Power Coupler for VLF and LF Antenna Applications

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1. Introduction

This is the third in a series of articles that describes VLF and LF antenna and receiver applications and accessories. The second article described the construction of VLF-LF radio frequency chokes for reducing common mode noise on loop antenna feeder cables {Reeve20-1}. The chokes were designed to support the refurbished HP 10509A active loop antenna described in the first article {Reeve20-2}. Two different *power couplers* for the refurbished antenna were briefly described but no design and construction details were given. The current article follows up with a detailed description of power couplers for the frequency range 10 to 100 kHz (figure 1).

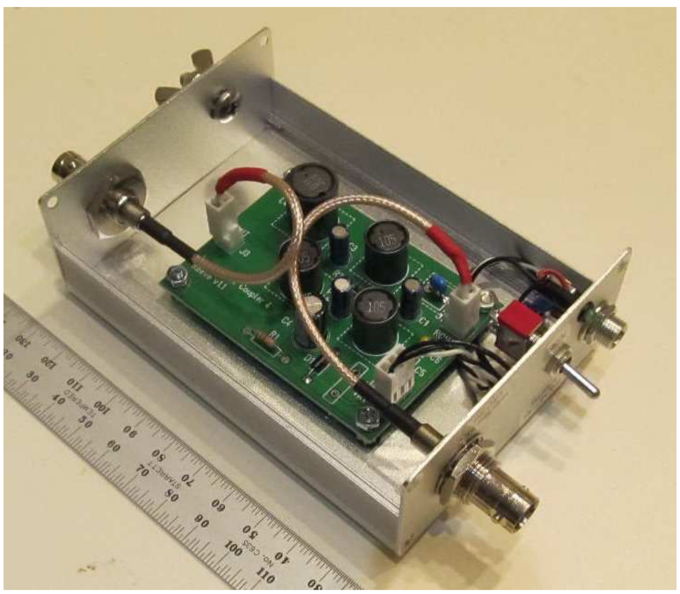

Figure 1 ~ Power coupler for VLF and LF applications with multi-stage lowpass filter and power controls in an extruded aluminum enclosure. This is one of several variations built over a 3-year period for the HP 10509A loop antenna. It uses RG-316 coaxial cables from the BNC-F bulkhead connectors to the PCB, but twisted pairs work just as well at the low frequencies of operation and have been used in other variations. Image © 2021 W. Reeve

An antenna power coupler, also called *bias-tee* or *power injector*, supplies power to the active electronics in the loop antenna over the same cable used to carry the antenna signals back to the receiver. The power coupler described here is designed for supply voltages up to 30 Vdc and currents up to 200 mA. The voltage and current limits can be reasonably increased by using higher rated components. This power coupler can be used with any loop antenna or active low frequency receive-only antenna system that operates within the limits.

4. Design Considerations

The major blocks of the loop power coupler are the ac and dc coupling elements, a multistage lowpass filter, and power control (figure 2). The schematic (figure 3) shows all components that are installed on the printed circuit board (PCB). The PCB (figure 4) uses through-hole components but it could be redesigned with surface mount technology (SMT) if necessary to reduce its size. All power control components (figure 5) are mounted separately on the enclosure panel.

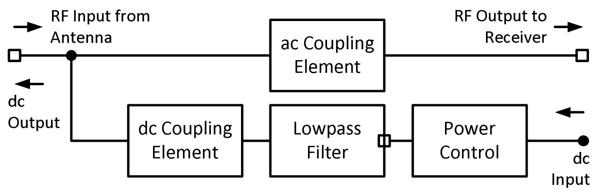

Figure 2 ~ Power coupler block diagram showing major components. Image © 2022 W. Reeve

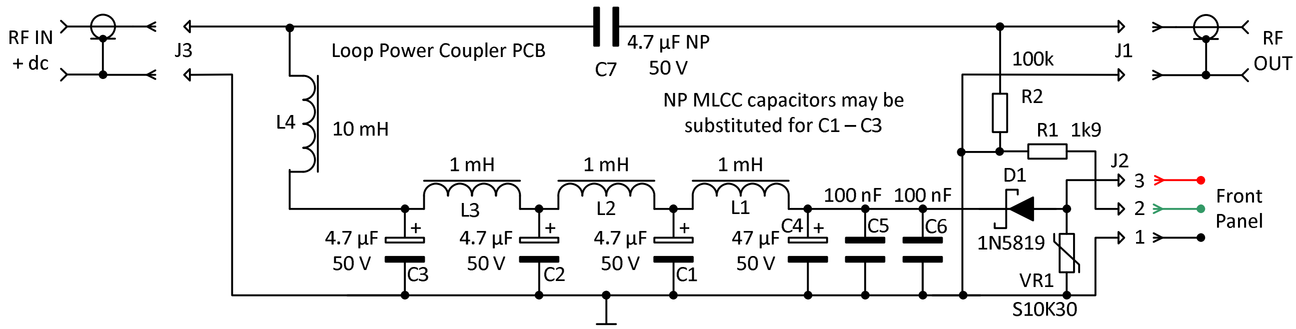

Figure 3 ~ Schematic showing the PCB-mounted components. The reactance of the inductor L4 at 32 kHz (the geometric mean operating frequency) is about 2000 kohms and provides plenty of dc power supply isolation. The multi-stage lowpass pi-filter prevents any dc supply noise from being coupled to the antenna or receiver. The combined dc resistance of the series elements in this dc circuit is 12.2 ohms (not including external power control components and assuming zero PCB ground plane resistance). R1 is a current limiting resistor for the power indicating LED on the front panel and R2 provides a discharge path to ground for C7. The PCB was built with both non-polar (NP) and polar capacitors (see text). Image © 2022 W. Reeve

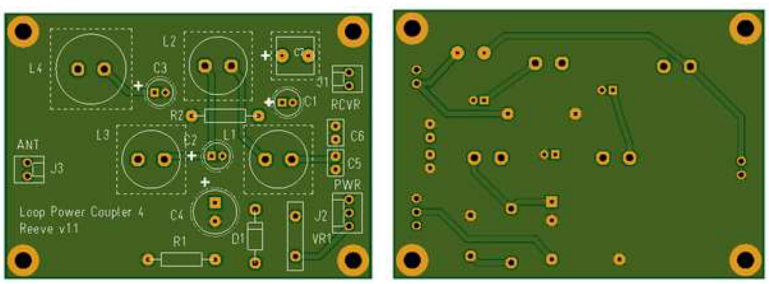

Figure 4 ~ The schematic previously shown was implemented on a printed circuit board with dimensions 70 L x 51 W mm. All components are through-hole types and latching headers are used to allow easy connection and disconnection. PCB cost is a couple dollars. It was designed with the Target 3001! PCB CAD software tool and produced by JLCPCB.

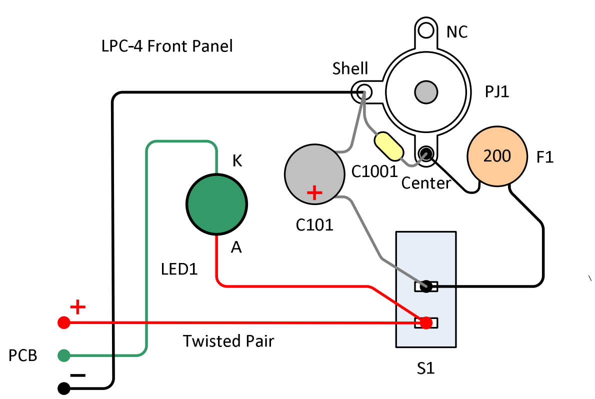

Figure 5 ~ Wiring diagram of the power control components on the front panel. The LED can have a built-in current limiting resistor or resistor R1 can be placed on the PCB to provide that function; if a built-in resistor is used, R1 is replaced by a wire jumper on the PCB or the LED cathode may be wired directly to the power connector shell. Capacitor C101 is 10 µF, 50 V and C1001 is 100 nF, 50 V. The dc resistance of the 200 mA PTC fuse is 2.8 ohms during normal operation. A miniature SPST toggle switch S1 provides the On-Off function. 24 AWG stranded twisted pair is used to connect the front panel to the PCB through a latching 3-pin connector. Image © 2022 W. Reeve

The current limit is determined by the resettable positive temperature coefficient (PTC) fuse and inductors and the voltage limit is determined by the filter capacitors. The inductors must be able to safely carry the powering current while not saturating the ferrite core. Temperature rise is used to define the safe powering current and percentage reduction in inductance is used to define the saturation current. As would be expected for wire and ferrite core inductors, a higher current raises the temperature while reducing the inductance due to the nonlinear characteristics of ferrite cores when saturated. I used the current that raises the temperature 20 °C above a 25 °C ambient. For all the inductors, this is less than the current that gives 10% inductance drop.

Other aspects of inductor applications are shielding and self-resonant frequency. The coils are in fairly close proximity on the PCB so to reduce mutual coupling, I chose shielded inductors from the Coilcraft RFS-series. Shielding adds cost but the bank does not get broken on small projects like this. The self-resonant frequency (SRF) ideally should be at least 10 times higher than the highest application frequency; however, this may not be possible with high value inductors such as used here. The inductors I used have an SRF of at least 450 kHz, 4.5 times the highest application frequency.

Important capacitor characteristics besides capacitance value include technology, temperature environment and voltage. Aluminum electrolytic capacitors are a common choice, but MLCC (MultiLayer Ceramic Capacitor) are economical in the capacitance and voltage ratings used in the filter. MLCCs do not suffer the problems associated with electrolytic capacitors such as temperature-related wearout and relatively high equivalent series resistance (ESR). MLCCs are available with many different dielectric classes or characteristics with X7R being the most common. I avoid using tantalum capacitors, mainly because they make a big, smelly mess when they fail.

I generally choose 105 °C rated electrolytic capacitors with a voltage rating 1.5 to 2.0 times higher than the working dc voltage. Other parameters affect electrolytic capacitor applications including their rated time (in hours) at rated temperature. I use the highest time rating available at a reasonable cost (usually 2000 hours). I prefer to use non-polar (NP) electrolytic capacitors or MLCC in low frequency ac coupling circuits but they can be more expensive than polar type electrolytics. As with the inductors, cost can be a factor in capacitor choice but for small projects it is not worth losing sleep over. I have built versions of the power coupler that use both electrolytic capacitors and MLCCs and they perform the same.

The lowpass filter in the dc feeder circuit reduces the noise coupled into the RF circuit from the power source and associated cabling. Filter parameters include cutoff, inband and band reject frequencies and input and output impedances. Generally, filters are designed according to a specified performance; however, in this case, I used components on-hand and then simulated it in the Almost All Digital Electronics (AADE) Filter Design software tool.

The dynamic output impedance, Z_{Out}, of the power source is estimated from

$$Z_{Out} = \frac{VR}{100} \cdot \frac{V_{Out}}{I_{Out}}$$

where VR is the output voltage regulation as a percentage, and V_{Out} and I_{Out} are the output voltage and current, respectively. Where VR = 2%, V_{Out} = 12 V and I_{Out} = 50 mA, then Z_{Out} = 9.6 ohms (call it 10 ohms). This impedance is assumed to be resistive. The impedance on the antenna side of the filter is based on the 50 ohm system impedance and it also is assumed to be resistive.

Under these conditions, the filter response shows several resonances and loss slopes, as determined with the AADE Filter tool (figure 6). The 3 dB corner frequency of the filter is about 100 Hz and it provides 40 dB attenuation at about 4 kHz and 60 dB at 5 kHz Above 9 kHz, the theoretical filter loss is over 120 dB (the loop antenna and receiver lower frequency limit is 10 kHz). This filter will not reduce the fundamental powerline frequency or its lower harmonics but can reduce noise from switching power supplies and other spurious sources that couple to the power cable.

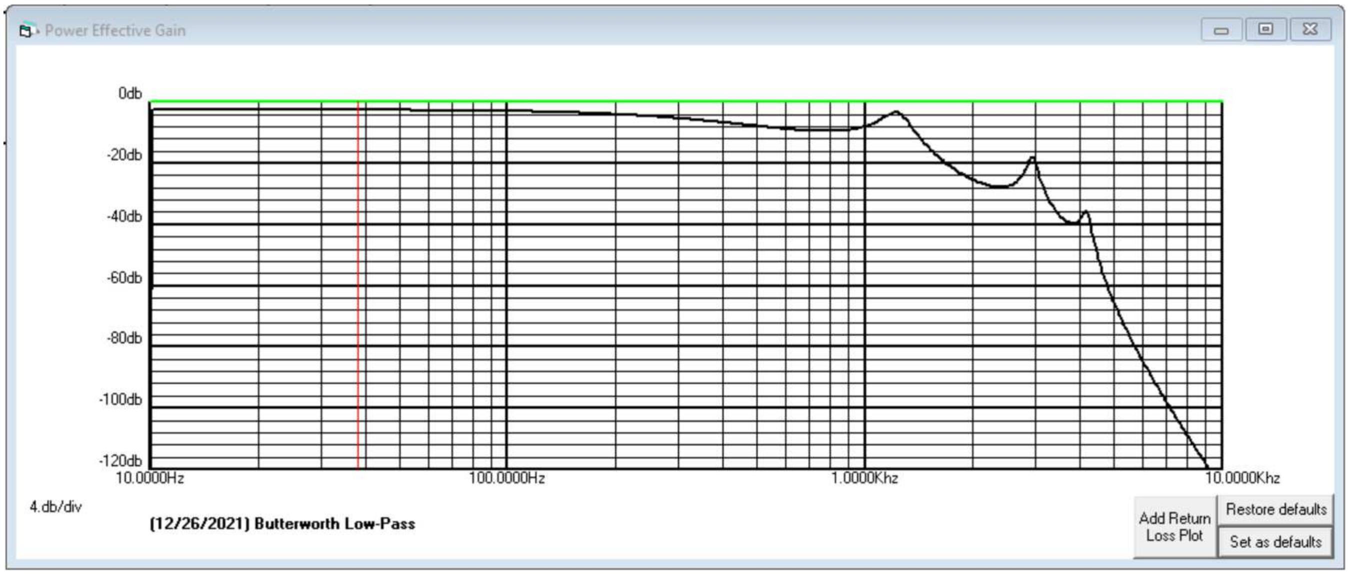

Figure 6 ~ Theoretical filter response from 10 Hz to 10 kHz with 10 ohm power supply and 50 ohm antenna impedance (both resistive). Not shown in this plot, but to be expected, are response changes if different input and output impedances are used. The red vertical line is an arbitrary cursor position. The minor tick marks on the vertical scale are 4 dB/division. An 8th order lowpass filter template was used for inputting the actual component values for simulation in the AADE Filter tool. A Q of 20 was used for all inductors. No attempt was made to optimize the filter component values; for example, the resonant peaks at 1200, 3000 and 4200 Hz could be reduced by using regular filter design procedures.

Protection circuitry consists of a 200 mA resettable PTC fuse, a 1 A, 40 V polarity guard diode and an S10K30 varistor, the latter for clamping input voltage transients. These components may be placed on the front panel with the coaxial dc power connector, power on-off switch and power indicating LED. However, the design described here has pads on the PCB for the diode and varistor so they can be populated if desired. I always try to place the overcurrent device, in this case the resettable PTC fuse, as close to the power inlet as possible, so it usually is on the front panel. I also place an electrolytic or MLCC bulk filter capacitor and a small MLCC filter capacitor on the front panel close to the power inlet. These are meant to reduce noise infiltration from the external power supply and connecting cable and are not included in the analysis of the pi-filter frequency response described above.

The power indicating LED on the front panel requires a current limiting resistor. LEDs can be obtained with built-in resistors or R1 can be placed on the PCB for this purpose. I generally operate power indicating LEDs between 7 and 10 mA and assume a voltage drop of 2.1 V across the LED. I also use very low-current (2 mA) LEDs. With a 24 Vdc input, the voltage drop across the current limiting resistor would be 21.9 V for regular LEDs. To limit the LED current to 10 mA, the resistor would be 21.9 V/0.010 A = 2190 ohms and for 2 mA would be 11 kohm. For 12 Vdc input, the resistors would be 990, rounded to 1 kohm, and 4950 ohms, rounded to 5 kohm, respectively.

In the 24 V example, the power would be $(0.010\ A)^2$ x 2190 ohms = 0.219 W. A 1/4 W resistor would have too little margin and would get hot, so a 1/2 W resistor would be used. With the very low-current LED, the power dissipation is only 0.04 W, so a 1/8 or 1/4 W resistor may be used.

The total dc resistance of the power control components (mainly the PTC fuse), wiring and filter and coupling components on the PCB is 15 ohms. For a 50 mA load current, the voltage drop is 0.75 V. To this is added the voltage drop across the polarity guard diode, which is on the order of 0.5 or 0.6 V. The voltage drop at full load (200 mA) is about 8 V including the diode. These voltage drops need to be taken into account to ensure the active electronics in the antenna are adequately powered, especially if they include voltage regulating components that require voltage overhead for regulation.

All components are enclosed in a metal box. For projects like this, I use extruded aluminum clamshell enclosures with dimensions 110 x 80 x 36 mm (figure 7). These enclosures are inexpensive, a few dollars each, and easy to drill. The PCB is mounted on brass hex standoffs, typically male-female, M3x6x6 mm.

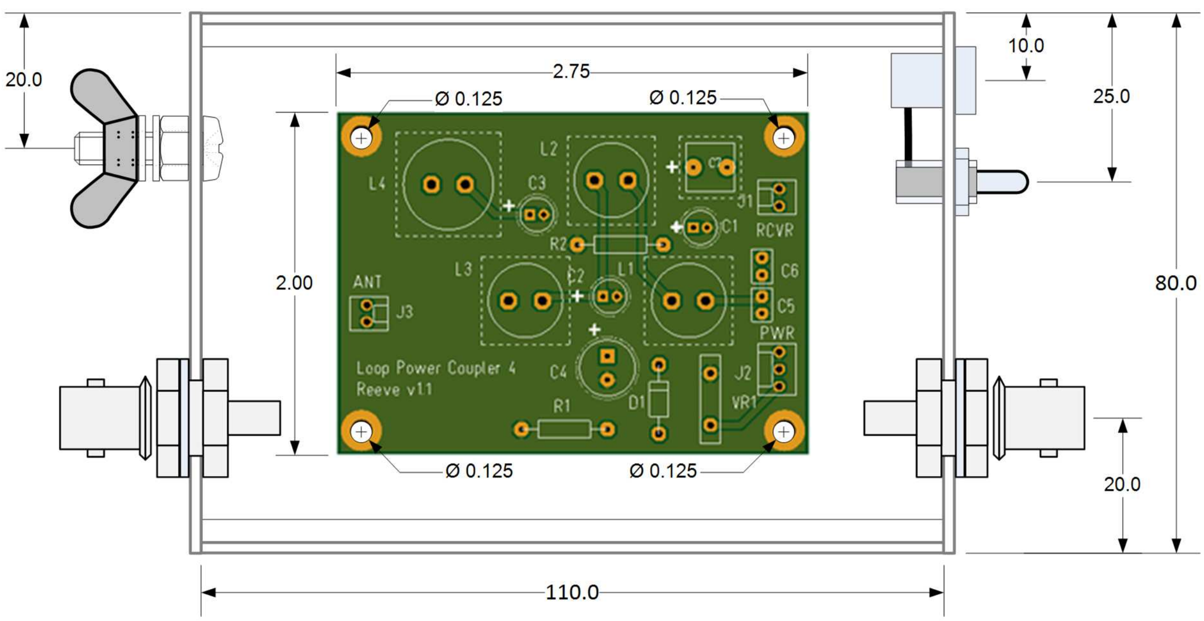

Figure 7.a ~ Enclosure interior layout shown at approximately 100% scale. The original drawing is used as a drilling template. Native dimensional units of components, either inches or millimeters, are used for convenience of shop construction and to reduce conversion errors. Image © 2022 W. Reeve

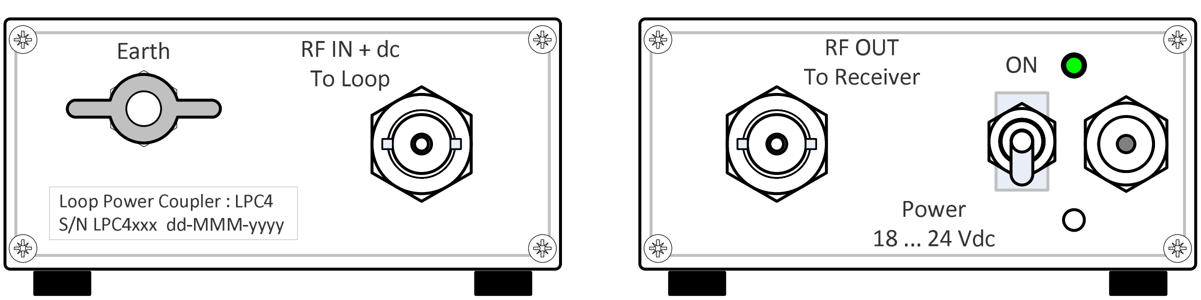

Figure 7.b ~ Front and rear panel layouts shown at approximately 100% scale. Crimp or solder-cup BNC-F connectors may be used for RF connections and a 2.1 x 5.5 mm coaxial dc power jack is used for power connections. A 10-32 stud and wing nut with washers are used for earth bonding. Image © 2022 W. Reeve

Twisted pairs or small coaxial cables can be used to connect the panel RF jacks to the PCB. I use aviation wire twisting pliers to twist two 24 AWG stranded hookup wires for this purpose. RG-316 or RG-174 are good choices if coaxial cable is used. BNC-F bulkhead mount connectors can be purchased with coaxial cable already crimped or they can be shop-assembled, or solder-cup type connectors may be used. RF and power connections to the PCB are through latching friction lock headers and wire housings to allow easy experimentation, assembly and test.

5. Variations

The basic power coupler design is flexible, and several variations have been built. One (figure 8) includes a linear step-down power supply that has as its input the observatory standard 12 (or 13.5) Vdc power supply voltage and outputs 8.7 Vdc for a special *wideband* (10 to 100 kHz) loop preamplifier design.

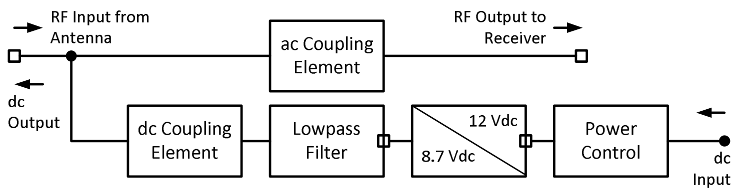

Figure 8.a ~ Block diagram of a power coupler variation with a step-down power supply. Compare to figure 2. Image © 2022 W. Reeve

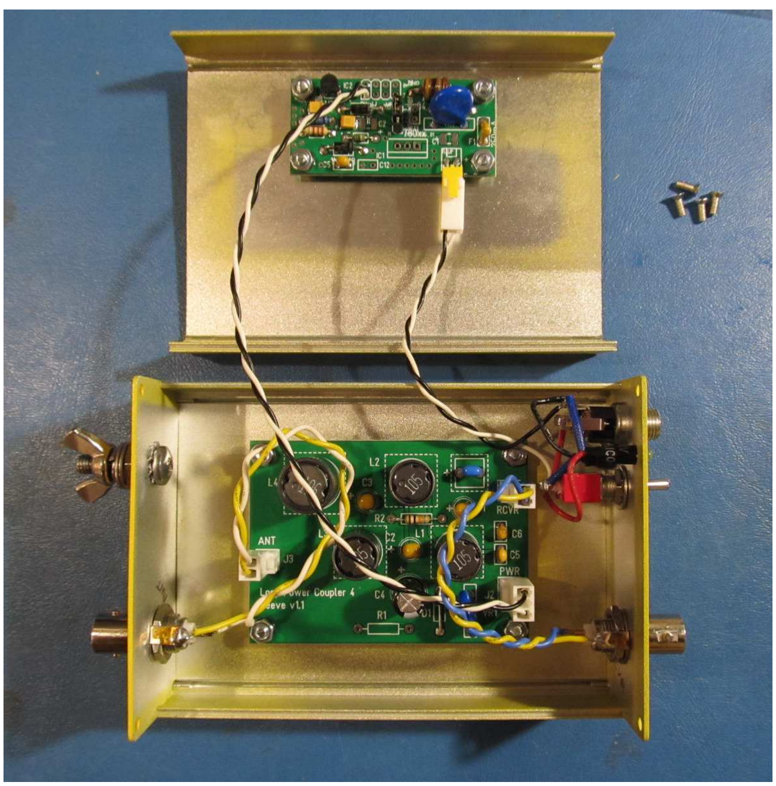

Figure 8.b ~ Alternative version with built-in step-down power supply. The bottom section of the clamshell enclosure holds the filter/power coupler PCB and the top section holds the step-down power supply. The step-down power supply uses a universal PCB that was designed for several applications. For clearance between the filter and power supply boards, the PCBs were installed with M3x4 mm brass hex standoffs. All connections are through latching wire housings and headers, which simplify experimentation and testing. This particular unit uses twisted pairs and solder-cup BNC-F bulkhead connectors for the RF connections. The enclosure was painted yellow to indicate its specific use with a similarly painted loop antenna. Image © 2022 W. Reeve

6. References and Weblinks

{Reeve20-1} Reeve, W., RF Choke for VLF and LF Applications, 2020, available at: https://www.reeve.com/Documents/Articles%20Papers/Reeve_VLF-LF-RFChoke.pdf

{Reeve20-2} Reeve, W., Solid-State Update for the HP 10509A Loop Antenna, 2020, available at: https://www.reeve.com/Documents/Articles%20Papers/Reeve_HP10509A_SSUpdate.pdf

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