Solid-State Update for the HP 10509A Loop Antenna

Whitham D. Reeve

1. Introduction

The HP 10509A loop antenna (figure 1) was originally included with the HP 117A VLF Comparator and described in the October 1964 Hewlett-Packard Journal [HPJournal]. This system was designed to receive narrowband 60 kHz signals from the WWVB time-frequency station in Colorado for comparison with local frequency standards. I acquired the loop (but not the comparator) in 2018 for propagation studies and sudden ionospheric disturbance (SID) detections at 60 kHz but, through measurements, found it could be used over a relatively wide frequency range by changing its built-in preamplifier.

Figure 1 ~ HP 10509A loop antenna originally supplied with the HP 117A VLF Comparator. The loop diameter is 43 in (1.09 m). A preamplifier is located in the enclosure at its base. Image source: [HPJournal]

The loop antenna is made from heavy-duty aluminum tubing and includes a built-in double-tuned preamplifier assembly mounted inside a cast aluminum enclosure at the base of the antenna. The only external connection is through a BNC-F connector for a coaxial cable that carries dc power to and RF signal from the preamplifier. The original system was designed for up to 1000 ft (300 m) of cable.

HP's first version of the preamplifier was based on a pair of 13CW4 Nuvistor triode vacuum tubes in a push-pull configuration with a *magnetostrictive* bandpass filter on the output. The filter, commonly called a *mechanical filter*, has a bandwidth of 30 Hz and apparently was needed to prevent RFI pickup on a long feedline cable from reverse blocking the push-pull preamplifier.

Later antenna versions were upgraded to solid-state technology using a dual N-channel J-FET with either a crystal filter or resonant output coupling transformer. The resonant coupling transformer has much wider bandwidth than either the mechanical or crystal filter. Four different versions of the preamplifier assembly were produced over time but the loop itself apparently remained the same. Although the original schematics and parts lists are available, no performance information is available for these different preamplifiers.

My antenna originally used the Nuvistor preamplifier but I upgraded it with a drop-in replacement, solid-state preamplifier that I shop-built based on a later HP design. I describe the upgrade in this article, which includes antenna refurbishment, design of the new preamplifier, comparative measurements of the old and new preamplifiers and field tests. Since no published performance data are available my goal was to simply provide equal or higher gain compared to the original preamplifier installed in my antenna. I also have been working on a drop-in replacement preamplifier that covers the frequency range 10 to 100 kHz and accessories for low frequency station operation including RF chokes and splitters. These will be described in future articles.

According to [HPJournal], the loop antenna's effective electrical height is 1.6 cm; therefore, it converts a signal with field strength of, say, 60 μV m^{-1} to an antenna terminal voltage of $60 \cdot 0.016 = 1$ μV where it is applied to the preamplifier and then the receiver. This field strength marks the advertised sensitivity of the original HP 117A system, which included a Nuvistor receiver with 120 dB gain. I expected the overall performance of my setup to be similar but certainly more versatile when used with a software defined radio (SDR) receiver.

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2. Refurbishment

After I acquired the loop antenna, I decided to refurbish it and investigate whether or not a solid-state conversion to the preamplifier would have any advantages. The resulting preamplifier is described in the next section. The loop itself is constructed of 1 in (25 mm) diameter heavy-duty aluminum tubing formed into a circle and attached to a weatherproof cast aluminum enclosure that is identical to a T-style conduit body used in ac electrical power distribution systems. The enclosure houses the preamplifier and has an O-ring gasket on its cover to keep moisture out.

The loop outside diameter is 43 in (1.09 m) and it weighs 12.5 lb (5.7 kg) without the mast. The loop is wound in a center-tapped configuration with the center-tap bonded to the base enclosure. The wire size and type and the number of windings are unknown. The windings are secured in the tubing with foamed-in-place polyurethane. A center brace, also made from 1 in diameter aluminum tubing, provides additional structural support. A 1 in (trade size) threaded pipe coupling is installed on the bottom of the preamplifier enclosure for easy mounting on a mast made from galvanized water pipe or electrical conduit. A 48 in (1.2 m) long x 1.3 in (33 mm) diameter factory mast was included with my antenna.

Figure 2 ~ Loop antenna sitting on saw horses after the paint has cured for 48 h. The threaded pipe coupling for mast mounting can be seen on the left, where it is connected to the preamplifier housing. Image © 2019 W. Reeve

As received, my loop was in surprisingly good mechanical condition considering its age; it needed only cleanup and refinishing. After removing the original Nuvistor preamplifier, I cleaned the loop assembly by wiping with a cloth dampened with lacquer thinner to remove any hardened oils followed by wiping with a cloth soaked in a mild solution of TSP (trisodium phosphate). After rinsing off the TSP solution and drying the loop, I lightly sanded the surfaces to remove scale and wiped again with a cloth dampened with lacquer thinner. Finally, I applied several coats of Krylon All-Purpose Bonding Primer followed by several coats of Krylon Gloss Ivy Leaf spray paint. The finish was cured at room temperature for 48 h before handling (figure 2). In addition to cleaning and painting the loop, I also checked the electrical continuity and ac characteristics of the windings. These measurements are discussed in section 5.

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3. Preamplifier design

I was intrigued by the simplicity of HP's last preamplifier design shown in the 1970s Operating and Service Manual [HP117A]. It uses a dual N-channel J-FET in a push-pull configuration and a unique tuned output coupling transformer. The transformer is based on four fixed RF choke coils mounted in pairs close to each other (touching) for coupling, two in the primary and two in the secondary. I decided to replicate this design as best I could. None of the original HP parts are available so I substituted modern parts and designed a printed circuit board (PCB) to accommodate them.

I used Target 3001! v19 PCB CAD tool to produce the schematic and PCB design. The PCBs were manufactured for me by Shenzhen JLC Electronics Co., Ltd (JLCPCB). The schematic (figure 3) and most component values are identical to the HP version. Of course, the parts themselves are different, particularly the dual J-FET and inductors used in the output coupling transformer. I initially built several preamplifiers with the same values as HP but later experimented with different source resistor values. Additional details are given in the **Appendix** (Note: The **Appendix** appears only in the online version of this article).

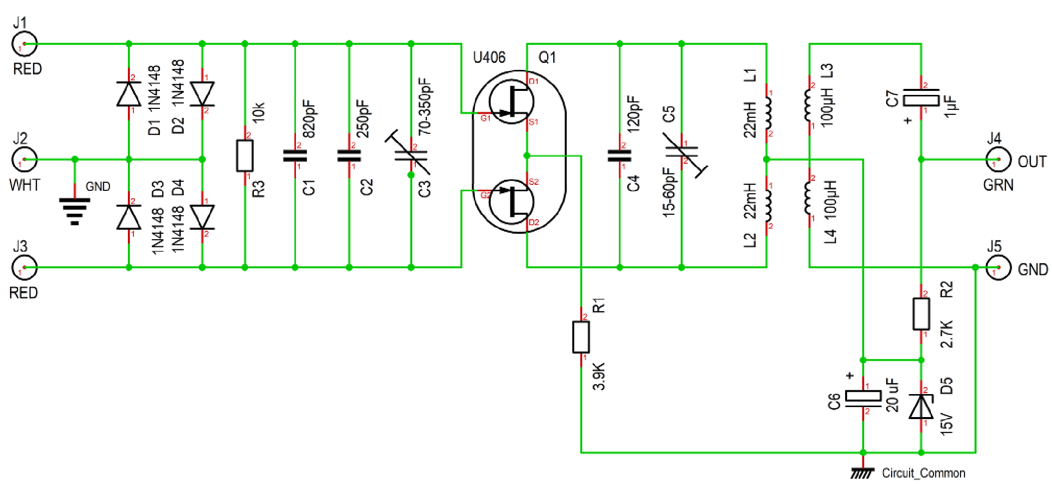

Figure 3 ~ Preamplifier schematic produced by the Target 3001! PCB CAD program. Note the two different ground reference points, one labeled GND on far-left connected to the antenna center-tap and the other labeled Circuit_Common on bottom-right connected to the dc input and RF output circuit. The references are isolated from each other on the PCB and then bonded through the aluminum enclosure at the base of the antenna (the same as in the original HP preamplifier). The input resonant circuit includes the loop inductance and capacitors C1, C2 and C3. The values shown for C1 and C2 are given in the HP 117A manual; I used a single 1500 pF silver mica capacitor and placed it in the C2 position. In my antenna this provided resonance at half-mesh of the trimmer capacitor C3. The output resonant circuit consists of C4 and C5 across the output transformer primary L1 and L2. The components at the lower-right of the schematic form a simple 15 V zener diode voltage regulator.

In terms of replicating the HP design, two aspects of the circuit required some investigation: First, no information is available for the transistor except that it is a dual N-channel J-FET, HP part number 1855-0050. No cross-reference is available, so I experimented with several different low noise devices including the 2N3954, 2N5517, IFN401 and U402. The IFN401 is supposed to be a higher performance replacement for the U401, which is a slightly better balanced version of the U402; Second, only the inductance values are given in the HP manual for the fixed inductors in the output transformer primary and secondary, so I experimented with several different types of inductors of the same values as original. I did not experiment with different inductance values.

The primary of the output coupling transformer consists of two 22 mH inductors, L1 and L2, which are resonant with C4 and C5. Two 100 μH inductors, L3 and L4, are mounted adjacent and inductively coupled to L1 and L2 for the output. I installed the inductor bodies 3 mm above the PCB, which allows their bodies to be easily adjusted for closest proximity to each other. The output transformer also functions as a balun to couple the balanced output from the dual J-FET to the unbalanced coaxial circuit to the receiver. The impedance of the transformer secondary is about 75 ohms (reactive) not considering the primary and mutual inductance. Power is supplied to the J-FET through the center-tap of the transformer primary.

The PCB layout (figure 4) follows the general circuit flow of the schematic. The PCB dimensions are 4.75 x 1.5 in (121 x 38 mm) and approximately the same dimensions as the original vacuum tube preamplifier (figure 5). The preamplifier input circuit resonates the antenna inductance, which I found through measurements is 3.9 mH at 60 kHz. The dual J-FET circuit has a very high input impedance that does not load the circuit.

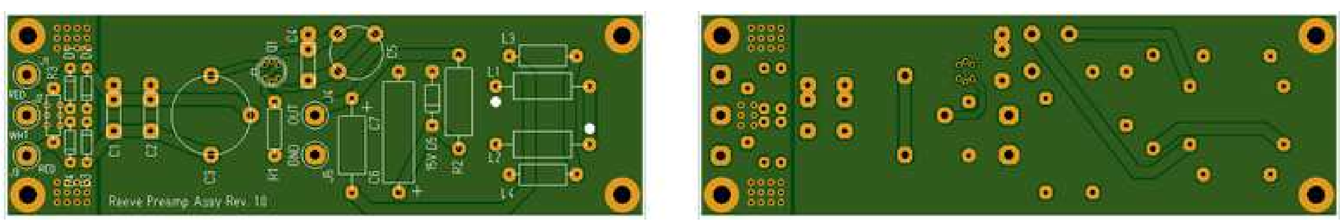

Figure 4 ~ Preamplifier 2-layer printed circuit board showing (left) top/component side and (right) bottom side (reversed from actual). The thin separation of the two reference grounds is visible near the left side of the images. The loop connects to the three terminals on the far-left between the mounting holes. The power input/RF output terminals are near the middle of the PCB. Images are rendered by a viewer that uses the PCB Gerber files.

On the PCB I isolated the ground associated with the loop windings center-tap and input protective diodes and the ground associated with the electronics, as in the original HP design. These are bonded though the cover of the aluminum enclosure on which the PCB is mounted. My PCB layout generally follows the original HP design shown in pictures provided in the HP 117A manual. I paid particular attention to the layout of the RF chokes used for the output coupling transformer. Of course, the PCB substrate and trace routing are not the same as the original. I used threaded tinned brass turret terminals for the five off-board connections: Loop A; Loop B; Loop center-tap/ground; Circuit common/ground; and RF out/dc in. These allow easy temporary test connections as well as durable permanent wiring connections. I built five preamplifiers with different combinations of transistors and inductors (figure 6). Inductor part numbers are given in the **Appendix**.

The new PCB is mounted to the enclosure cover with four 6-32 x 1/4 in (6.35 mm) threaded hex stand-offs (the original vacuum tube PCB had three built-in round stand-offs). I hoped to use the original three mounting holes but their locations presented problems with the layout of the new PCB. I ended up cutting three new holes (figure 7) and plugging the unused holes with epoxy. Some of the original fasteners had some rust so I replaced all fasteners with stainless steel equivalents.

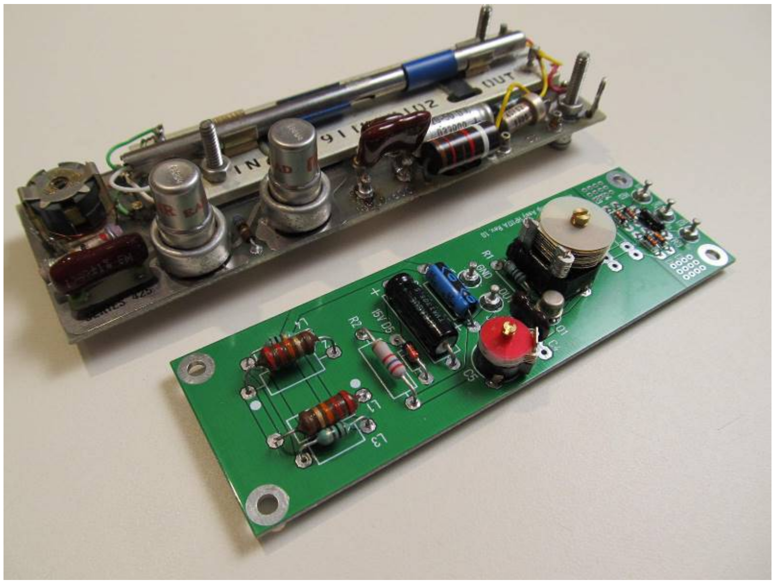

Figure 5 ~ Comparison of the original Nuvistor-based loop preamplifier (rear) and new preamplifier. The 60 kHz mechanical filter is the long cylinder along the back of the preamplifier and the two Nuvistors are the vertical silver cylinders. The preamplifier uses only a few components and represents the technologies of the early 1960s. The new preamplifier in the front uses FR4 PCB substrate. Nothing in the new preamplifier represents state-of-the-art technologies but the components are far more modern than the original. Image © 2019 W. Reeve

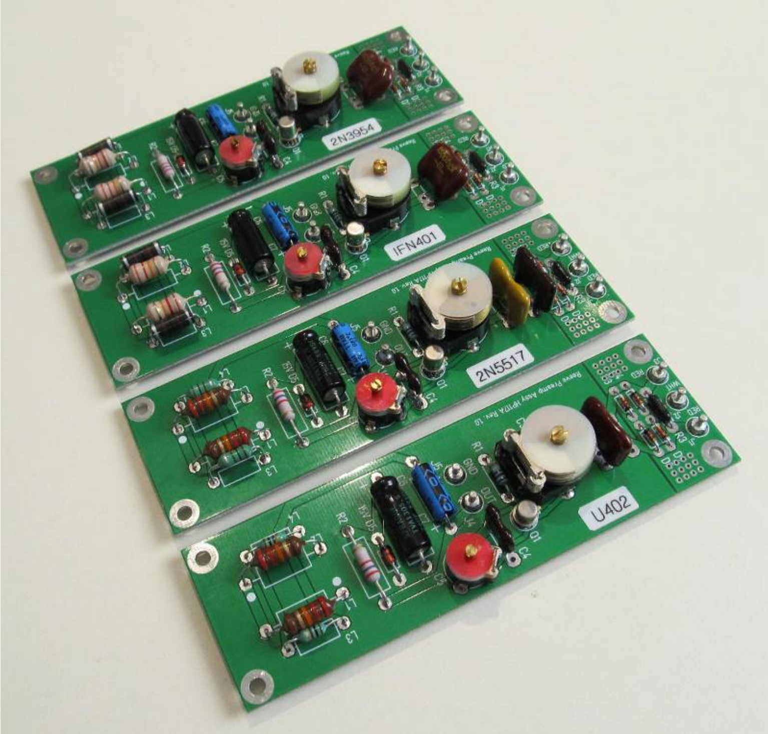

Figure 6 ~ Four of five new preamplifiers used for testing and measurements. The output transformer composed of four fixed inductors is on the far-left of each board and the antenna turret terminals are on the far-right. The red trimmer capacitor near the middle-edge of the PCB tunes the output and the white trimmer capacitor to the right tunes the input. Each PCB is labeled with the dual J-FET transistor type. Image © 2019 W. Reeve

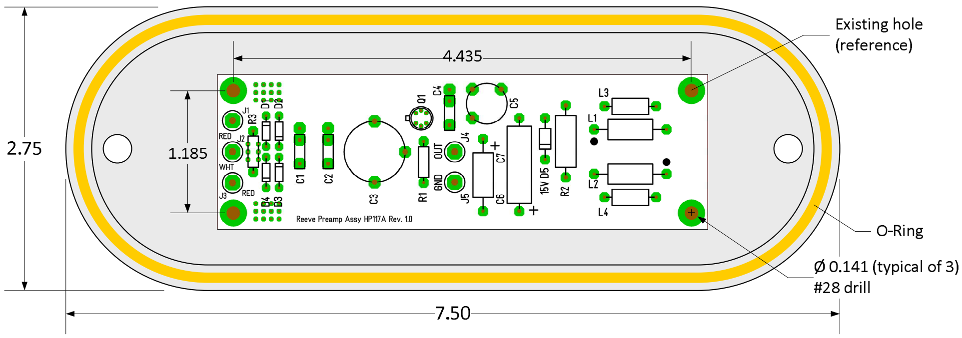

Figure 7 ~ Antenna base enclosure cover dimensional drawing. The cover has three holes for the original vacuum tube preamplifier but only one of them is used with the new preamplifier. Image © 2019 W. Reeve

4. Preamplifier power

The original vacuum tube preamplifier required 35 Vdc at 60 mA, or 2.1 W. The new amplifier requires 18 Vdc at 6 mA or 24 Vdc at 4 mA, around 0.1 W. For initial test purposes I built a simple bias-tee circuit made from a single inductor and capacitor (figure 8). The original HP 117A comparator chassis had a slightly more complicated integral power feed circuit composed of a multi-stage pi-filter and coupling transformer. I later built something similar for additional testing (figures 9), which resulted in a final design (figures 10).

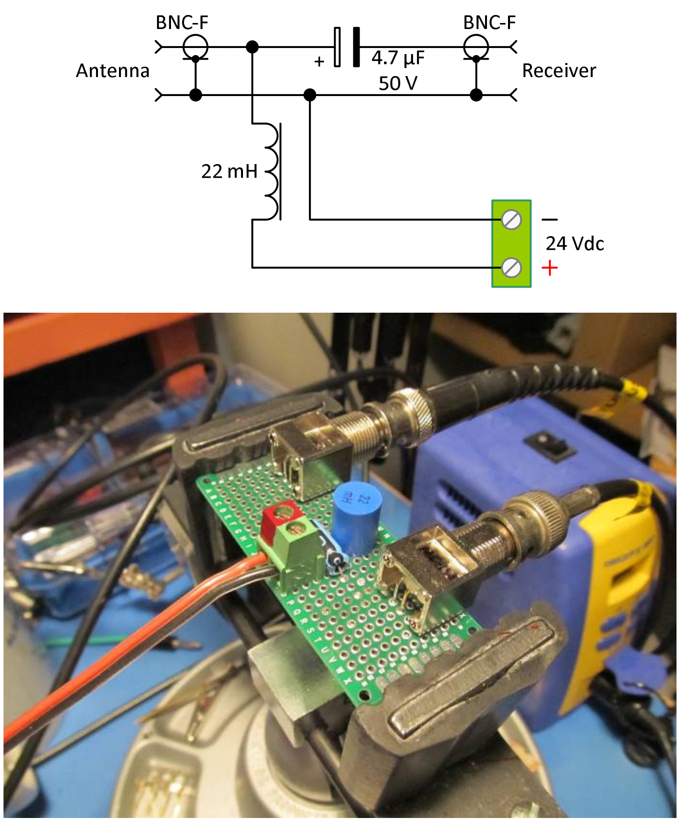

Figure 8 ~ Upper: Schematic of a simple bias-tee circuit used for initial preamplifier testing. It consists of a single inductor and electrolytic capacitor for the lowpass filter, two BNC-F connectors for the RF connections and a terminal block for the dc power connection. The reactance of the inductor at 60 kHz is about 8300 ohms and provides plenty of dc power supply isolation. The reactance of the capacitor is about 0.6 ohms and essentially is a short-circuit to the RF.

Lower: Circuit built on prototype PCB material and mounted in a PanaVise during use.

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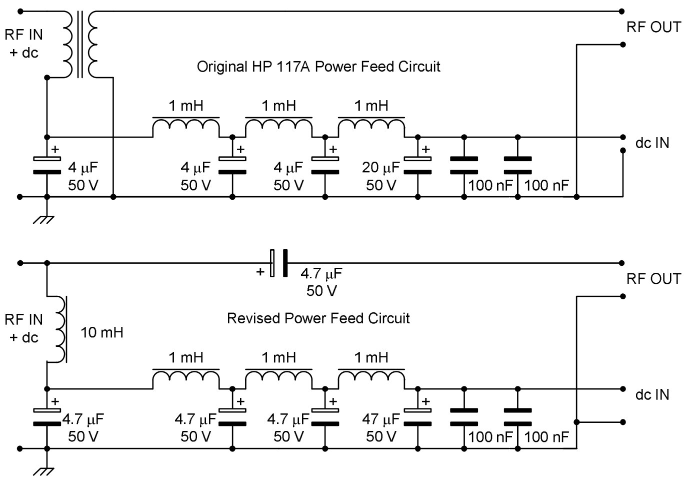

Figure 9 ~ Upper schematic: Original HP power feed circuit. The HP circuit isolates the receiver from the power supply with an input coupling transformer. The HP transformer was specially made and no longer available. The corner (3 dB) frequency of the pi-filter is 3 kHz and it introduces 40 dB attenuation at 6 kHz as determined with the AADE Filter Design software tool.

Lower schematic: Prototype power coupler with bias-tee components. This unit was used for extensive testing of the various preamplifiers. My circuit substitutes a 10 mH inductor for the coupling transformer and uses a capacitor to isolate the power supply from the receiver. My pi-filter capacitor values are slightly different than the HP version. Images © 2019 W. Reeve

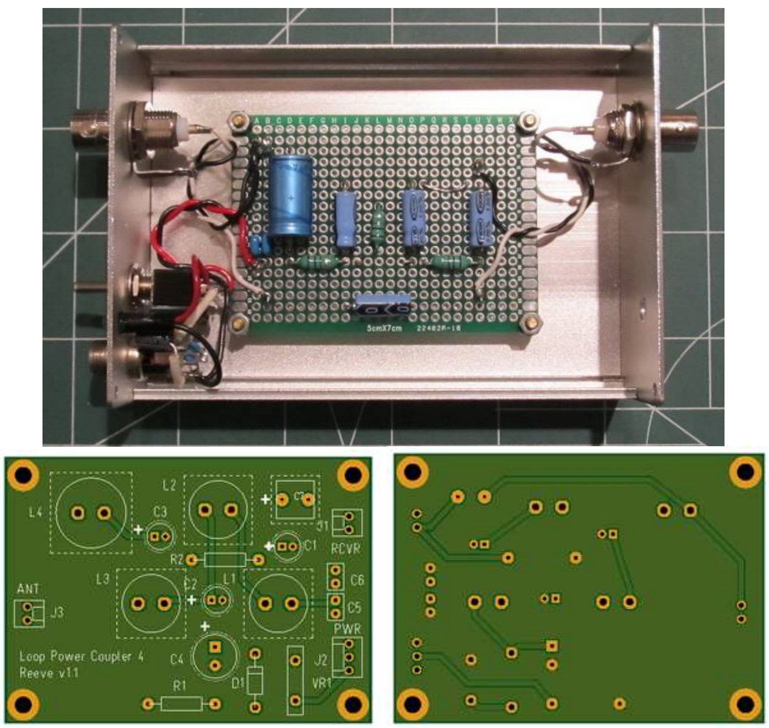

Figure 10 ~ Upper: Prototype PCB for power feed circuit in an enclosure and wired for service. The extruded aluminum enclosure is 110 x 80 x 36 mm. The end panels include a power switch, power input jack and associated protective and noise filter circuitry, power indicating LED, and BNC-F connectors for RF input + dc and RF output.

Lower: The above circuitry was later implemented on a printed circuit board. The PCB top (left) and bottom (right) are shown here. All components are through-hole types, and the PCB dimensions are 70 L x 51 W mm.

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5. Lab Measurements

The measurements are broken down into those for the loop antenna by itself and for the preamplifier and loop antenna together. I decided to not attempt standalone measurements of the preamplifier because its operation with the loop is what is important to me. I did spend some time comparing the original Nuvistor version with my modern version and these results are briefly described later in this section. For all lab measurements I mounted the loop antenna on a pipe mast fastened to a surveyor's tripod (figure 11).

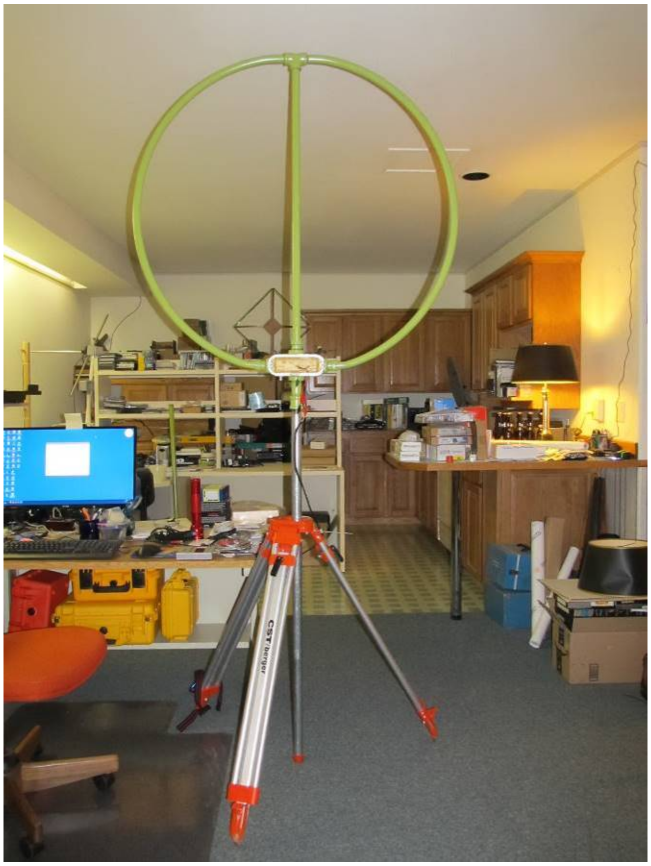


Figure 11 ~ Loop antenna on tripod test stand in the lab. The loop is supported by a 4 ft (1.2 m) length of 1 in (25 mm) galvanized steel pipe that is attached to the tripod. This setup was used for all measurements. Image © 2019 W. Reeve

Loop antenna:
This subsection describes the test equipment and methods used to measure the loop antenna inductance and impedance at 60 kHz as well as over the range of 10 to 100 kHz.

Test equipment:

- SDR-Kits FA-VA5 Vector Antenna Analyzer (RF)
- Keithley 2110-120 digital multimeter (dc)
- Siglent SPD3303X power supply

Calibration: All vector network analyzers require calibration at the measurement plane and the FA-VA5 is no exception. My test setup required flying leads for connection to the antenna so I used a short section of RG-58/U coaxial cable with a BNC-F connector on one end and small alligator clips on the other. I then performed a Short-Open-Load (SOL) calibration for the frequency range 10 to 100 kHz by simply connecting or disconnecting the clips to each other or to a 50 ohm resistor. Such a calibration procedure is adequate for the low frequencies used here.

Loop measurements: All loop measurements were made at the loop winding leads in the antenna base enclosure with the preamplifier removed (figure 12). The FA-VA5 cannot be set to sweep below 100 kHz with its built-in keyboard but its full frequency range is accessible and its operation is compatible with the DG8SAQ Vector Network Analyzer Software. Using the VNWA software I ran a sweep measurement from 10 to 100 kHz (figure 13). The measurement revealed that the loop's self-resonant frequency is almost 100 kHz. This means I can use the loop with an untuned preamplifier at least as low as 10 kHz and up to about 90 kHz, a range that is of most interest to me. However, my initial preamplifier design is tuned for operation at only 60 kHz.

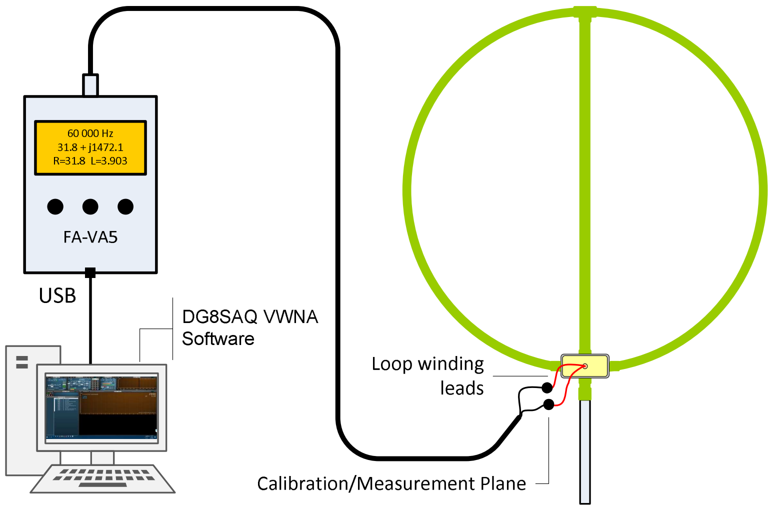


Figure 12 ~ Measurement setup using the FA-VA5 Vector Antenna Analyzer and DG8SAQ VNWA software. The analyzer was calibrated with the same coaxial cable used in the measurements. The calibration and measurement planes were at the end of the coaxial cable clip leads. The analyzer was controlled by the VNWA software rather than the keyboard due to limitations with its pushbutton controls. Image © 2019 W. Reeve

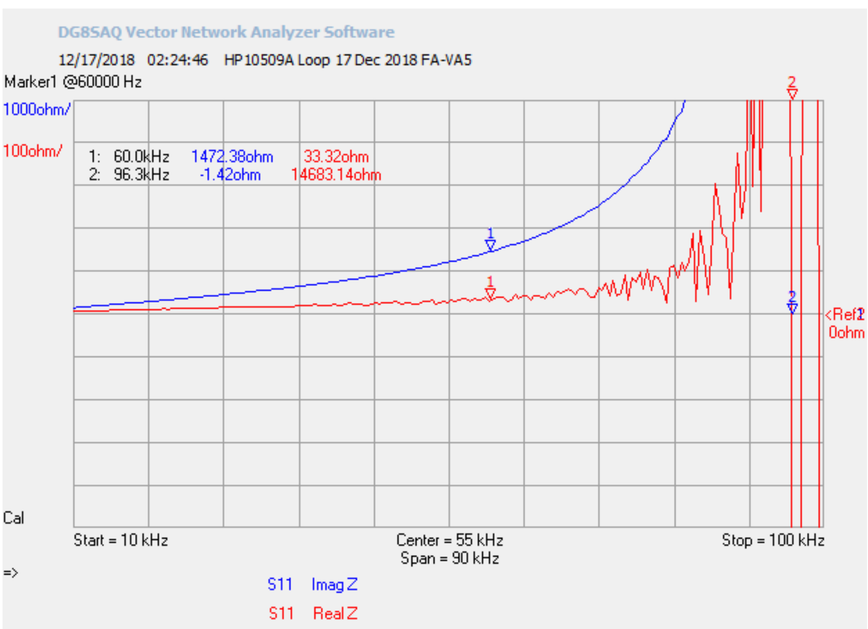
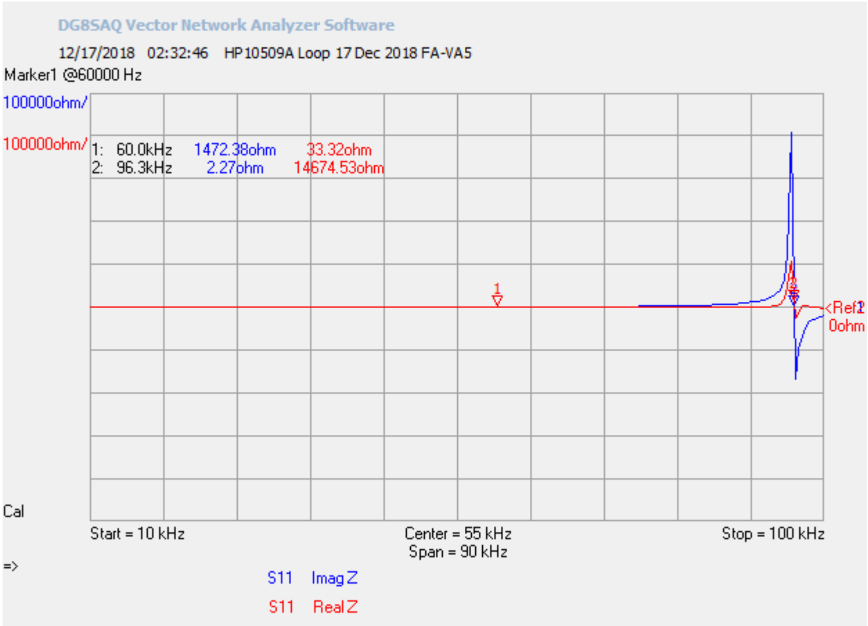
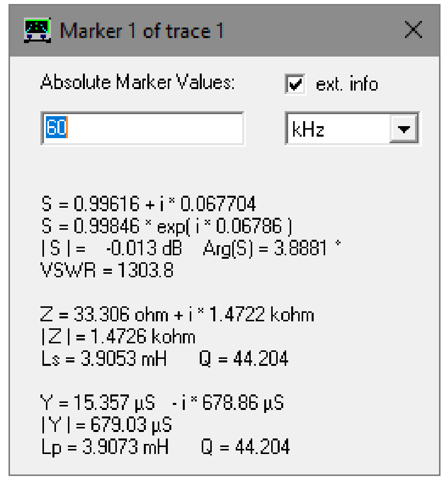


Figure 13 ~ Impedance measurements are plotted with rectangular coordinates and linear frequency sweep from 10 to 100 kHz. The plot at upper-left shows the real (red trace) and imaginary (blue trace) components of the complex impedance. The vertical scale is 1000 ohms per division with the zero reference at division 5. Marker 1 shows the values for 60 kHz. I determined the resonant point by adjusting marker 2 frequency until it showed zero reactance. The lower-left image shows the same plot but with the vertical scale compressed to 100 000 ohms per division to better show the resonance peak. The image below shows additional data associated with the marker position at 60 kHz. Image © 2019 W. Reeve





Preamplifier measurements: After the loop measurements were completed, I installed the preamplifiers for comparison (figures 14, 15 and 16). The measurements revealed some performance differences between the various transistors and inductors used in the new preamplifiers. Of the five different transistors, the U402 provided the highest output for a given input. I found that I could increase the power gain by about 2.5 dB by adjusting the transistor bias to the value used in the datasheet, 0.6 V, and another 0.6 dB by setting the bias voltage to 0.0 V. As for the several inductor types, I accidentally included a shielded inductor that provided comparatively low coupling and low output; the mistake was easy to correct. The other inductors worked approximately the same (within about 1 dB voltage gain). See **Appendix** for additional details.

Figure 14 ~ Measurement setup with square signal loop wound with green coated wire in the foreground. Separation between the two loops was a couple meters and not critical. Note that the flat sides of the loops are approximately parallel. The separation and orientation were held constant for all comparative measurements. Image © 2019 W. Reeve

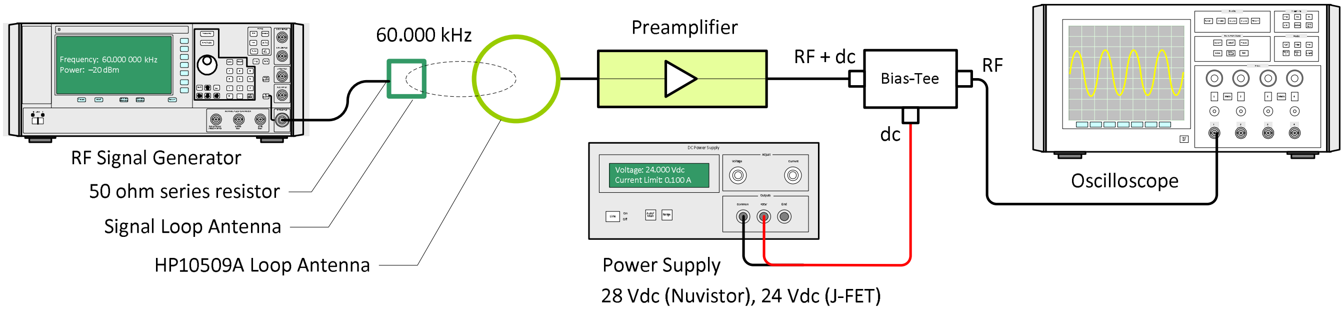


Figure 15 ~ Test setup for the preamplifiers includes the smaller test signal loop for coupling the 60 kHz test signal from a signal generator. The test signal flows left-to-right. The preamplifier output was measured with an oscilloscope setup with 50 ohms termination and X1 probe setting. Image © 2019 W. Reeve

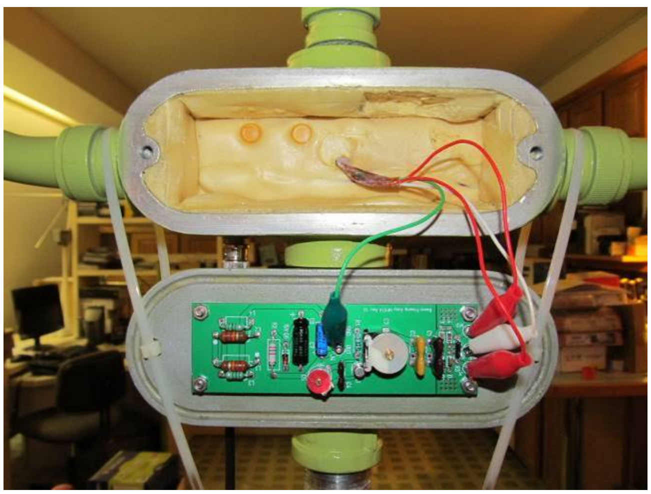


Figure 16 ~ One of the new preamplifiers temporarily mounted on the enclosure cover with test connections through alligator clips. The two red clips (winding ends) and one white clip (center-tap) come from the loop and the green clip goes to the BNC-F connector (barely visible to left between the enclosure and cover). All preamplifiers were mounted and measured as shown. The enclosure is polyurethane foam filled except for a rectangular space for the preamplifier. Two dimples from the original Nuvistor tubes can be seen inside the enclosure at upper-left. Image © 2019 W. Reeve

Since I do not have the original performance specifications for the antenna, I could only make comparative measurements between the original Nuvistor and my new preamplifiers. My assumption throughout is that the original Nuvistor preamplifier in my loop antenna is operating normally. For a given input level to the test signal loop, the first new preamplifier I tested showed about 7.8 dB voltage gain compared to the original Nuvistor preamplifier (figure 17). This difference varied a little with other versions of the new preamplifier.

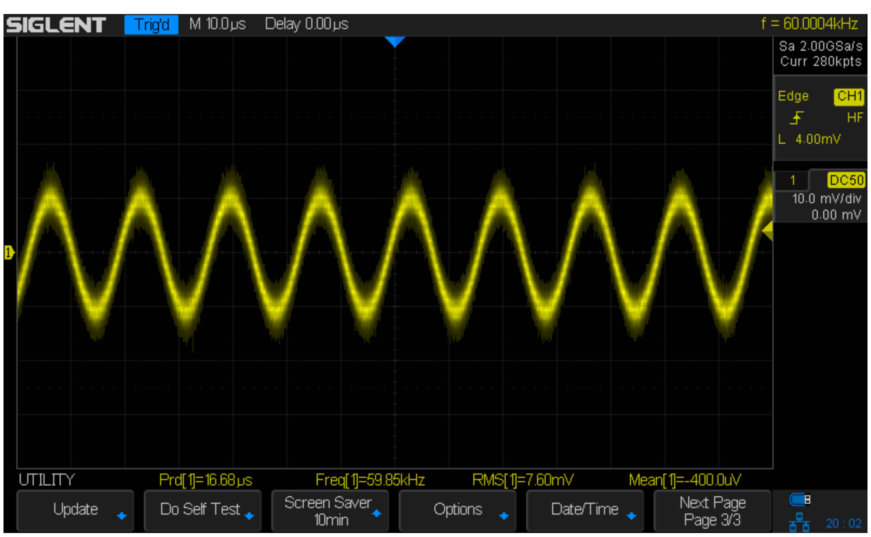


Figure 17.a ~ New dual J-FET preamplifier test output. The measured voltage is 7.60 Vrms for an arbitrary 60 kHz input to the coupling loop. For these measurements the oscilloscope vertical amplifier was set for X1 probe and to terminate the coaxial input with 50 ohms. Image © 2019 W. Reeve

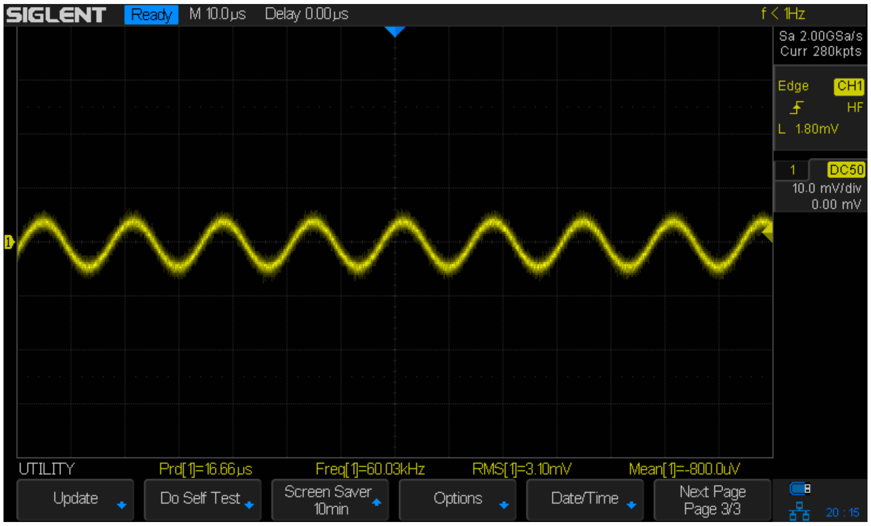


Figure 16.b ~ Original Nuvistor preamplifier output. The measured voltage is 3.10 Vrms for the same conditions as above. Image © 2019 W. Reeve

Tuning: The preamplifier's input resonant circuit consists of the loop inductance, printed circuit traces and loop leads, input protective diode capacitances, input tuning capacitors and J-FET gate-source capacitance. The input tuning is quite broad. On the other hand, the output circuit response is much sharper with a half-power (3 dB) bandwidth of approximately 3 kHz. It is interesting that the original preamplifiers with the mechanical and crystal filters had much narrower bandwidths on the order of 30 Hz. However, it would be impossible to achieve this bandwidth with the choke inductor transformer because the reactive components would need to have a Q of about 2000, a value unrealizable in ordinary capacitors and inductors with ferromagnetic cores.

The inductors available today for low frequency applications have a Q in the range of 40 to 50 at 60 kHz so, even if resonated with very high-quality capacitors, the output transformer bandwidth will be much wider than 30 Hz. The original HP inductors may have had higher Q but they are no longer available. I tried several different contemporary inductors to see what could be achieved and the results were as expected. I measured a half-power bandwidth of 2.93 kHz (from 58.550 to 61.480 kHz), or 4.9% of the 60 kHz center frequency. A crystal filter would be a better narrowband choice but I do not plan to pursue that type of design.

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6. Field Tests

Live tests at my Anchorage lab with the actual WWVB signal at 60 kHz are not possible due to high RFI levels. WWVB is 3800 km from Anchorage and its signal is very weak everywhere in Alaska except possibly the southeastern part. However, Cohoe Radio Observatory is much quieter, so I was able to perform live tests there in mid-September 2020. I had successfully received WWVB at CRO with a less sophisticated passive loop antenna (for descriptions of that antenna and its application see {Reeve18-1} and {Reeve18-2}), and I was anxious to see how well the refurbished antenna worked.

I setup the loop antenna and an RF choke on a temporary stand (figure 18) and connected it through the bias-tee previously described to an SDRPlay RSPdx software defined radio receiver under control of SDRuno software (v1.40.1). The bias-tee was connected to the observatory 24 Vdc power supply. Using 2 MHz sampling rate with 8 decimation in SDRuno, the resulting 125 kHz spectrum was narrowed to a displayed span of 1 kHz with 3.8 Hz resolution bandwidth (figure 19). The displayed signal was much stronger than I had observed with the passive loop antenna, indicating a successful refurbishment project.

Figure 18 ~ Outdoor test setup at Cohoe Radio Observatory for the HP 10509A loop. The loop is supported by a bar stool with outriggers to prevent it from falling over in the wind. An RF choke is mounted on the mast just below the loop. The bottom of the loop is about eye-level. For the field tests, the loop plane was pointed 104° true azimuth, corresponding to the great circle propagation path from WWVB. The receiver connection is through ground-laid LMR-240 coaxial cable, which is protected from being chewed by porcupines with 1 in (25 mm) diameter plastic water pipe. The yellow guy-guard seen in the left-background is for the nearby tower. Image © 2020 W. Reeve

VLF and LF signals received over long distances (> 1000 km) show a characteristic daily variation in which the signal level increases at night and decreases during the day with dips at sunset and sunrise. To observe these variations, I setup SDRuno to sample the rms signal level and signal-to-noise ratio (SNR) at 30 s intervals. These data are saved as a comma separated variable (*.csv) file and then post-processed and plotted in Excel (figure 20).

The sampling is not synchronized to the WWVB modulation format, so the resulting plot traces appear noisy because of the way the 60 kHz carrier is modulated. The carrier power is reduced 17 dB at the start of each second and restored 0.2 or 0.5 seconds later depending on the logic value being transmitted. The received power varies in the same manner and may be sampled at any time during the 1 second bit interval. For more information on VLF and LF propagation, see {Reeve19-1. For more information on SDRuno data plotting, see {Reeve19-2}, and for more information on the WWVB transmission format see {WWVB}.

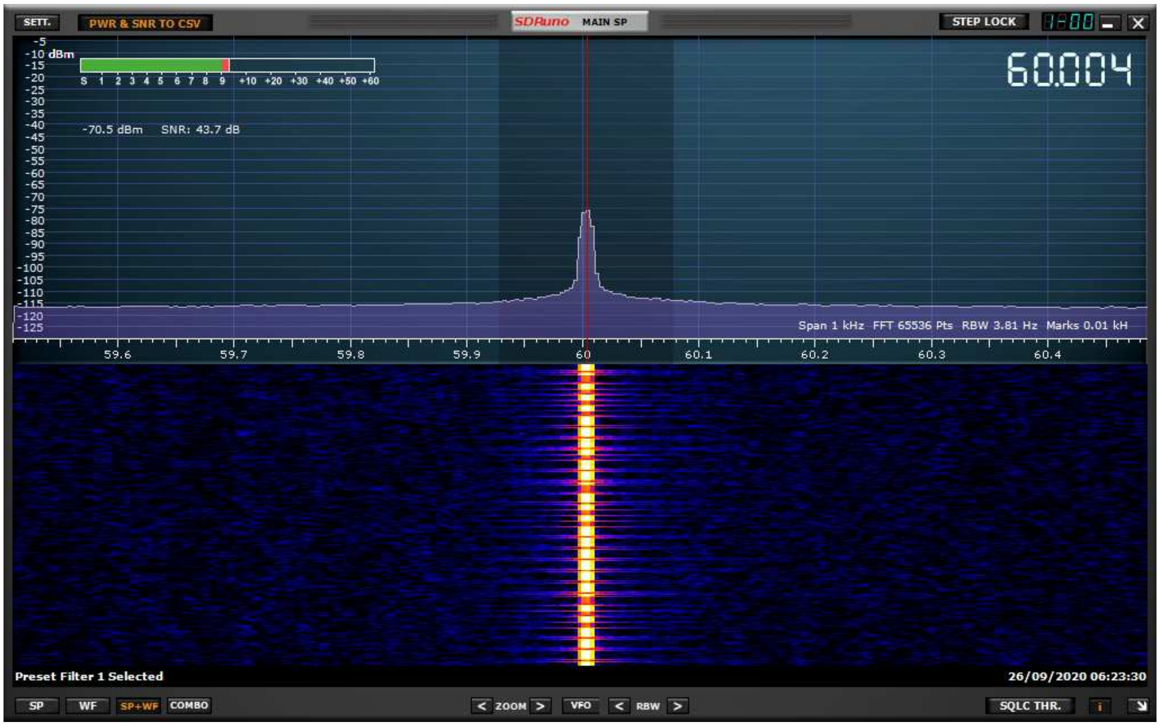

Figure 19 ~ Screenshot of the SDRuno main spectrum and waterfall window (SP1) showing a 1 kHz wide span centered on 60 kHz. This image was taken at 0623 UTC on 26 September 2020, 2.5 h after local sunset. The displayed spectrum has been smoothed by FFT averaging. The WWVB pulse width modulation/phase modulation (PWM/PM) format can be seen in the waterfall. The indicated receiver input signal level is –70.5 dBm and signal-to-noise ratio (SNR) is 43.7 dB. The signal peak has a 4 Hz offset, which may be due to receiver local oscillator error or the 3.8 Hz resolution bandwidth, or a combination of both. Image © 2020 W. Reeve

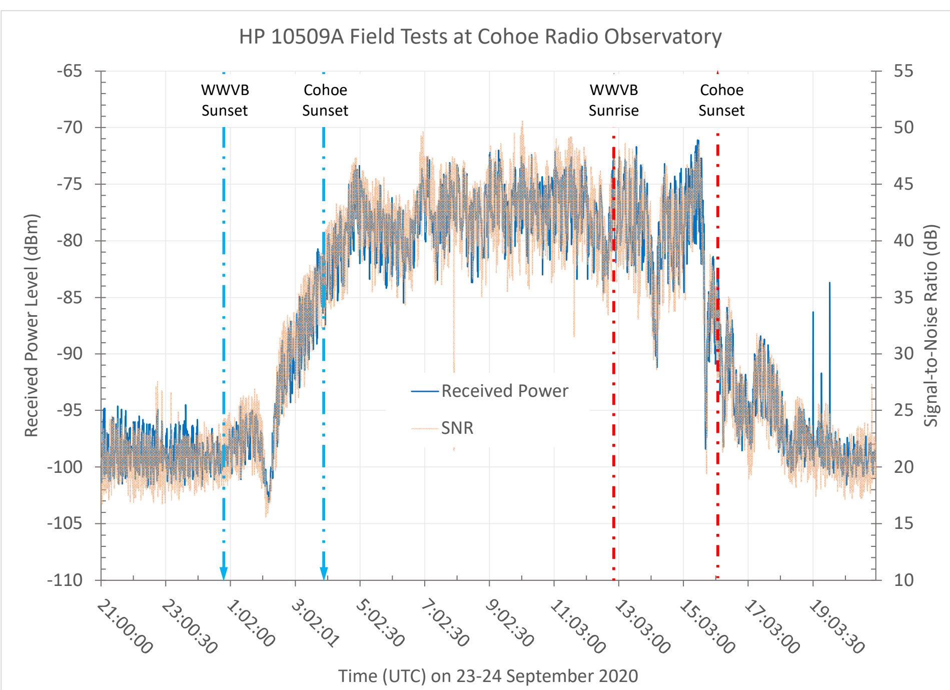

Figure 20 ~ Plot of received signal level (blue trace) and SNR (faint orange trace) for a 24 h period on 23-24 September 2020. The plot starts at 2100 UTC, or 1:00 PM local time, on 23 September. The traces are noisy due to the modulation format; see text. The plot shows the characteristic diurnal variations expected for VLF and LF signals received on a long east-west propagation path. In this case, obvious signal dips are seen between the sunset and sunrise times at the two ends as the solar terminator passes the path's approximate midpoint. Note that the power and SNR traces almost perfectly overlap. Image © 2020 W. Reeve

7. Conclusions

The HP 10509A loop antenna was first produced in the 1960s for reception of WWVB at 60 kHz and it still is a viable antenna for low frequency work today. A relatively simple upgrade replaces the original preamplifier with one that uses contemporary components, is easy to build and provides more gain. Measurements show the loop to be usable over a frequency range from at least 10 to 90 kHz with a suitable preamplifier. The design of such an amplifier will be described in a future paper.

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8. References and Weblinks

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Appendix ~ Additional Test Data

Test equipment:

- Siglent SDS2302X oscilloscope: 10.0 mV/division vertical setting, 10.0 µs/division horizontal setting
- Telulex SG-100A signal generator: 60 000 Hz sinewave, +10 dBm output setting, 50 ohm series resistor
- Siglent SPD3303X power supply: 24 Vdc output setting
- Shop-built test signal loop: Square, 0.4 m side length

Preamplifier power: V_{in} = 24.0 Vdc, I_{in} = 4 mA (bias-tee adds 3 mA for power indicating LED)
Distance between signal loop (square UKRAA loop) and HP10509A: 71.5 in (1.8 m), flat sides parallel

PCB Label	J-FET Type	L1/L2 Mfr and part number	L3/L4 Mfr and part number	Vout (mVrms)	Mean (µV)	Remarks
U402	U402	TDK B82144A2226J (5%)	Bourns 78F101J-RC (5%)	6.73	–537	Baseline, A.2
U402	U402	TDK B82144A2226J (5%)	Miller 9210-76 (5%)	6.81	–753	Replaced L3, L4, A.3
U402	U402	TDK B82144A2226J (5%)	Miller 9210-76 (5%)	9.05	–401	0.6 V bias, A.4
2N5517	2N5517	TDK B82144A2226J (5%)	Unknown stock	6.48	–765	
IFN401	IFN401	Fastron HBCC-223J (5%)	Bourns 78F101J-RC (5%)	4.67	–475	Baseline, A.4
IFN401	IFN401	Fastron HBCC-223J (5%)	Miller 9210-76 (5%)	5.06	–666	Replaced L3, L4, A.5
2N3954	2N3954	Fastron HBCC-223J (5%)	Bourns 9250A-104-RC (10%)	6.08	–683	
U402-2	U402	TDK B82144A2226J (5%)	Bourns 9250A-104-RC (10%)	8.09	–488	Baseline, A.1

Table notes:

1. Remarks refer to oscilloscope screenshots below. Screenshots appear only in the online version of this paper.
2. The IFN401 is supposed to be a better device than the U402 but did not perform very will in the tested circuits.

Inductors:

L1, L2: TDK B82144A2226J, 22 mH 5%
L1, L2: Fastron HBCC-223J-01, 22000 µH .02 MHz 5%
L1, L2: Bourns (Miller) 8250-223K-RC, 22mH 10%
L1, L2: HP 9140-0128, 22 mH 5% (not available)

L3, L4: Bourns 78F101J-RC, 100uH 5%
L3, L4: Bourns (Miller) 9250A-104-RC, 100 µH 10%
L3, L4: Unknown (larger conformal coated from stock), 100 µH 10%
L3, L4: L.W. Miller 9210-76, 100 µH 5%
L3, L4: HP 9140-0210, 100 µH 5% (not available)

Transistor bias:

The value of the original J-FET source resistor, R1 in the schematic, is 3900 ohms. The source resistor sets the gate-source bias voltage. The gate is grounded through the loop resistance. The gate current is very small and, along with the low dc resistance of the loop, the gate voltage to ground for practical purposes is 0 V. The J-FET source is raised above ground potential by R1 due to drain-source current. For R1 = 3900 ohms, the measured J-FET source voltage is +1.10 V, which is equivalent to –1.10 V bias at the gate with respect to the source. The total drain-source current for both J-FETs is the voltage drop across R1 divided by its resistance, or 0.3 mA. Assuming the currents are equal in each of the two J-FETs, the drain current is 0.15 mA per J-FET.

Most of my testing used the original R1 source resistance value (3900 ohms), but I also experimented by replacing the fixed resistor with a 10 kohm 10-turn trimmer resistor. The U402 J-FET datasheet indicates that most specified values are given with 0.2 mA drain-source current and not 0.15 mA noted above. In order to achieve the higher current in the drain-source circuit, I had to lower the series resistance in the zener diode shunt regulator, R2 in the schematic. The original value is 2700 ohms, which provides only 0.3 mA total current to the J-FET and diode for an input voltage of 24 V. The 2700 ohm resistor was suitable for the original 35 V feed voltage but I decided to use 24 V because my stations already have that voltage available. The zener diode current should be closer to 15 mA. Adding the J-FET current (0.4 mA total for the dual J-FET) gives 15.4 mA. The input voltage to the shunt regulator is a nominal 24 V and the regulated voltage is 15 V, a difference of 9 V. Dividing the required voltage drop of 9 V by 15.4 mA gives a value of 584 ohms for the series resistor R2. To provide some margin I used 470 ohms, which provided a total current of 20 mA. The power dissipation when R2 = 470 ohms is about 0.19 W; I used a 0.5 W resistor.

After the above modifications, I adjusted the bias to 0.6 V (0.2 mA drain current per J-FET), and found the power gain increased by 2.5 dB. By reducing the bias to zero, corresponding to a source resistance of 0 ohms, the gain increased another 0.6 dB.

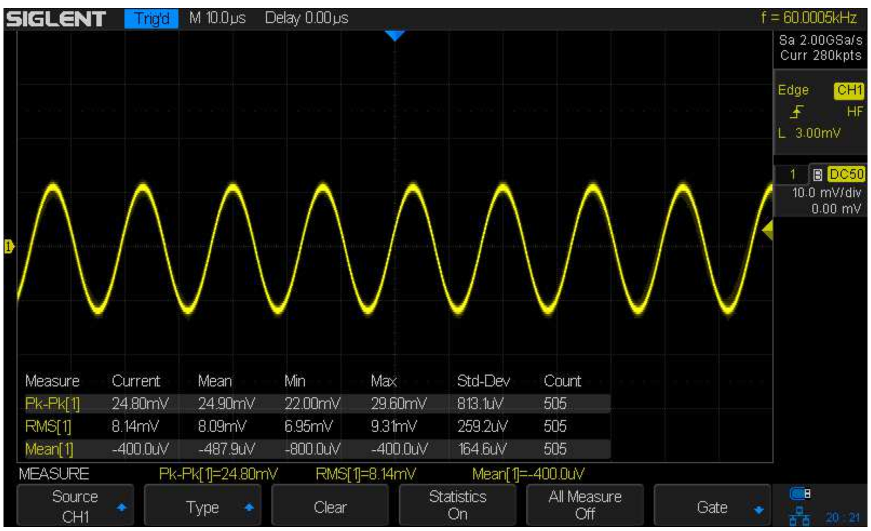

Figure A.1 ~ U402-2 Baseliine. In this and following images, a statistics table shows mean, minimum, maximum, standard deviation, and average count for peak-peak voltage, rms voltage and average voltage. Image © 2019 W. Reeve

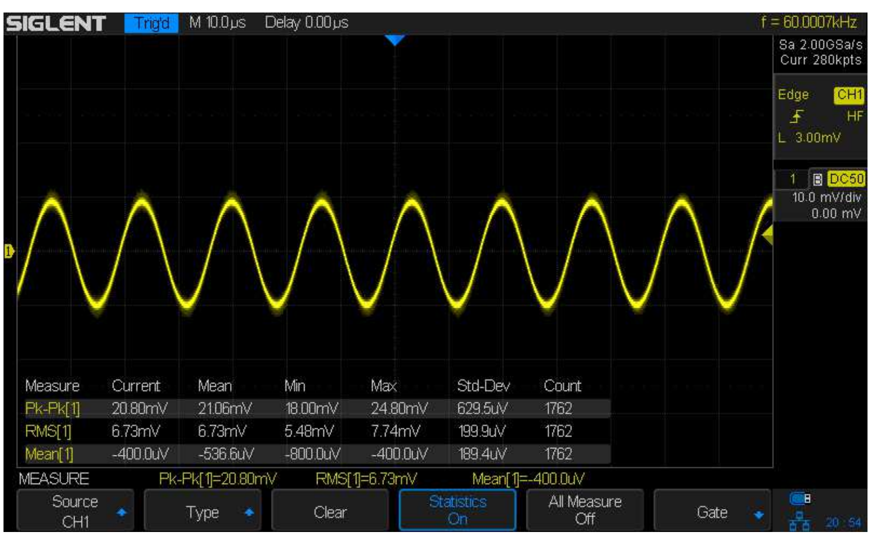

Figure A.2 ~ U402 Baseliine. Image © 2019 W. Reeve

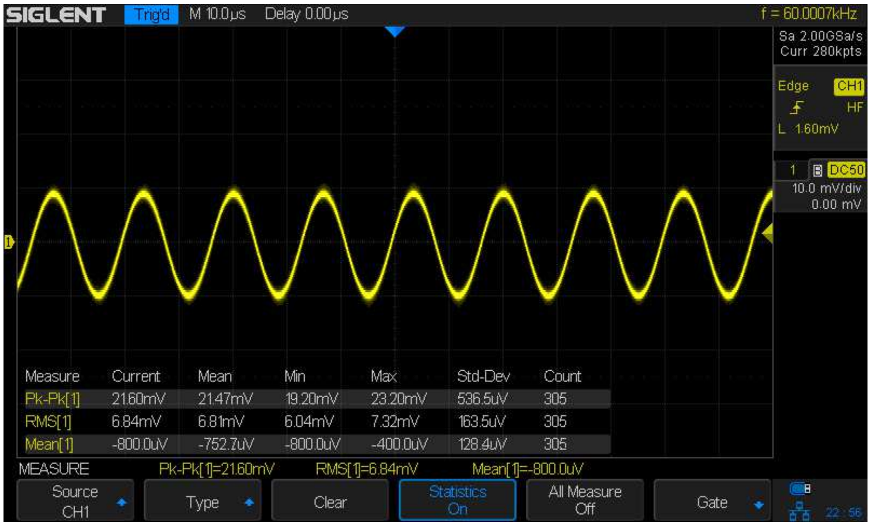

Figure A.3 ~ U402 Replaced L3, L4. Image © 2019 W. Reeve

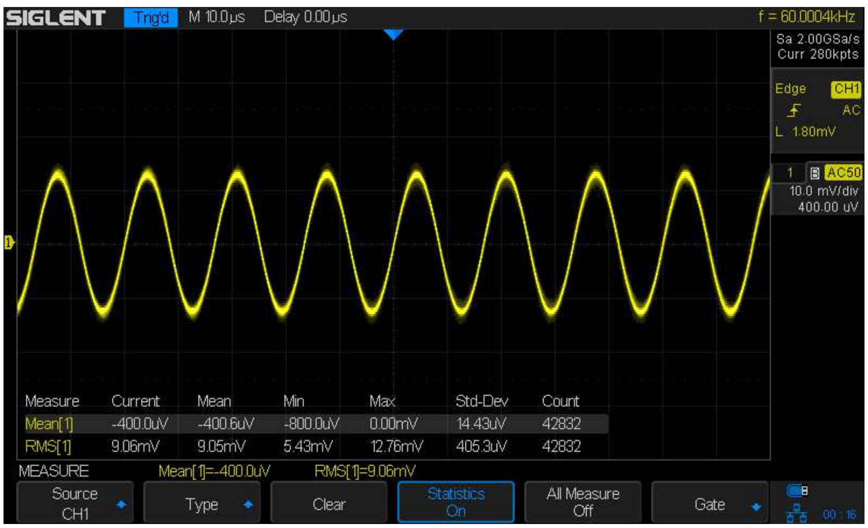

Figure A.4 ~ U402 Replaced R1 with trimmer resistor and adjusted bias to 0.6 V. Image © 2019 W. Reeve

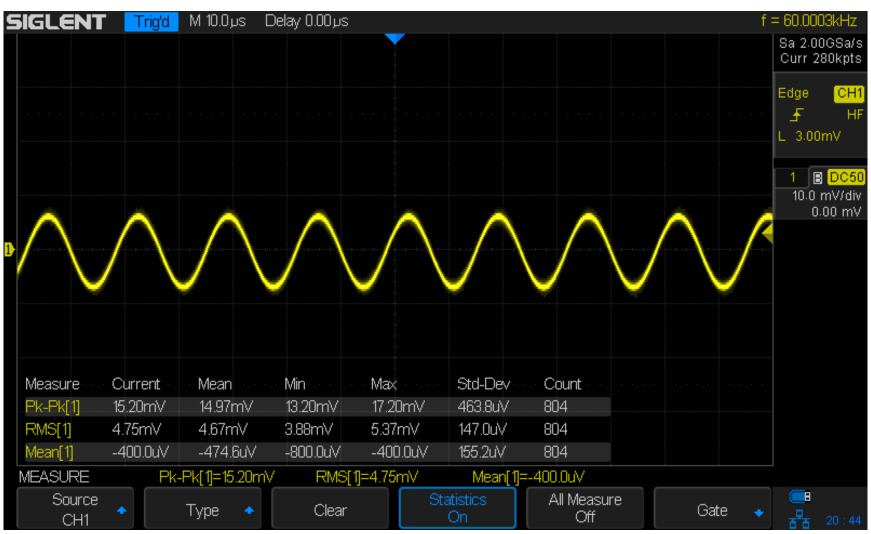

Figure A.5 ~ IFN401 Baseliine. Image © 2019 W. Reeve

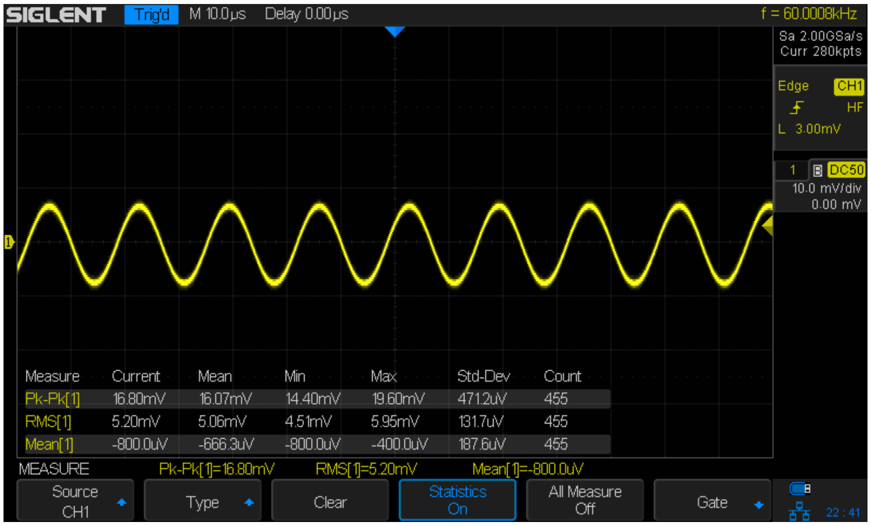

Figure A.6 ~ IFN401 Replaced L3, L4.
Image © 2019 W. Reeve

Document information

Author: Whitham D. Reeve

Revision:
- 0.0 (Original draft started, 17 Dec 2018)
- 0.1 (Added loop measurements, 18 Dec 2018)
- 0.2 (Added preamplifier measurements, 28 Dec 2018)
- 0.3 (Added images and formatted, 14 Jan 2019)
- 0.4 (Added images to Appendix, 19 Jan 2019)
- 0.5 (Completed 1st draft, 21 Jan 2019)
- 0.6 (Added info on different bias voltages, 02 Mar 2019)
- 0.7 (Updated and completed 2nd draft, 14 Jul 2020)
- 0.8 (Added live tests at Cohoe, 15 Sep 2020)
- 0.9 (Edited field test section, 22 Sep 2020)
- 1.0 (Distribution, 27 Sep 2020)

Word count: 5880
File size: 4273664