was to create a step attenuator that would allow me to set just the right amount of attenuation to reduce strong signals while still allowing weak signal readability. I wanted a front-end attenuator that was easily switchable in reasonable steps with known increments to maximize its usability. Of course, one of the steps should be 0 dB.

What Others Have Done

Commercially available communications receivers frequently offer front-end RF attenuators, sometimes in conjunction with a preamplifier. For example, the Ten-Tec RX-340 provides a switchable 15-dB attenuator and a switchable 10-dB preamplifier. The RF Space NetSDR+ has a three-step attenuator providing 10, 20, and 30 dB. The Icom R70 and R71A have a front panel switch that allows selection of either a preamplifier, a single attenuator of about 20 dB, or neither. The newer R75 has separate switches for the preamp and single-stage 20-dB attenuator. By comparison, the top-of-the line Icom R9500 receiver employs several receiving band dependent step attenuators. For the HF bands, attenuation up to 30 dB can be selected in 6-dB steps. For VHF/UHF, the steps are 10, 20, and 30 dB. Above 1150 MHz only a single 20-dB attenuator may be selected. The venerable Kenwood R-1000 (c. 1980) had a step attenuator providing 0 to 60 dB in 20-dB steps. The later (c. 1990) Kenwood R-5000 receiver had a selectable 0 to 30dB attenuator in 10-dB steps.

RF step attenuators have frequently appeared in Amateur Radio literature. Bramwell[1] described a general purpose step attenuator that used a series of slide switches to bring any of 10 attenuator "pads" into the RF path. Attenuations between 1 and 71 dB in 1-dB steps were available. Bramwell relied exclusively on 1% metal film resistors rather than compromising on less-precise 5% values. Oñate and Fortuny[2] employed a two-stage step attenuator with relays to select each attenuator section in a software controlled preselector that provided 6, 12, and 18-dB of front end attenuation. A similar two-stage step attenuator was described in the *2019 ARRL Handbook*[3] using manual switches. Ostapchuk[4] described a rugged step attenuator that used a machined enclosure so each Pi-configured resistor network and DPDT toggle switch was in its own shielded compartment. He noted that an earlier iteration that did not employ this extensive shielding was a failure. He also used 1% metal film resistors. An earlier design by Shriner and Pagel[5] that used an enclosure made from PC board also employed shielded partitions between each attenuator section.

Attenuator Design

I chose a step attenuator design that allows for selection of attenuation from 0 to 21 dB in 3-dB steps, with fast relay switching and a rotary binary coded decimal or "BCD" switch for attenuation selection. I chose 3-dB steps because it seemed more relevant than any other step size. A 3-dB change is at the upper end of what most people can perceive[6] and it represents a half-power reduction, so each step should be immediately apparent to the ear and sound roughly equal. Also, a maximum attenuation of 21 dB should be sufficient in most cases and makes it easier to provide enough isolation between sections. Using relays also helps preserve section isolation. Each attenuator section is further isolated by ground plane routing and vertical shields.

Resistor values for these attenuator "pads" are widely available in the literature and online[7]. While the Pi- and T-network topologies are theoretically equal, most applications seem to rely on the Pi-network, probably because real resistors approximating the theoretical values are easier to find and implement for most common attenuations. I chose to use the Pi-network in my design.

The step attenuator circuit (Figure 1) has three sections providing 3-dB, 6-dB, and 12-dB attenuation respectively.

Each attenuation section is switched in or out of the signal line with NEC EC2-5NJ non-latching miniature DPDT relays. These relays are specifically designed for electronic switching and telecommunications service. They are very compact, very fast (rated operation time is approximately 2 ms) and should be adequate for use through the HF band. These relays are energized with +5 V applied to the relay coils at points A, B, and C. Table 1 shows how the relay points A, B, and C are switched to get 0 to 21 dB in 3-dB increments.

When all relays are un-energized, the signal passes through without attenuation — that is, the relays in their "normally closed" (NC) condition and correspond to the 0 dB setting. General purpose diodes (1N4001 or equivalent) bridge the relay coils to provide

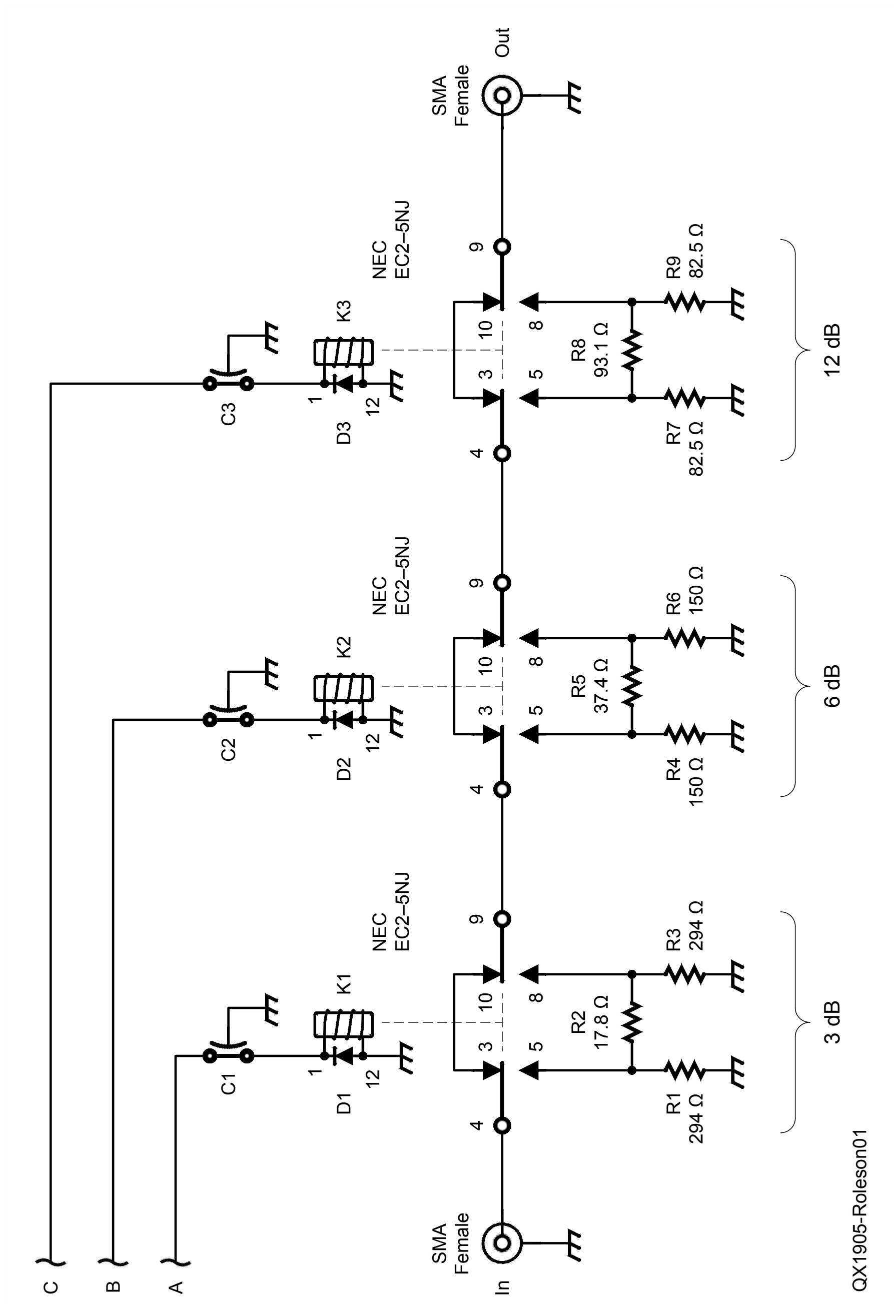


Figure 1 — Three-stage step attenuator schematic. Relays are shown in their non-energized state.

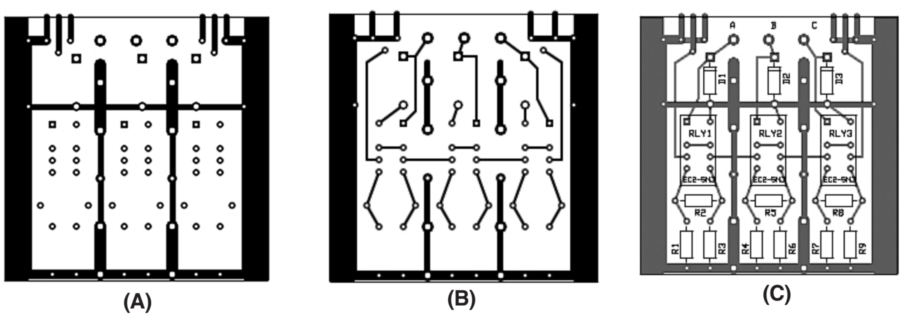


Figure 2 — Step attenuator PC board, (A) top layer, (B) mirrored bottom layer, (C) full layout. The board is 2.185 inches wide and 2.20 inches tall.

Table 1
Attenuation for activation of relay coils at points A, B, and C.

C	*B*	*A*	*Atten., dB*
0	0	0	0
0	0	1	3
0	1	0	6
0	1	1	9
1	0	0	12
1	0	1	15
1	1	0	18
1	1	1	21

discharge paths for inductive field collapse when the relays are turned off. These are sometimes called fly back diodes. Feedthrough capacitors (0.01 μF) shunt impulsive RF to ground that the relay switching might produce, and keep RF from getting into or out of the shielded attenuator assembly via the control lines.

For ease of construction, I chose to use 1/4 W axial-leaded resistors. While 5% resistors are arguably adequate for Amateur Radio use, I used my multimeter and dug into my stash of 5% resistors, selecting resistors that were as close as possible to theoretical values.

As others have described, the enclosure, shielding, and printed circuit board (PCB) layout are important especially when it comes to isolating the three attenuator sections. Figure 2 shows that each attenuator section on this compact 2-sided PCB (~2.2 inches square) is surrounded by ground plane. Since I needed only one of each PCB, I chose to make the boards myself, but I used the free *ExpressPCB* software for the layout. My preferred method is to print reversed black images of the PCB layers on clear plastic "overhead sheets" with a laser printer. I then lay this over the blank PCB, and cover with a thin cotton cloth (old T-shirt is ideal), and use a hot clothing iron to transfer the printer toner to the PCB. The toner then becomes the etchant resist. I used the same method to make the switching control dial, skipping the etchant step but instead coating the final product with a thin coat of clear acrylic.

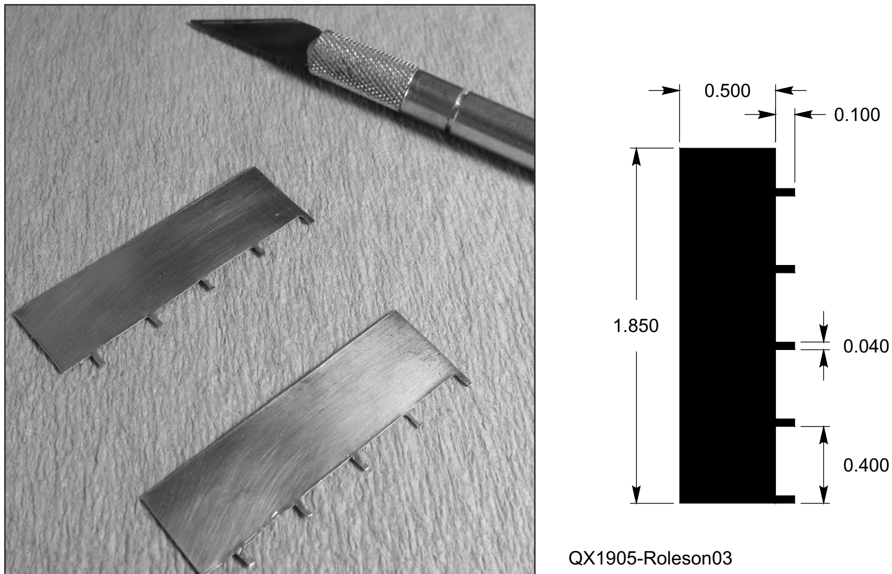
Two section shields (Figure 3) were cut from 0.010 inch thick brass sheet, and were soldered onto the PCB to separate the attenuator sections. Brass sheet 0.010 inches thick (30 gauge) suitable for cutting into the attenuator section shields is typically available from hobby and some hardware stores. The K&S brand is often shown in displays where individual 4 inch by 10 inch sheets are available for purchase. This material is easily cut with sharp scissors or a metal nibbler.

The RF and control connections are all along one edge. The completed PCB assembly is shown in Figure 4. Female SMA bulkhead connectors soldered to the PCB provide RF input and output, ground to shield integrity from the PCB to the enclosure through the end plate, and hold the board to the end plate of the enclosure. The three feed-through capacitors are mounted in the end plate between the two SMA connectors and connected to the PCB by short wires. Ground integrity is further enhanced by horizontal ground traces on the PCB and wide ground planes along each edge on both sides of the PCB that slide into slotted shelves in the main body of the enclosure. These features should minimize ground plane potential differences across the PCB and provide redundant ground connection to the enclosure when the PCB is slid into slots inside the main enclosure.

The enclosure provides RF shielding as well as a mechanically sturdy housing. I chose the Hammond 1457C1201 enclosure, cut in half. Other enclosures may also work, but when cut in half this one provided the most compact overall enclosure. It is basically a short length of extruded aluminum channel with two aluminum end caps or panels, and internal ribbing features to provide for attaching the end panels and sliding a PCB into the channel.

As provided by the manufacturer, several cosmetic and weatherproofing features compromise the shielding effectiveness. Hammond also sells an EMI/RFI version of this enclosure, part number 1457C1201E. It includes end plate EMI gaskets, and it appears that the end plates may not be completely powder coated. In hindsight, I should have purchased this version if only because I might have needed to remove less powder coating from the end plates. The E-version costs $4 more.

The end panels are provided with waterproofing (and insulating) rubber gaskets, which I discarded. Both end panels and the exterior of the main extruded body were powder coated. This powder coating is an insulator. I wanted a well-shielded enclosure, so this powder coating had to be removed in those places where I needed good metal-to-metal contact. I used sand-paper wheels and a wire brush in a Dremel® tool, and a wire brush mounted in a 1/4-inch drill to remove the coating from the inside surface of the end plates and around the mating edges of the main extruded body. A viable alternative would have been to use sand or bead blasting to remove the powder coating and polish the metal, but I do not have this capability at hand. I also buffed the open ends of the extrusion on flat sheets of fine sandpaper and emery cloth to ensure it was flat and clean to give the end panels the best chance to fit snuggly and without gaps.



(B)

(A)

Figure 3 — Attenuator section shields (A) are cut from 0.010 inch thick brass sheet, with dimensions in (B).

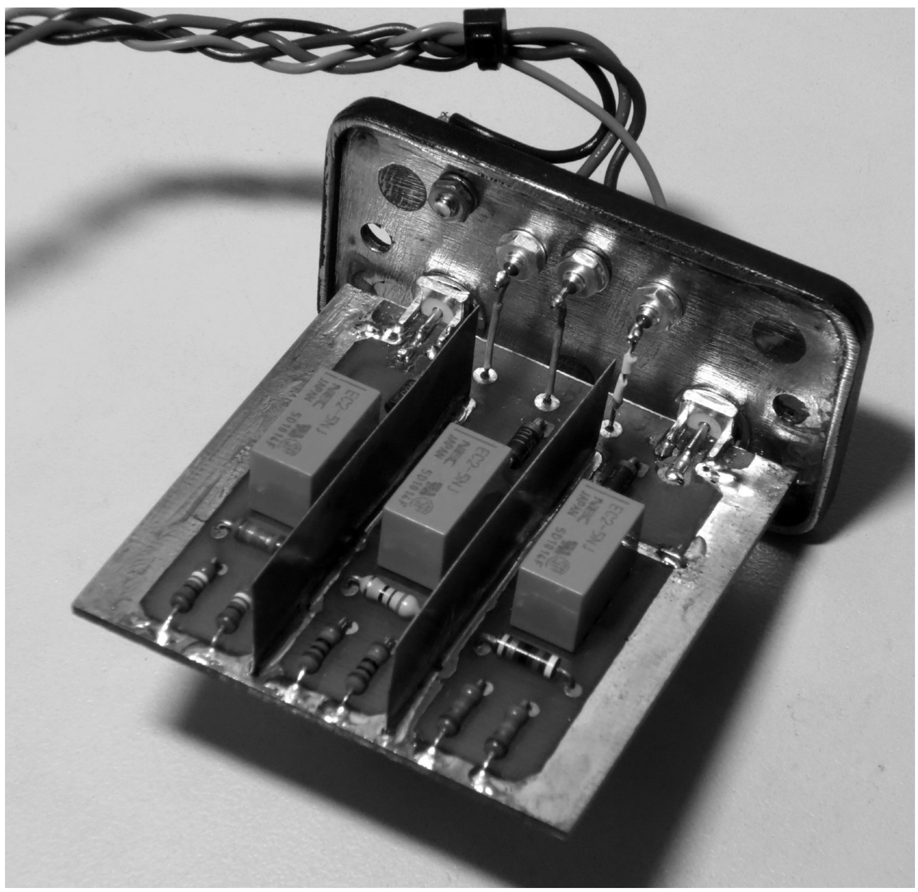


Figure 4 — Completed attenuator PC board and lid assembly.

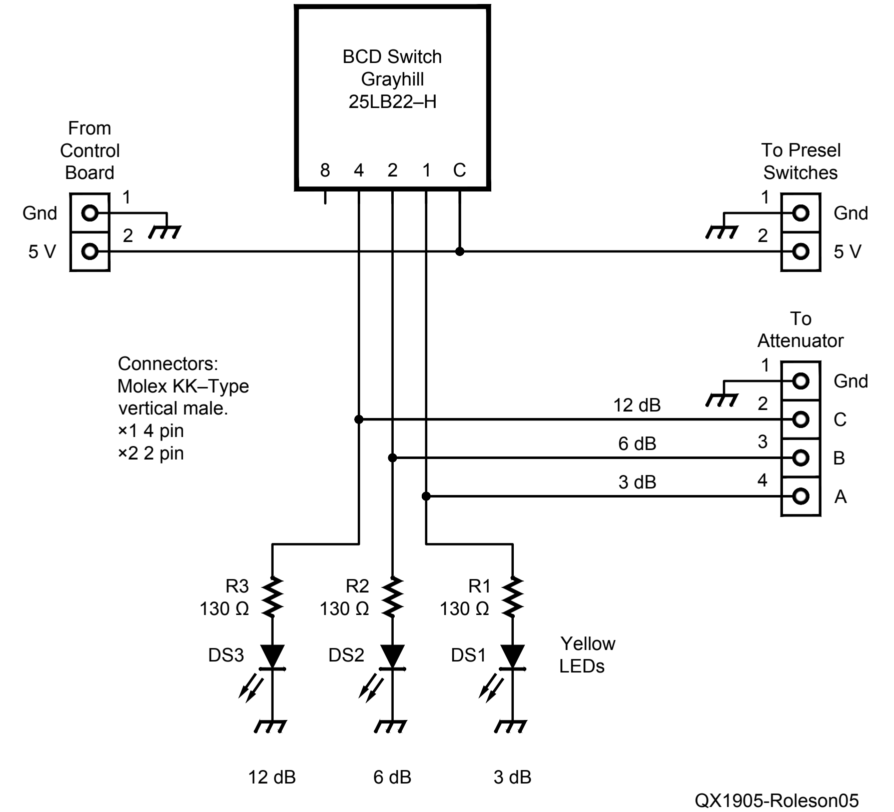


Figure 5 — BCD or hexadecimal switch assembly schematic.

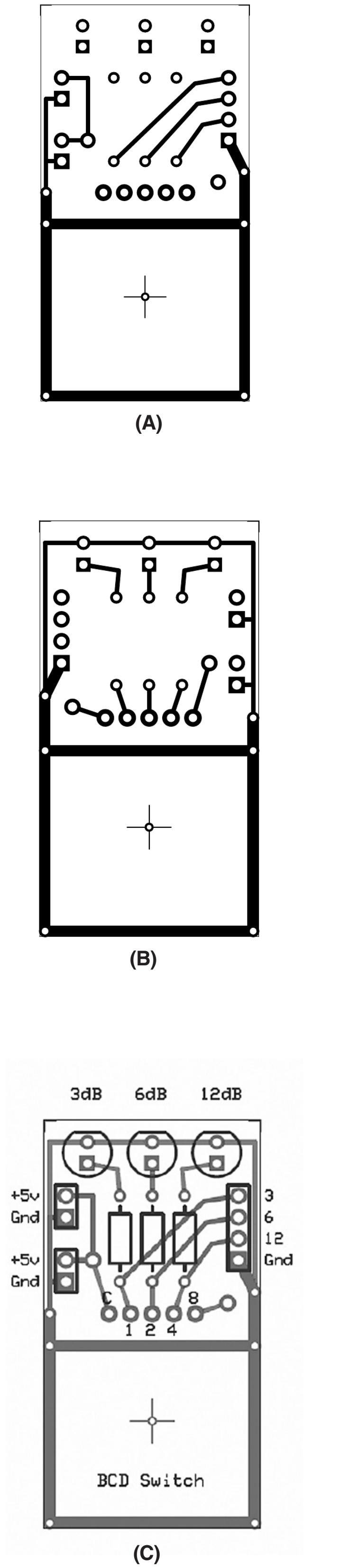


Figure 6 — BCD/hexadecimal switch PC board, (A) top layer, (B) mirrored bottom layer, (C) full layout. The board is 1.9 inches tall by 1 inch wide.

The end panels are held in place on the extrusion with the provided #6 screws, two to each panel. The groove features in the main extrusion that hold the end panel screws were not tapped, and I was concerned that simply screwing into these with the provided screws might liberate small chunks of aluminum that could get into the circuitry. I was also worried that the black coating of the provided screws might be an insulator. Consequently, I tapped the grooves with a #6-32 tap and thoroughly cleaned them afterward to make sure there were no loose bits of aluminum. I also used 1/2-inch long #6 stainless steel machine screws instead of the provided screws.

Just for good measure, on final assembly I used a thin coating of electrical anti-oxidant joint compound on all interconnecting metal surfaces, including the ground plane edges of the PCB where it slides into the main extruded enclosure. Anti-oxidant joint compound is sold in electrical supply and home repair stores. A little bit goes a long way. It is basically a viscous lubricant (polybutene) infused with powdered zinc. It inhibits corrosion by sealing pressure-fit dissimilar metal joints from air. One common brand is the NOALOX® compound from Ideal Industries.[8]

I had tinned the ground plane edges of the PCB, but the galvanic potential difference between aluminum and tin/lead is large enough that I was concerned about oxidation.[9] Hopefully, the joint compound will help keep corrosion at bay. I was concerned that excessive joint compound might migrate over time, get into the circuitry, and degrade performance of the attenuators, so I used the joint compound sparingly.

Switching Control

I considered simply using three toggle switches to route +5 V to the three control inputs of the attenuator, but settled on a more elegant method that used a Grayhill 25LB22-H binary coded decimal (BCD) or hexadecimal (hex) mechanical encoder. This is basically a rotary switch with one input and 4 outputs. Since I had a three-section attenuator, I needed only three of the 4 BCD outputs. Rotating the switch connects the input to the outputs in a BCD or hexadecimal sequence. This allows for selecting attenuation from zero to 21 dB in 3 dB steps.

The control circuit is shown in Figure 5. A two-pin Molex KK-style connector provides for connection of 5 V dc to the "C" or common pin of the rotary encoder, and the lowest three output pins are routed to a 4-pin connector that is wired to the attenuator. Three yellow LEDs and current limiting resistors provide visible indication of attenuator selection. The small PC board I used is shown in Figure 6, and the final assembly is shown in Figure 7.

I also created a position or dial plate, shown in Figure 8. I created the lettering design with the same PCB software that I used to make the PC boards, transferred the image to a piece of brass sheet just as I had done when making PCBs, then coated the plate with clear spray acrylic. I carefully cut a 3/8 inch diameter hole in the center to fit over the rotary switch.

The final attenuator and control are shown in Figure 9. I soldered a short cable made from 4 wires to the feed-through capacitor attenuator control points and a ground point and connected the other end to the control assembly with a 4-pin Molex KK-series connector. While not entirely necessary, I braided the 4 wires so they would stay together in a bundle.

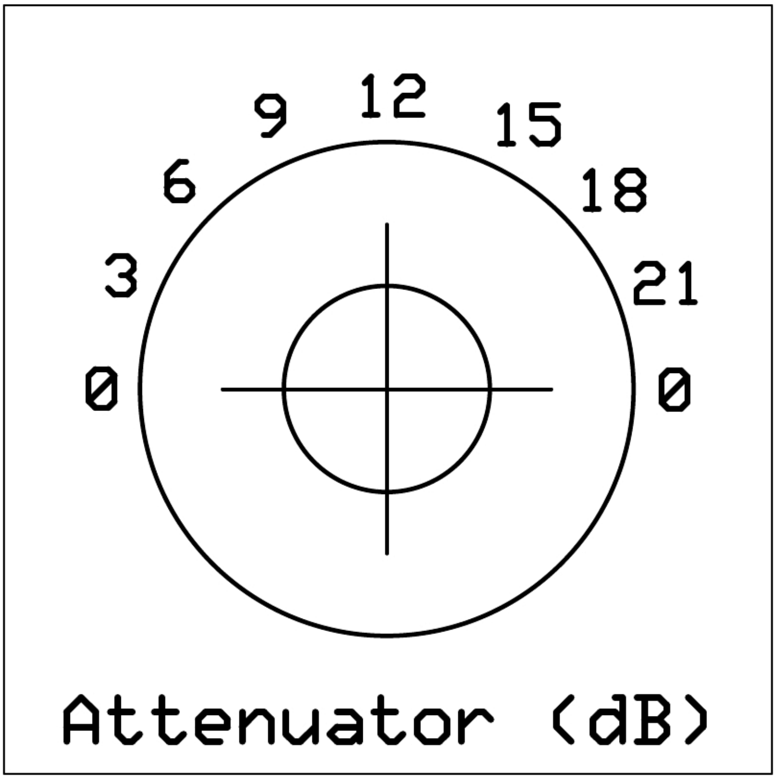


Figure 8 — BCD/hexadecimal switch position dial plate.

Verifying the Design

Not having access to the sort of test equipment needed to properly and comprehensively test this step attenuator, and not being willing to simply incorporate the attenuator assembly into a receiver without further design verification, I was compelled to improvise.

Input and Output Resistance Values

Firstly, while clearly insufficient, a simple dc resistance test provides a useful check of the basic assembly and design. When each relay is engaged, the Pi-network attenuator sections represent an easily calculated dc resistance to both the input and output ports. This test also checks relay function and shows mistakes like resistor selection errors or inadvertent solder bridges.

The dc resistance of a simple resistive Pi-network(Figure 10) is,

$$R_{in} = R_{out} = \frac{(R_1 + R_2)R_1}{2R_1 + R_2}$$

Table 2 shows the resistances for each of the three attenuator sections (Figure 1). For example, for an attenuation of 3 dB in a 50 Ω Pi-network, R_1 is 294 Ω and R_2 is17.8 Ω so,

$$R_{in} = R_{out} = \frac{(294 + 17.8)294}{2 \cdot 294 + 17.8} .$$
$$= 151.3\ \Omega$$

I used a multimeter to check the dc resistances at the input and output jacks with each of these attenuator sections engaged in turn. The measured resistances were all very close to the values in Table 2.

Table 2.
Attenuation for the shown resistance values.

Atten., dB	R_1	R_2	$R_{in} = R_{out}$
3	294	17.8	151.3
6	150	36	83
12	82.5	91.9	56

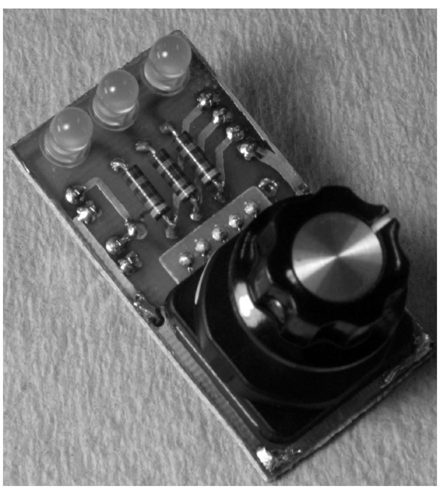


Figure 7 — Completed BCD/hexadecimal switch assembly.

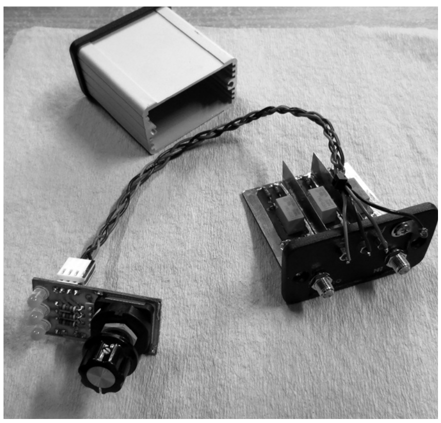


Figure 9 — Completed attenuator and BCD/hexadecimal switch.

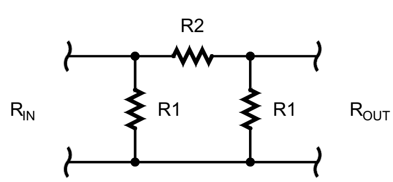


Figure 10 — Simple resistive Pi-network.

Attenuation at Different Frequencies

I also wanted a way to check the attenuation at each step and in the shortwave bands. My intention is to eventually incorporate this step attenuator in a software-defined radio, so I connected a DVB-T "dongle" with an HF up-converter to a fast desktop computer and downloaded a copy of *SDR#* software.[10] I connected the step attenuator between the HF converter and an outdoor HF antenna to verify that this lash-up functioned as a receiver on the HF bands. It did, so I disconnected the antenna and instead connected the input to an 80-meter VFO that I had built many years ago. I fed the VFO output through a 10- or 20-dB fixed attenuator both to reduce the signal to within the receiver's range and to ensure the VFO was driving into a fixed 50 Ω circuit to help stabilize the VFO performance. This VFO and attenuator provided a very adequate signal at 4.0 MHz, and adequate harmonics at 12 MHz and 24 MHz.

This receiver functioned as a tunable RF voltmeter that displayed signal amplitude in relative field strength decibel values — what *SDR#* refers to as "FSDB". The absolute FSDB didn't matter, since I was interested in the signal strength relative to a 0 dB attenuator setting. In this way I was able to measure the VFO signals at each of the 3-dB steps up to 21 dB and calculate the actual attenuation at each step. Results are shown in Table 3.

Closing Remarks

The attenuations at HF for the three attenuator sections (3, 6, and 12 dB) all appear very close to nominal, with the exception that the 12 MHz measurements were all slightly low. I also observed that the measured attenuations at the upper settings (18 and 21 dB) are consistently low for all three test frequencies. I will speculate that the isolation between sections may be the culprit, and that signal is leaking around the attenuators. As I noted earlier, others have reported that isolation between attenuator sections was important.

At one point I considered adding a fourth section (24 dB) to allow for higher attenuation settings, but it seems now that it might have been difficult to realize uniform higher attenuation steps without greater internal isolation. This probably would have required a much larger enclosure and larger section shields on the PC board, or possibly a design that would have better isolation between the attenuator sections. If I were to build a second unit I would try to increase the size of the internal shields to whatever the enclosure would allow to see if that would help on the higher attenuation settings. There might also be a way to use brass EMI finger stock to improve the ground connections along the edges of the PCB where it slides into the extrusion.

This step attenuator was clearly adequate for my intended use. When tuning around the HF bands, this step attenuator was a useful addition. The 3-dB steps felt about right. Smaller steps would not have been helpful. Certain very strong signals were immediately shown to be generated internally by the SDR circuit when changes in the attenuation showed no amplitude change. It was also helpful to use the attenuator in combination with the *SDR#* RF gain control to find just the right compromise of receiver sensitivity and reduction of splatter and noise from strong local signals.

Table 3.
Measured attenuation at 4, 12 and 24 MHz.

Atten., dB	*4 MHz*	*12 MHz*	*24 MHz*
3	3.1	2.7	3.1
6	6.1	5.7	5.9
9	9.0	8.5	9.0
12	12.3	11.4	12.1
15	15.5	14.2	14.8
18	17.9	17.0	17.7
21	20.4	19.8	20.6

Scott Roleson, KC7CJ, was first licensed in 1964. He has been an ARRL member for over 50 years. Scott has a BSEE from Arizona State University, an MSEE from the University of Arizona, is a licensed Professional Engineer in California, and is a Life Senior Member of the IEEE. From 1993 to 1995 he was a Distinguished Lecturer of the IEEE EMC Society, and was the Distinguished Lecturer program chair 1995-1997. He retired after a 32-year career in electrical engineering where he worked on spectrum analyzer design, EMC and telecom regulatory engineering, Scott now gets to pick his own projects to maximize the fun return-on-investment.'

Notes

[1] Bramwell, W7OWJ, "An RF Step Attenuator," *QST*, Jun. 1995, pp. 33-34.

[2] J. J.de Oñate, MØWWA and X. R. Junqué de Fortuny, "A Software Controlled Radio Preselector," *QEX*, May/June 2008, pp. 11-18.

[3] An RF step attenuator is shown on p. 25.56 in *The ARRL Handbook for Radio Communications,* 2019 Edition. Available from your ARRL dealer or the ARRL Bookstore, ARRL item no. 0888. Telephone 860-594-0355, or toll-free in the US 888-277-5289; **www.arrl.org/shop**; **pubsales@arrl.org**.

[4] P. Ostapchuk, N9SFX, "A Rugged, Compact Attenuator," *QST*, May 1998, pp. 41-43.

[5] B. Shriner, WAØUZO and P. K. Pagel, N1FB, "A Step Attenuator You Can Build," *QST*, Sep. 1982, pp. 11-13.

[6] *Audioholic*s magazine reviewed several studies of minimum detectable fluctuation in normal human hearing and found a range of values between 0.25 and 3 dB. See: Mark, "Human Hearing: Amplitude Sensitivity Part 1," Audioholics, 4 Apr. 2005; online at: **www.audioholics.com/room-acoustics/human-hearing-amplitude-sensitivity-part-1**.

[7] Resistor values for Pi- and T-networks are on p. 22.44 in *The ARRL Handbook for Radio Communications,* 2019 Edition (op. cit.), also in **www.microwaves101.com/encyclopedias/attenuator-calculator** and **chemandy.com/calculators/matching-pi-attenuator-calculator.htm**.

[8] For more information, see: **www.idealindustries.ca/products/wire_installation/accessories/noalox.php**.

[9] A good discussion of galvanic corrosion can be found at: H. W. Ott, *Noise Reduction Techniques in Electronic Systems, Second Edition*, John Wiley & Sons, 1988, pp. 23-25.

[10] This simple SDR arrangement was similar to those described by R. Nickels, W9RAN, "Cheap and Easy SDR," *QST*, Jan. 2013, pp. 30-35, and J. Forkin, WA3TFS, "All-Mode 1 kHz to 1.7 GHz SDR Receiver," *QST*, Jan. 2016, pp. 30-33.

Table 4
Bill of materials.

Item	*Qty*	*Source*
Brass sheet, 0.010 inch thick, K&S Stock #251 or equiv.	1	Available in hobby or hardware stores
Diodes, 1N4001 or equiv.	3	www.jameco.com
EMI filters, Tusonix bushing style (0.01μF feed-thru capacitors), type 4400-035LF	3	www.mouser.com
Enclosure, Hammond 1457C1201 or 1457C1201E	1	www.digikey.com – HM1012-ND
Hex rotary encoder, Grayhill 25LB22-H	1	www.digikey.com – GH3074-ND
LED, yellow	3	DigiKey, Mouser, or Jameco
Molex KK connectors (0.100 inch) 4-pin and 2-pin, male and female	5	DigiKey, Mouser, or Jameco
Relays, NEC EC2-5NJ	3	www.jameco.com
Resistors (see Note 7), Metal film, 1/4 W, 5%	9	www.mouser.com
Resistors, 130 Ω, 1/4 W	3	DigiKey, Mouser, or Jameco
SMA female, PCB mount bulkhead connectors	2	www.amazon.com