EMP-HARDENED DIGITALLY CONTROLLED HIGH-FREQUENCY ACCURACY VACUUM TUBE TRANSCEIVER

Figure: A digitally synthesized external VFO for older transceivers such as Heathkits build around the HFSIGNALS Raduino with incredible accuracy, computer controllability and additional features over the original internal VFO.

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This article explains how to develop an EMP-hardened transceiver for HF voice (SSB), digital (e.g., PSK, WINLINK, ft8) or CW usage. At the same time, you obtain fantastically improved frequency accuracy out of an older transceiver! That happens because the Si5351 phase locked loop chip develops almost any frequency required, and all are intimately related to the driving crystal of its internal 25 MHz oscillator. Older rigs which used to have only 1-10 kHz of frequency accuracy can suddenly have accuracy to +/- 100 Hz or better. (See DDS VFO article in March 2016 QST, and here: http://www.farrukhzia.com/k2zia/ ; also see this discussion: https://forums.hamisland.net/showthread.php/20077-DDS-VFO also the N3ZI external VFO here: http://www.pongrance.com/DDS2016.html) The EMP protection is almost "icing on the cake." And on top of this, on any given band, the transceiver is now able to have its frequency computer - controlled as well.

Brief Explanation of EMP

EMP is an electromagnetic outcome of a high-altitude nuclear explosion of either fission or fusion type. EMP is a devastating attack on a society that destroys a large percentage of unprotecteed solid state equipment (think: radios, routers, communications & control equipment) in a widespread area of up to thousands of miles, and also may destroy the nation's electrical grid. Congressional committees have produced bulky reports suggesting that the mortality rate in a nation could be extremely high. (See: https://www.forbes.com/sites/brucedorminey/2017/10/23/north-korea-emp-attack-would-cause-mass-u-s-starvation-says-congressional-report/#5e89f5fe740a and https://oversight.house.gov/wp-content/uploads/2015/05/Baker-Statement-5-13-EMP.pdf) Information about EMP is readily available from qualified sources (as well as many unqualified sources) and the reader is referred to one inexpensive (and apparently penname-authored) text that specifically addresses hardened consumer radios: https://www.amazon.com/EMP-Hardened-Radio-Communications-William-Prepperdoc/dp/154077760X That text includes scores of scholarly references. *The author there argues that merely storing radios in a Faraday cage (such as a metal garbage can with a tight-fitting lid) will be an inadequate strategy as fear of a secondary attack would make survivors unwilling to actually remove the stored radios and expose them to possible catastrophic damage.* Much better is to harden equipment, and this is quite possible based on published articles in QST. See: http://qsl.net/kx4z/QST-Electromagnetic_Pulse_and_the_Radio_Amateur.pdf

EMP consists of three components, E1, E2 and E3. The first two are high amplitude wide-bandwidth RFI events which develop truly huge instantaneous voltages on currents on typical amateur radio antennas --- kilovolts and kiloamperes that last for nanoseconds but fry sensitive solid state components. The E3 event is a geomagnetic disturbance similar to a very strong coronal mass ejection that develops damaging quasi-DC currents on interstate AC power transmission lines that drive extraordinarily massive transformers into saturation and self-destruction. Protection against E3 is possible but has been mandated in only a state or two; national solutions have been argued about but not implemented. The amateur would be wise to have backup power sources.

The major risk to communications transceivers is the incredibly strong E1 wave, which is like an instantaneous GHz bandwidth lightning strike that is over in nanoseconds. The published 4-part QST article series (referenced above) showed that with simple gas-discharge-tube feedline protection (similar to many high quality lightning arrestors) vacuum tube gear survived and functioned intact. Therefore, I'm exploiting this technique in this article. Although the turn-on time of gas discharge tubes is not instantaneous, the filtering effect of an HF antenna system and coax can eliminate some of the higher GHz components, slowing down the waveform enough that protection can be achieved. Then the vacuum tubes of the receiver and transmitter are able to survive the remaining incoming voltages.

OPERATION

Once constructed and equipped with the proper software, the Raduino version replaces the internal VFO of the transceiver and offers three basic benefits:

1. Extraordinary frequency accuracy, likely better than 100 Hz
2. Ability to tune somewhat farther than the original VFO, allowing reception of some MARS, calibration and other useful stations
3. Ability to be computer controlled (emulating a Yaesu transceiver for computer control)

The supplied 10K frequency potentiometer allows careful tuning of any 50kHz segment; holding the dial to the upper or lower end will move the segment up or down by 25kHz at a time until you move the dial off the upper or lower end. This allows you to easily select any section of any ham band. The dial reads out in full frequency (e.g., 3.595.5 kHz) and shows USB or LSB – but you must select the proper "mode" and "Band" on the Heathkit transceiver also, of course!

When moving between the 80/40/20/15 ham bands, the segments will move past much more quickly, so that you don't have to wait inordinately long. However, it is set to slow down when reaching areas just outside of the normal ham bands, to allow use of the receiver/transceiver in nearby MARS frequencies, or to receive for example CHU Canada time/frequency station broadcasts. The internal bandpass filters of the Heathkit radios do not allow large movements outside the normal hand bands (receiver sensitivity and transmitter power output will suffer), but 200 kHz is often possible.

Suitable Radios

The Heathkit SB-100, SB-101, SB-102, HW-100 and HW-101 line of transceivers is an easy set of refurbishable transceivers. These transceivers provided roughly 100watts output on 80/40/20/15/10 meter bands, upper / lower sideband and CW. Designed for amateur construction, the circuitry is open and easy to reach, schematics are available and circuit explanations are well known. (This same basic modification can likely be done to any of the Heathkit single-bander HW series and would probably allow for increased usable frequency band as well.)

SB-102 Manual: http://www.qsl.net/nf4rc/SB102Manual.pdf
HW-101 Manual: https://www.vintage-radio.info/download.php?id=155
Heathkit power supply manual: https://www.vintage-radio.info/download.php?id=135

Heathkit service bulletins: http://www.w7ekb.com/glowbugs/ModsEtc/HW-101%20Service%20Bulletins.pdf ; http://www.w7ekb.com/glowbugs/ModsEtc/HW-SBServBull_1.pdf
Possible improvements:
http://www.w7ekb.com/glowbugs/ModsEtc/Optimizing%20the%20HW101.pdf ;
http://www.w7ekb.com/glowbugs/ModsEtc/HW-101tips.pdf

The typical steps in a Heathkit HW- or SB- series refurbishment include:

- Verifying that the correct tubes are in the right sockets.
- Replacing any missing vacuum tubes from Internet sources (all but the final audio amplifier tube are fairly reasonable) (e.g.: http://www.thetubestore.com/ https://tubedepot.com/
- Wiggling each tube to deal with corrosion issues on the pins and sockets – if there are still problems a tiny bit of contact cleaner or Brasso might be utilized.
- O-rings: Try the 53mm N4.00x053: 4mmx53mm Buna N70 Metric O rings for the driver gangs, and the N4.00x55: 4mmx55 mm Buna N-70 Metric Orings for the Loading capacitor in the final amplifier tuning circuit; all from: http://www.theoringstore.com They can also be obtained on ebay frequently, but in quantity theoringstore will be cheaper.
- Replacing all the high voltage audio bypass electrolytics in the transceiver unit with 20 microfarad 450V capacitors. (C12 mic amp filter; C304 in the receiver audio amplifier; also C2 cathode audio bypass)
- Replacing (or sistering) all the electrolytic capacitors in the separate power supply (HP-23 and variants) with newer components. Since the original electrolytics were used also as physical mounts for various resistors and diodes of the power supply design, removing this is problematic and I've had good success in merely adding additional capacitors in parallel—- provided that the original capacitors are not showing signs of WARMTH when the power supply is on for 30 minutes or more
- Rejecting a power supply that has a transformer that gets hot without any load --- a sign of internal problems.
- Cleaning the contacts of rotary switches, particularly the bandswitch and MODE switch, with commercially available contact cleaner. Be very careful – adjusting the fragile contacts in these switches is fraught with risk.
- If necessary, constructing a new power supply cable from 11-pin male and female plugs/sockets and appropriate wiring. (These can be found on DigiKey, or Ebay.)
- Realignment as necessary and a check on the neutralization of the finals --- if the peak output and minimum input power are obtained simultaneously on 20 or 15 meters you're in pretty good shape. A 100-watt incandescent light bulb works pretty well as an easy dummy load for these older vacuum tube transceivers.
- These transceivers require a healthy input audio voltage --- either a crystal or amplified microphone may be necessary. The unique microphone connector may be replaced with one that fits standard CB 'powered' microphones without too much difficulty – hole size is correct. These 4-pin male chassis connectors from Amazon work well: https://www.amazon.com/gp/product/B01238Y6EC/ref=oh_aui_search_detailpage?ie=UTF8&psc=1
- Replacing the power cord with a 3-wire plug, and adding 3-wire surge protection.
- Adding a gas-discharge-tube based protection in the feedline. This can be as expensive as a PolyPhaser or AlphaDelta, or as simple as a $2 340-volt gas discharge tube soldered with very short leads across the feedline at a convenient point. (For example: https://www.digikey.com/product-detail/en/epcos-tdk/B88069X2380S102/495-4271-ND/2269480 and https://www.digikey.com/product-detail/en/littelfuse-inc/CG2350L/F2737-ND/950218 Devices such as this are widely utilized now to protect semiconductor devices from electrostatic discharge (ESD). See the discussion in the QST EMP articles.

Unusual problems I've encountered in several refurbishments:

- A leaky V12A 6EA8 that caused a transmitter to send out a strong signal completely unrelated to the desired SSB signal--2nd receiver mixer did not turn OFF in transmit position.
- One transceiver with the wrong tube in one socket.
- An SB-100 with an unusual tube in the VFO – these were privately manufactured and some versions use a 6AU6 and others use a different tube with a completely different pinout; carefully observe and notate which tube is correct if your vacuum tube SB-series VFO works properly for later knowledge.   The SB-102 utilized a solid state LMO (VFO).

Basic EMP-Hardened SSB Transceiver

Once the basic transceiver is working well-- you should be able to get a bright 100-watt light bulb output on 80 meters and 20 meters, perhaps a little less on 40 due to the 8.5MHz filter, but considerably less on 10 meters is normal – then you can move on to adding an EMP-hardened digitally synthesized VFO to these units.

Figure.   Excellent power output from a refurbished Heathkit SB-series SSB transceiver.

Digitally Synthesized VFO

The Raduino utilized in the HFSignals Bitx40 and uBitx designs produces a computer controllable digital square wave signals on any frequency from down in the kilohertz to beyond 100 MHz – it is easy for it to be programmed to provide the reverse-tuning 4.5-5 MHz VFO signal required by these Heathkit rigs, and simultaneously displaying the exact frequency of the rig. (http://www.hfsignals.com/)   Other sources also exist for the same technology: https://www.qrp-labs.com/vfo.html

Figure. Simple implementation in a bread-baking tin.

First measure the exact frequency of the heterodyne oscillator crystals and bfo crystals in the Heathkit transceiver after at least 15 minutes of warmup. An easy way to do this is to use an accurate modern digital communications transceiver/receiver and add a 6-inch “antenna” to the feedline, laying it amongst the various oscillators of the Heathkit under test. A strong S9+ signal will be received when you come upon each of the oscillators. With a communications receiver able to go to 30 MHz, you'll be able to measure all the oscillators up to the 15 MHz band.

The “nominal” frequencies of each of the oscillators are as follows:

Oscillator	Nominal frequency
80 meter heterodyne	12.395 MHz
40 meter heterodyne	15.895 MHz
20 meter heterodyne	22.895 MHz
15 Meter heterodyne	29.895 MHz
BFO LSB	3.3936 MHz
BFO USB	3.3964 MHz
BFO CW	3.3954 MHz

After measuring the correct frequencies, download the Heathkit arduino vfo software from: https://github.com/ggibby1/HeathkitRaduino/blob/master/HeathkitCATTry3.ino and find the appropriate crystal frequencies in that software and replace them with your known actual frequencies. Look for this portion of the sketch:

```
#define HET80M 12392590UL
                                             #define HET40M 15888760UL
```

```
#define HET20M 22893940UL
#define HET15M 29894430UL
#define HET10M1 36895000UL
#define BFOLSB 3393630UL
#define BFOUSB 3396460UL
#define BFOCW 3395400UL
```

Often you can hear the 25 MHz base oscillator with your communications receiver, measure its exact frequency (typically 3.5- 4 kHz above 25.000 MHz) and correct the numerical frequency in the software. Put its ACTUAL frequency where you find the following statement:

```
#define SI5351BX_XTAL 25004460
```

If the signal isn't strong enough, you can load a sketch that will force the entire Raduino output to present the crystal output frequency.

Replacing the Heathkit VFO signal with the Raduino Signal

With the SB- series, this is very easy, because there is a front panel switch that selects either the internal VFO or an internal optional crystal oscillator – simply remove the miniature RG-174 coax cable from the crystal oscillator and patch in an additional length to reach an unused back panel RCA phono plug, and mark it EXT VFO IN. See the schematic below

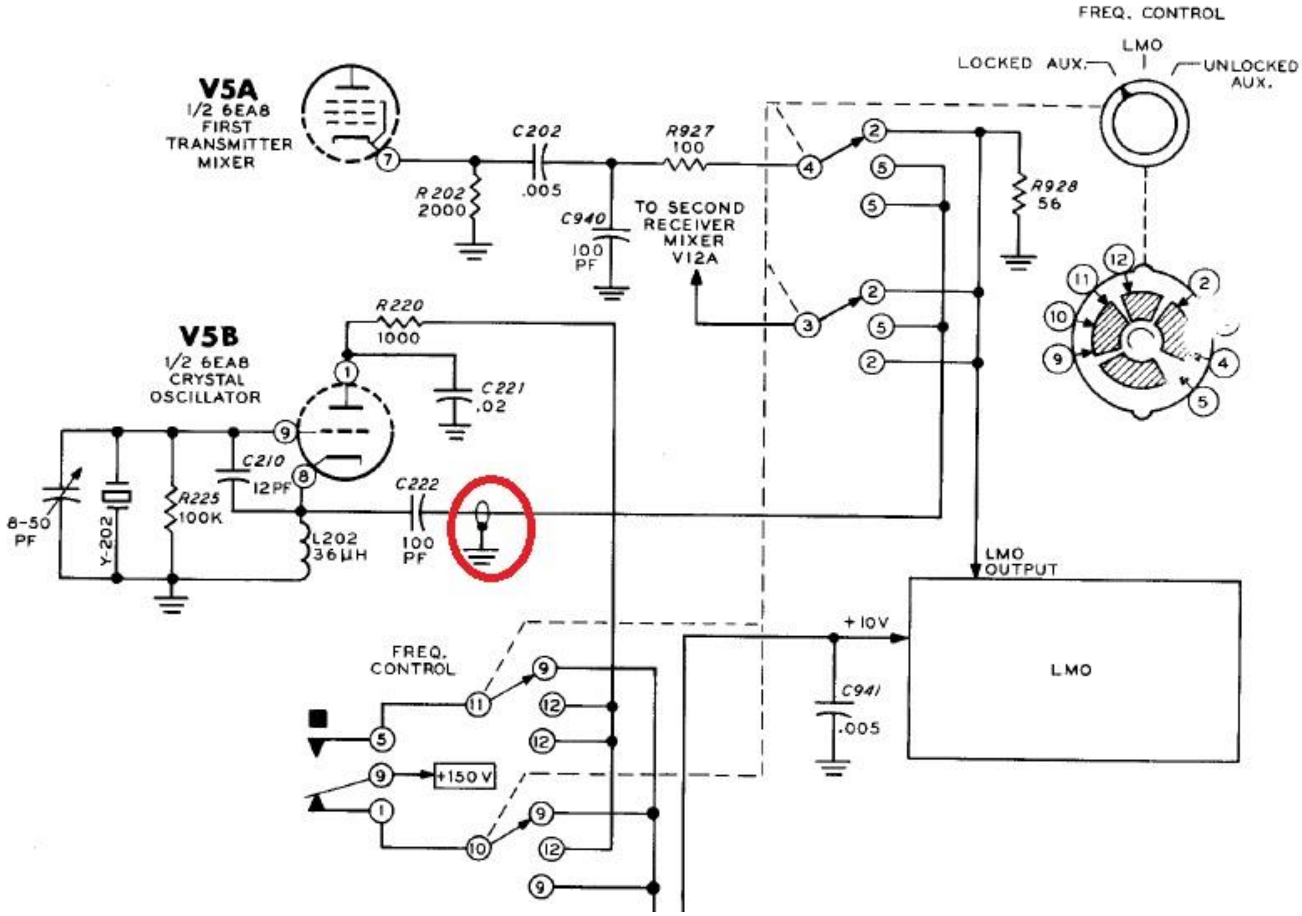


Figure: Appropriating the coax cable (circled in red) that previously went to the SB- series V5B crystal oscillator and utilize it to allow an external VFO input signal from the Raduino Various models of the SB- series name the options differently. Heathkit prefers to call their internal VFO an "LMO" (Linear Master Oscillator).

The HW- series did not include this extra feature of a selectable VFO frequency source, but the cable to the internal VFO included a convenient RCA phono-plug connection. Using a SPDT toggle switch, one can allow the choice of the internal VFO or the external Raduino VFO. See the schematic below:

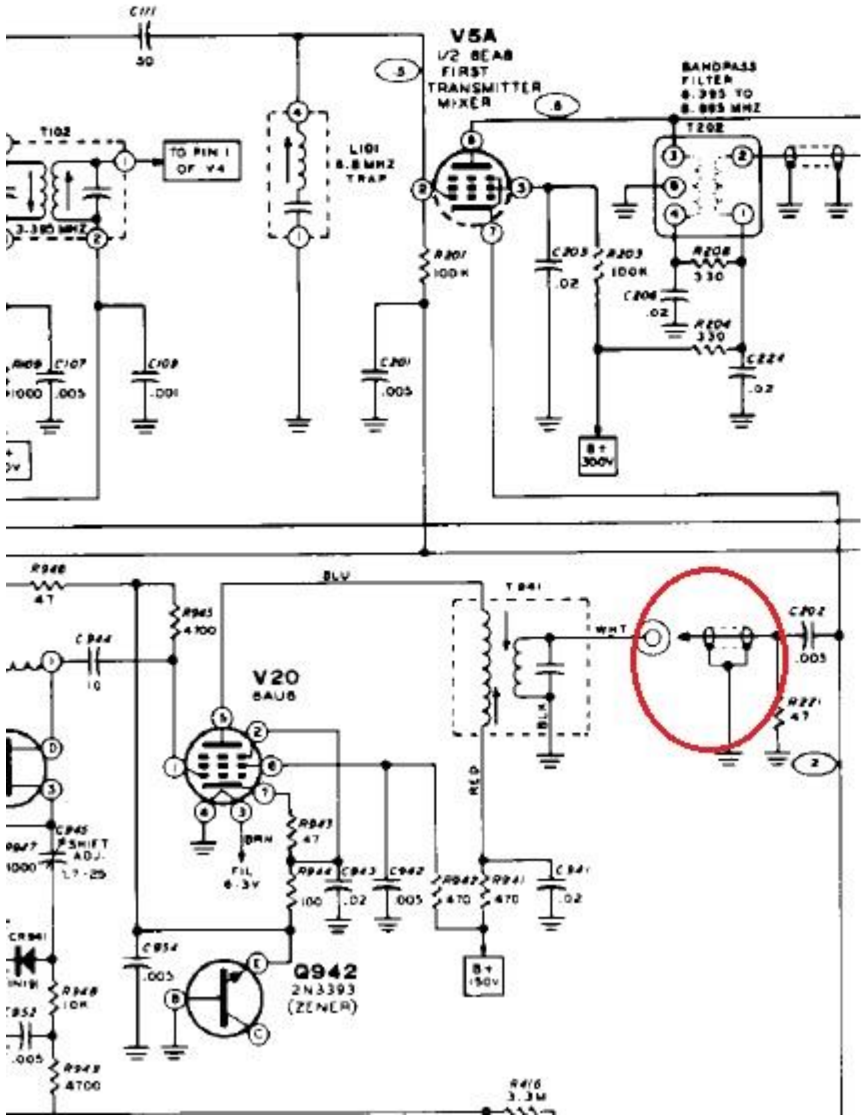


Figure. HW series has a RCA phono plug-terminated coax cable to their internal VFO.   This can either be re-routed to the external input, or a SPDT switch can be provided to allow convenient selection of one or the other (but not both!).

Initial tests can be carried out by simply taking the digital output square wave from the Raduino and using it to replace the signal from the Heathkit vfo—which in many units was connected with an RCA phono plug!   The signal amplitudes were quite similar so the replacement works quite well.

<u>EMP PROTECTION FOR THE DIGITAL VFO</u>

Once you've gotten used to the replacement, you'll want to solidly mount the Raduino and then provide it with EMP protection: both the output signal line and the input power line must be protected.   The accompanying schematic shows how to accomplish this.   The 10 MHz filter is a kit product, used to dramatically reduce the vulnerable bandwidth of outside RFI that can reach back to the digital VFO.

(See parts list below.) The other components can be obtained from Mouser or Digikey. Mount the entire assembly in a metallic enclosure.

Figure: Assembled EMP Protection for both signal and power lines.

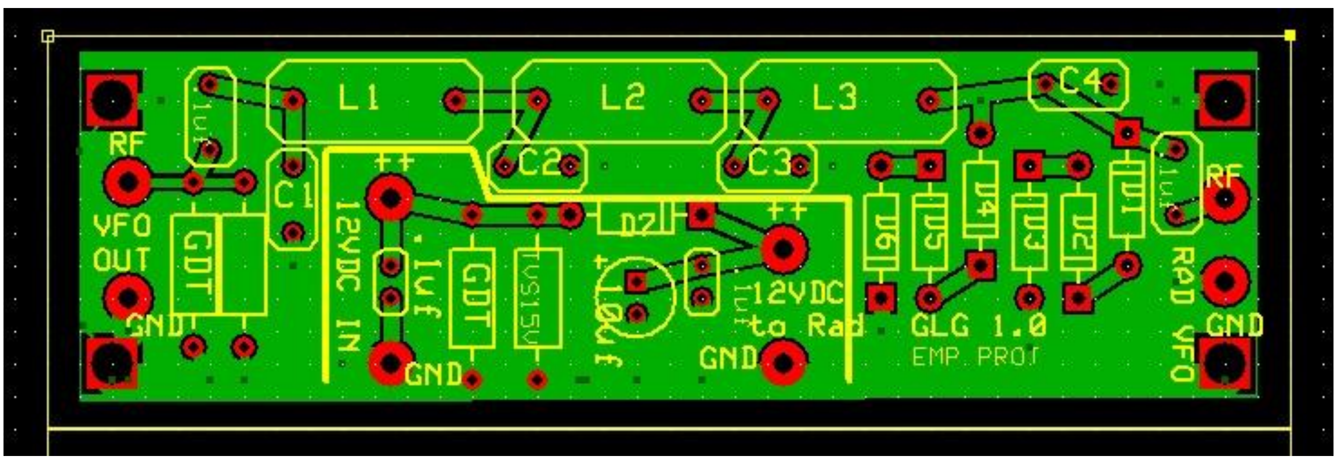
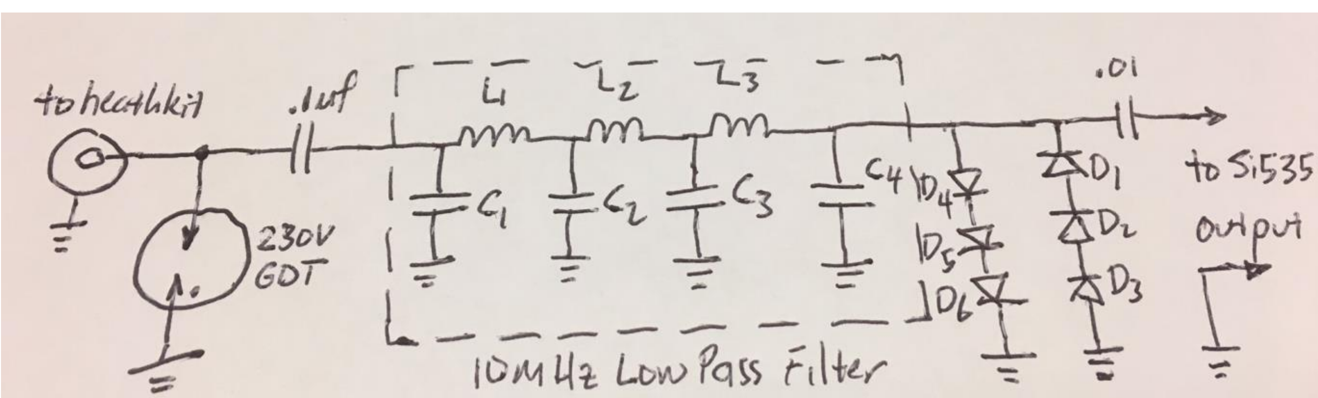
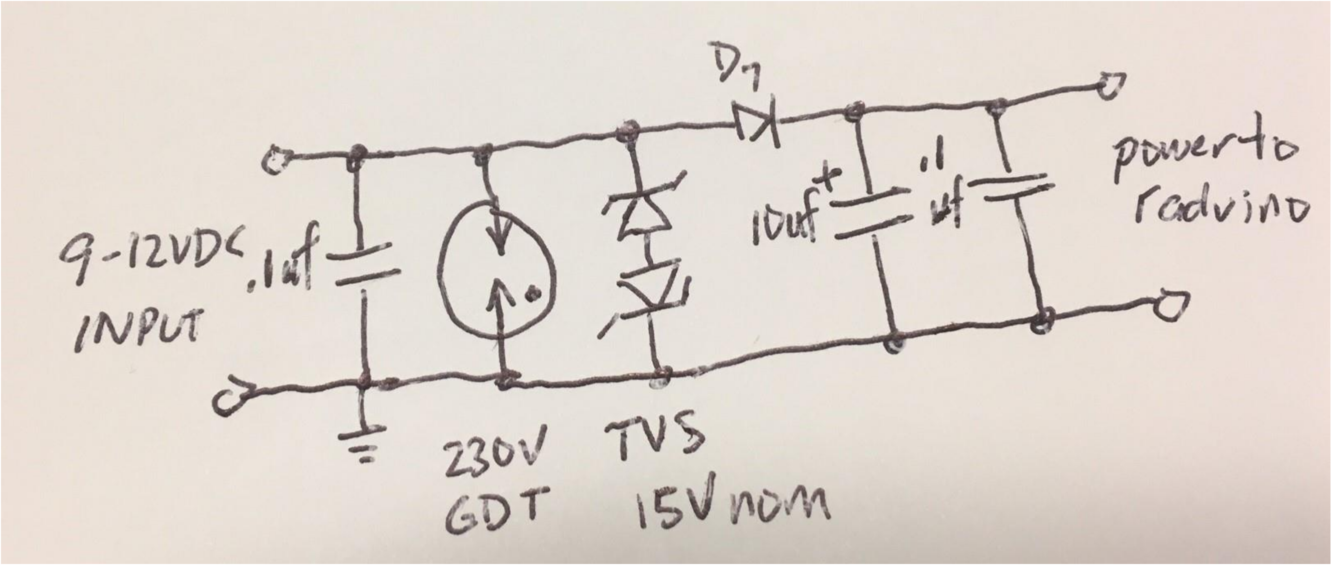


Figure: Printed circuit board layout; protection can also be assembled on hobbyist perf-board.





MATERIALS

GDT - 230V gas discharge tube - https://www.digikey.com/product-detail/en/bourns-inc/2035-23-BLF/2035-23-BLF-ND/1220311

C 0.1 uF – ceramic, 50 or higher volt rating (lower voltage devices may be damaged by EMP)

C 10 uF – electrolytic, 50 V or higher-power

TVS – 15V nominal bidirection (polarity insensitive) transient voltage suppressor: https://www.digikey.com/product-detail/en/littelfuse-inc/P6KE16CA/P6KE16CALFCT-ND/407666 or similar

Diodes D1-D7: any 1A silicon diode from 400PIV or up; 1N4007 is fine

Low Pass Filter: use the components from the qrp-labs.com 30 meter low pass filter http://shop.qrp-labs.com/LPF

COMPUTER CONTROL

The Arduino software responds to frequency control commands as if it were a Yaesu FT857 transceiver. This works well with ALE and WINLINK software, but may not work properly with other driving software. USB output from the controlling computer may be plugged directly into the USB socket of the Arduino Nano on the Raduino. Improved software is being developed by others on the bitx20 forum and may be captured and used to improve the computer control.

Recognize that it is extremely difficult to adequately EMP-harden the hf signals of the USB bus – so if computer control is required and EMP-hardening is also desired, place both the driving computer and the Raduino system within a Faraday cage, possibly with the Heathkit transceiver as well – allowing only power and antenna feedline cables to penetrate the Faraday shielding. A cardboard box with aluminum foil lining would be a reasonable choice. Provide some ventilation holes of roughly 1" in diameter --- insignificant RF should get through those. Computer controlled operation should then be possible even in the face of EMP risk.