THE INSPIRE VLF-3 RECEIVER
Theory of Operation

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PURPOSE

In June of 2006, the author was visiting with Bill Pine and a discussion of the VLF-3 occurred. One issue that Bill raised was the absence of both technical information and trouble shooting guidance for the receiver. I agreed that the lack of information is a problem and volunteered to write articles for the Journal on VLF-3 theory and trouble shooting.

BACKGROUND

The VLF-3 is the third receiver developed by The INSPIRE Project. The VLF-3 replaced the VLF-2 receiver which was the standard INSPIRE receiver for over 10 years. The VLF-2 had to be replaced because existing stocks of the receiver had been depleted and some of its components were no longer manufactured. It was not economically feasible to attempt another production run of the VLF-2. Like its predecessors, the RS-4 and the VLF-2, the VLF-3 was designed to satisfy three important constraints.

1. The receiver must be low cost, provided as a kit and simple enough for high school students to assemble and use. The receiver is to be lightweight and easily transportable. The cost goal was to be in the $100 range per kit.
2. The receiver must be designed to use a simple, short (3 to 10 feet long) vertical antenna. The vertical antenna forms an E-Field probe to pick-up natural radio signals.
3. The receiver must be powered from common, easy to obtain batteries such as the 9 VDC primary cell (Fro example IEC type 6LR61, NEDA 1604A or Radio Shack 23-553).

RECEIVER OVERVIEW

The signals of interest lie in the 300 HZ to 20 KHZ portion of the spectrum. The design chosen for the VLF-3 is a combination of filtering and direct amplification. That is, the desired signal is filtered to remove undesired out-of-band signals and amplified until the desired signals are strong enough to record on a portable stereo cassette recorder. Helliwell[1] reports that medium latitude whistlers have a field strength ranging from about 5 μV/M to 4 mV/M. Most inexpensive portable stereo cassette recorders require an input level of about 1mV (mic input) for adequate

[1] "WHISTLERS and RELATED IONOSPHERIC PHENOMENA", Robert Helliwell, Stanford University Press, 1965

recording. Assuming a 1- to 3-meter antenna, the total receiver gain needs to be about 30 DB. These two considerations form the basic technical requirements for the receiver.

Perhaps the best way to technically describe the receiver is to present a block diagram showing the individual stages and describe each stage's purpose in general terms. After the general description, the circuitry for each individual stage will be described. Detailed circuit theory will not be presented; however, some sections of the receiver contain uncommon circuit features, these will be covered in more detail. Figure-1 presents a block diagram for the VLF-3. Figure-2 contains the complete circuit diagram. Please refer to the Figures for the following discussion.

1. Antenna Circuit.

Starting on the top of Figure-1, the first block or stage of the receiver is the "antenna circuit". The antenna circuit connects the external antenna and ground to the input stage of the receiver. The antenna circuit has both binding posts and a BNC connector. For most applications the antenna and ground are connected to the appropriate binding posts. The BNC connector is included for test purposes and use by advanced experimenters. More information about possible applications for the BNC connector is covered in a later paragraph.

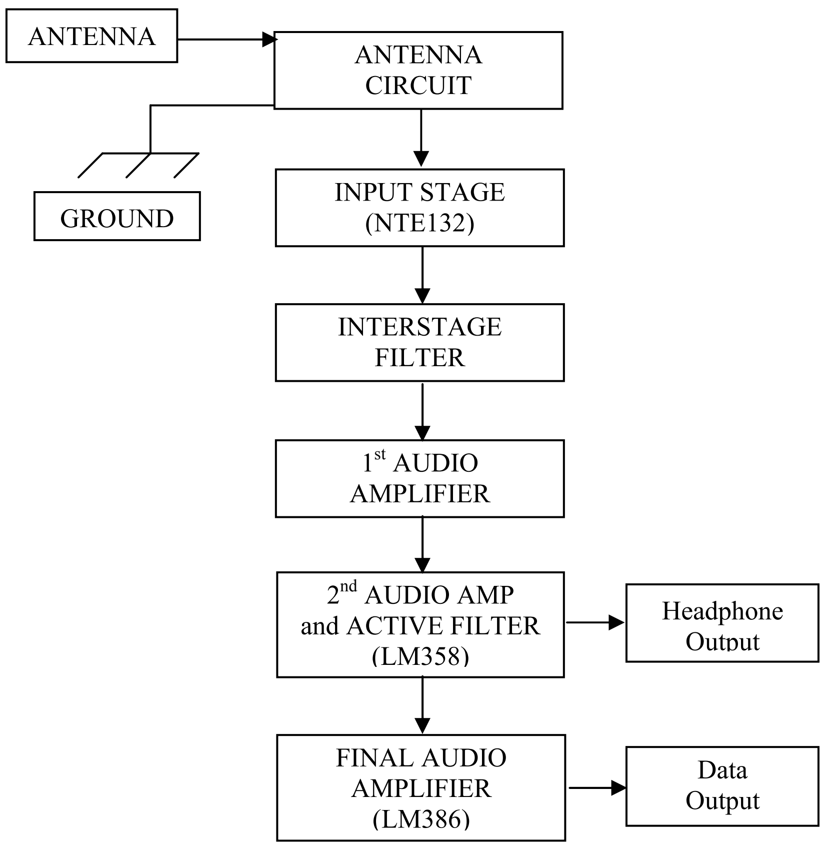

Figure-1. Block Diagram of the VLF-3 INSPIRE Receiver.

The antenna circuit is totally passive and contains an inductor plus several capacitors and resistors. Referring to the schematic in Figure-2 (top left corner), note that two components are always in the circuit (L1 and C1) and the rest are switched into the circuit by closing switch S1. L1 and C1 form a low pass filter whose purpose is to attenuate signals in the AM broadcast band. This low pass filter has little impact on VLF signals. When switch S1 is closed, two changes are made to the antenna circuit. First resistors R1 and R3 are placed in the circuit forming an attenuator between the antenna and the input stage. This attenuator reduces the signal provided by the antenna by 6 DB. Second

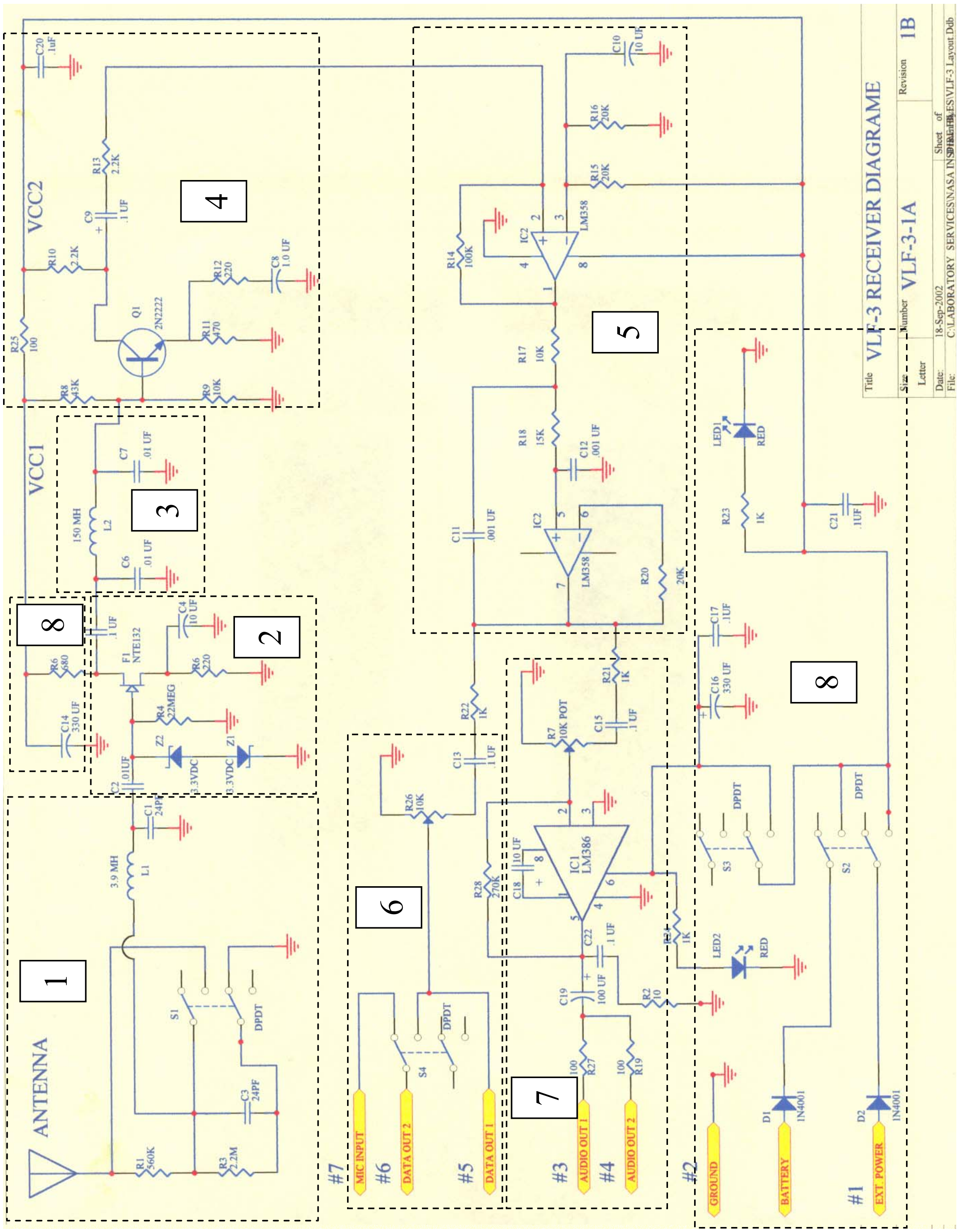

Figure-2 Schematic diagram of the INSPIRE VLF-3 receiver.

another capacitor, C3, is placed in the circuit. This capacitor further lowers the cutoff frequency of the low pass filter L1/C1.

The circuitry associated with switch S1 was specifically added to help reduce the pulse interference generated by close LORAN transmitters. Even though the frequency of LORAN (100 KHZ) is outside the pass band of the VLF-3, the LORAN signal is often strong enough to produce intermodulation in the first active stage of the receiver, which gets passed through the receiver to the recorder as a series of pulses or clicks. Closing S1 reduces all the input signals by 6-10 DB. The added capacitor C3 lowers the cut off frequency of low pass filter C3/L1/C1, which further reduces LORAN interference. The added circuitry will eliminate all but the most severe cases of LORAN interference. This circuitry is also effective against MF and HF transmitters that are close enough to cause interference.

It is important to realize that LORAN suppression (closing S1) also degrades receiver performance in two ways. First all signals, including the desired natural radio signals, are attenuated by 6 to 10 DB. Second resistor R1 will generate thermal noise when in the circuit. This resistor is in the highest gain part of the receiver and its thermal noise will be very evident in the receiver output. This additional noise will tend to mask some weaker desired signals. The bottom line is; don't use LORAN suppression unless it is absolutely necessary.

The VLF-3 also contains a "ground" terminal. The ground terminal connects to the receiver's circuit common. It is important to connect this terminal to a ground stake. The ground stake can be as simple as a foot long metal rod driven into the ground. In the author's experience, the LORAN suppression circuits won't work if the ground terminal is left unconnected. When unconnected, the VLF-3 is referenced to Earth potential through stray capacitance and is floating at some undefined voltage above ground. Thus, the Earth return needed to make the input attenuator work is not present.

2. Input Stage

The second block in the diagram of Figure-1 is the "Input Stage". This stage consists of the field effect transistor (FET) F1 (an NTE132 device) and associated components. F1 is the first active device in the receiver's signal path. The main purpose of this stage is to convert the very high impedance of the antenna to a lower value so that the signal can be more efficiently amplified. In the frequency range 300 HZ to 20 KHZ, the E-Field probe antenna has impedance between 30 and 800 MΩ[2]. The input stage converts this very high impedance to a value in the 100-Ohm range and also provides about 3 dB signal gain. Three points are worth noting concerning the input stage; refer to Figure-2 for the following discussion. First, the back-to-back Zener diodes Z1 and Z2 are included to protect the FET from damage due to static. Static discharges and distant lightning can induce voltage at the antenna terminal sufficient to damage the FET. The diodes clamp the input voltage to the FET to between +3.3 and –3.3 Volts. Second, capacitor C2 establishes the receiver's low frequency cut off point and also provides DC isolation for the antenna. This capacitor's value was chosen to reduce 60 hertz power grid interference. Finally, the FET Gate resistor R4 is the main component that determines how much of the voltage

[2] For information on the impedance of short E-Field probes, see "VLF RADIO ENGINEERING" by Watt, Pergamon Press. 1967.

captured by the antenna will actually be amplified in the receiver. Stated a different way, R4 determines the ultimate sensitivity of the receiver. The value chosen for R4 (22MΩ) is a compromise value considering costs, component availability, circuit board layout and receiver sensitivity. For maximum sensitivity a value >100 MΩ should have been chosen; however, use of such a high value would significantly increase costs.

3. Inter-Stage Filter

The next stage shown in Figure-1 is the inter-stage low pass filter consisting of inductor L2 and capacitors C6 and C7 (see Figure-2). In Figure-2, these components are located in the signal path between F1 and Q1. The inter-stage filter is needed because the input stage is broadBand and capable of amplifying signals in the LF, MF and HF bands in addition to the VLF band. Even though the antenna circuit provides some filtering to reject signals in the MF and HF bands, a strong signal (for instance from an AM broadcast station) will get through and be audible in the receiver output. The low pass filter has an upper cut off frequency of about 12 kHz and strongly attenuates signals above about 20 kHz.

4. First Audio Amplifier

The next stage shown in Figure-1 is the first audio amplifier. This is a conventional discrete component design using a 2N2222A transistor (Q1). This stage provides the first significant signal gain in the receiver, about 10 DB.

5. Second Audio Amplifier and Active Filter

The fifth stage shown in Figure-1 is the 2^{nd} audio amplifier/filter. This stage uses ½ of the LM358 integrated circuit (IC2) as an amplifier with a gain of about 15 dB and its frequency response is flat from about 300 HZ to well over 100 kHz. This is followed by the second part of the LM358 configured as a Sallen-Key second order low pass filter. This filter had unity gain and its frequency response is flat from about 300 HZ to approximately 20 KHZ.[3]

6. Data Output

The output of the 2^{nd} audio amplifier/filter is coupled through a resistor, blocking capacitor and level control (R22, C13, and R26) to the left channel of the stereo data output jack (see Figure-2). The potentiometer R26 serves as the level control. The left channel signal is also applied to switch S4, which selects either an external input (labeled “Mic Input” on the schematic) or the radio output for the right channel. Thus the left channel always contains the radio output and the right channel can be either the radio output or a signal from an external source such as a microphone or a WWV receiver. The output at the data jack has sufficient amplitude to drive a recorder but will not adequately drive a headset or speaker.

[3] Additional details about this circuit can be found in “OPERATIONAL AMPLIFIERS-Design and Applications”, Tobey and Graeme, McGraw-Hill, 1971.

7. Final Audio Amplifier

The last block in Figure-1 is the final audio amplifier. Its circuit is on the lower left of Figure-2. The final audio amplifier uses a LM386 IC (IC1). The output of the second audio amplifier/filter is applied to the LM386 through a resistor, coupling capacitor and volume control potentiometer (R21, C15 and R7). The IC amplifies the input signal increasing its level sufficiently to drive a set of headphones or a small speaker. The audio output phone jack is a stereo unit with the same signal being applied to both left and right channels. The resistor R27 is used to protect the LM386 IC in the event that a mono headset is accidentally plugged into the audio output jack. Capacitor C19 is used to block DC from the amplifier preventing it from reaching the headset. Note that the final audio amplifier is not powered when the receiver main power switch is turned on. This audio amp has its own power switch, S3. This switch allows the audio amp to be turned off when not needed to conserve battery power.

8. Power Supply

Referring to the schematic of Figure-2 (lower left), note that the radio can use two power sources. Either an internal 9 VDC battery or an external 9-14 VDC source can be used. The diodes D1 and D2 serve to isolate the two power sources. The diodes prevent the external source from attempting to charge the internal battery and vice versa. Note that if a rechargeable 9 VDC battery is installed internally the battery cannot be recharged by connecting a charger to the external power input. These diodes also protect the receiver's circuitry from damage if a battery should be connected with reversed polarity.

Power for all portions of the radio is applied through the main on-off switch S2. When S2 is on, all circuits are energized except for the final audio amplifier. The main power buss is decoupled by capacitor C21. LED-1 is also energized any time the main power switch is on. The main power buss is also filtered and decoupled by capacitor C14 and resistor R25 before it is applied to the FET stage. These two components prevent the high level signals present in the later stages from being coupled via the power buss into the sensitive input stage. Should this coupling occur, the radio will oscillate. The main buss is also coupled through switch S3 to the final audio amplifier. The buss to the final amp is also decoupled by capacitors C16 and C17 for reasons discussed above. LED-2 will be illuminated anytime the final amp is powered.

The BNC Antenna Connector.

A BNC connector is provided as an alternate connection point for an antenna. Before anything is connected to this connector, the impedance at this point must carefully be considered. The effective impedance at the BNC connector is in the 20MΩ range. Normally, BNC connectors are used with coax cables with impedance nominally in the 50-75 ohm range. If a 50 or 75-Ohm device is connected to the VLF-3 BNC connector, there will be a severe impedance mismatch that will degrade the VLF-3 performance.

The author has found three acceptable ways to use the receiver's BNC input.

1. When portable operation is desired, connect a short telescoping whip antenna to the BNC connector. Commercially made telescoping antennas with lengths of from 1 to 6 feet with attached BNC connectors are readily available. These antennas were designed for use with handheld radios and scanners. The author uses the VLF-3 with a 6-foot telescoping whip and stereo headset to walk around an area testing for the presence of 60 Hz, LORAN and AM broadcast interference. This simple test can help locate the quietest location in a given area. When using such a setup, be careful to keep the antenna well away from the headset cord.

2. It is possible to exploit the impedance mismatch to reduce interference. The author experimentally determined that by using a 20-foot long length of RG-8M to connect the antenna to the receiver, LORAN interference was eliminated without use of the receiver's built in LORAN suppression. This is desirable because it eliminates the extra broadband noise generated by the built-in suppression circuit. The coax provides shunt capacitance to ground sufficient to eliminate the interfering signal.

3. Finally, the author has used the BNC connector to connect a signal generator to the receiver for various sensitivity and response measurements. An interface box is required. The interface box contains a 50-Ohm resistor to ground and a series 24-pF capacitor. The capacitor simulates a short antenna and this interface box is commonly called a dummy antenna. The dummy antenna must be well shielded. The authors unit was built inside a short length of copper water pipe with BNC connectors on each end.