The VLF-3A or yet another VLF receiver

Joachim Köppen,
DF3GJ,
koppen@astro.u-strasbg.fr,
Observatoire Astronomique,
11, rue de l'université,
F-67000 Strasbourg,
France,
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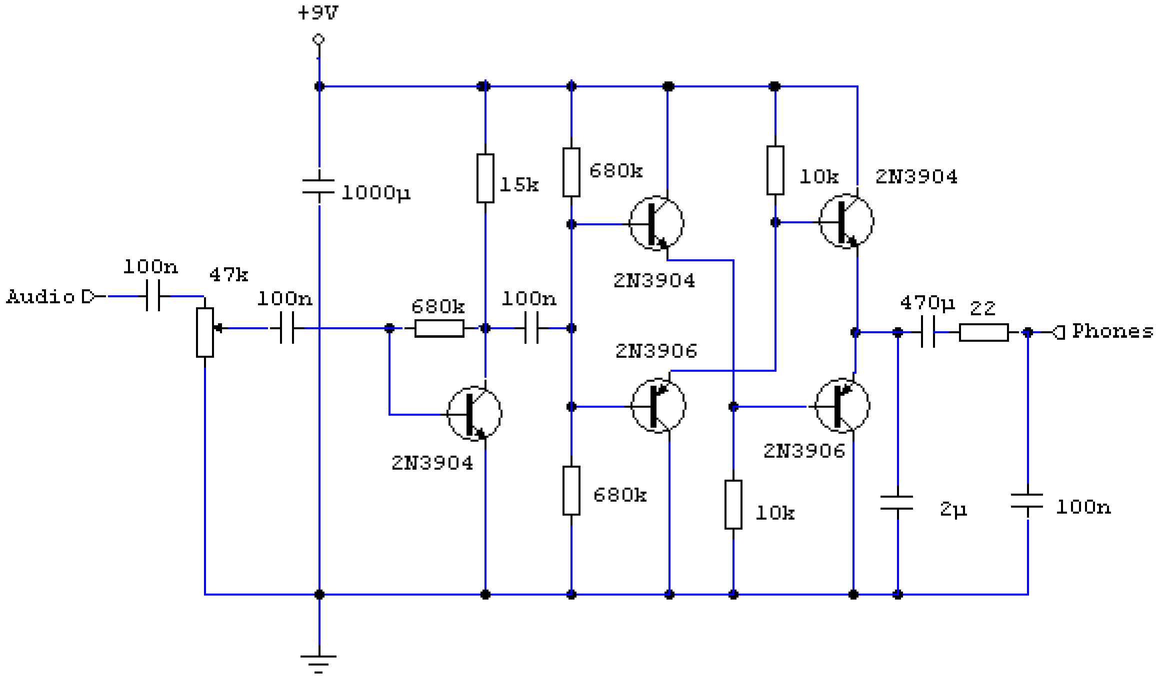
How it all started

A few years ago I sat on a bench near a dyke on the Baltic Sea shore and tried out one of the first VLF-3 receivers which Jim Green had given to me, I switched on at lunch-time, and was surprised to hear whistlers piling up on each other, as I had not heard it before. It was as if someone had placed a whistler attractor in that small box. As an electronics amateur I became very curious what it was that made the set work so nicely … shouldn't it be possible to improve my own receivers and perhaps make even better ones? This unleashed a continuous comparison with the VLF-3 and ongoing perfectionist's effort, which is very interesting, entertaining, and fruitful. During a couple of years of experimentation with various circuits, trying them out under diverse conditions (on the beach, in a square in front of my apartment, on my balcony, in open spaces in parks, even in different cities), my receivers – and there are quite a few now in use – evolved to this latest version which I shall describe in this article; along with some design comments that might help others to build their receivers or to adapt their VLF-3 to their own special needs.

Audio amplifier

Let us start from the back, the output end. Since this part is the least critical and the easiest to test – as we do not yet need weak signals, one would usually start construction of a receiver with this section. The preceding stages would be added one after another, and the set becomes progressively more sensitive, which requires more care for construction and testing.

Also, the audio output stage is the one where no changes from the concept of the VLF3 would be needed. However, since I have plenty of transistors in my junk box, I built a discrete audio power amplifier instead of an IC such as the LM 358. The circuit which uses two pairs of complementary transistors I had came across many years ago in an electronics journal, and I have found it very useful for any situation where I needed to drive a low impedance load, such as ear phones. A single gain stage suffices, which amplifies the audio coming from the volume control. The coupling capacitors have only 100nF, because we want to give less emphasis to the low audio frequencies which contain the mains hum.



Circuit diagram of the audio amplifier

At the output, I added some low pass filtering which I had found helpful cutting the overall gain at high frequencies, which makes the receiver less prone to feedback via the earphone and the tape recorder. These measures might not be necessary in your receiver.

The transistors can be any silicon transistors. No special attention needs be paid to matching them, and it is not necessary to use 2N3904/3906. I have used with success other npn-pnp transistors, such as those recycled from used audio and TV equipment. As a test one should measure the voltage at the meeting point of the emitters of the final transistors: one should find that it is one half of the supply voltage. If one connects an earphone to the output, one should hear some noise when the bases of the first transistor pair are touched with a screw driver metal.

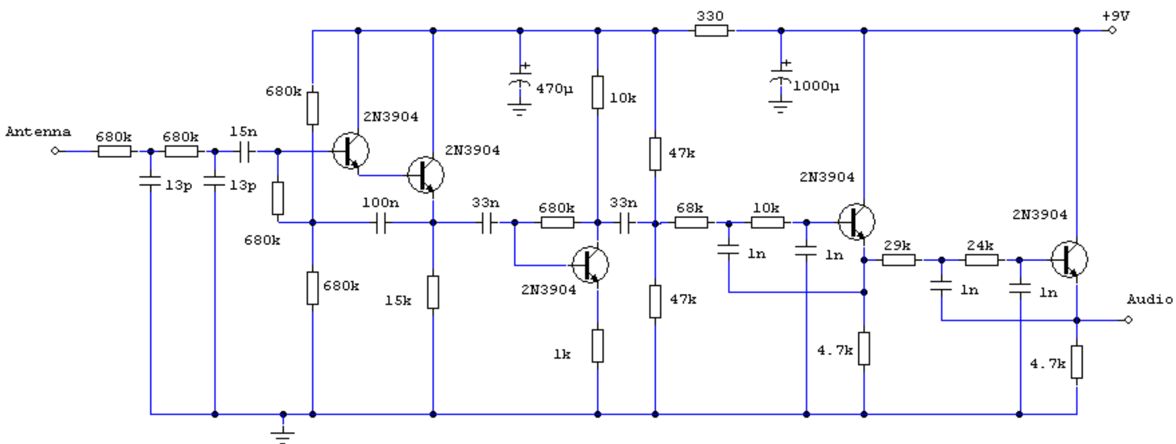
The preceding stage amplifies the signal about 100 times (or by 40dB). The voltage of the collector should be somewhere between 1 and 3 V. When touching the base terminal, hum should be heard clearly in the earphone. When one touches the 'hot' solder lug of the volume control potentiometer, one should hear the hum becoming weaker or louder, if one operates the control appropriately.

The low-pass filter

In principle one could build the VLF receiver by successively adding more amplifier stages, such as the first transistor of the audio amplifier. The value of the collector resistor determines the gain, values between 10 and 47 kOhm can be used. The bias resistors can be between about 470kOhm and 1 MOhm. The essential test would be to measure the collector voltage to

be in the range of 1 to 3 V. Such a developmental approach would be my advice, as one can observe the increasing sensitivity of the circuit. One simply stops when at full volume the hissing noise from the stage in the front would just be audible.
However, a crucial part is to limit the frequency domain to frequencies above about 500 Hz and below about 10000 Hz. At lower frequencies the mains hum is a nuisance, which may be present more or less strongly. I have experimented with high-pass filters, such as sharply cutting out frequencies below about 500 Hz. Unfortunately, this measure results in a quite unpleasant audio impression due to its lack of balance by the lower frequencies. Furthermore, whistlers may be heard down to frequencies as low as 200 Hz, so one loses some interesting information. But good results are obtained, if we weaken the low frequencies to some extend, as is done by selecting coupling capacitors smaller than usual in audio amplifiers. It depends on one's personal preference, but values of 100nF or somewhat smaller are a good starting point.
At higher frequencies there is not much important information for the common whistler, our ear cuts off at about 20000 Hz anyway, and the frequency response of tape recorders also starts to drop off above about 10000 Hz (recordings with MP3 players offer better fidely up to their limit frequency of usually 22000 Hz). On the other hand, there may be some VLF transmissions sufficiently strong to cause problems: in my place in Northern Germany there are fairly strong signals on 18 and 23 kHz which appear as a high pitched whine, and because my tape recorder uses a 20 kHz to erase the tape, this frequency is mixed with any ultrasonic signal that might be coming in, causing a fairly irritant high pitched whine in the recordings as well. Therefore, a strong and (preferentially) sharp suppression above about 10 kHz is needed.

One way is implemented in the VLF-3 by C6, L2, C7 which gives 13 dB attenuation at 10kHz and 65 dB at 100 kHz. The ferrite of the inductor may add to the pickup of mechanical noise, but an inductance/capacitance-filter has the advantage of not adding any noise. However, one needs a fairly large inductance – 150mH – which is quite hard to find in thrown away HiFi and TV equipment from which I like to scrounge many components for reuse. So I decided to use an active low-pass filter, but instead of employing operational amplifiers as in the VLF-3 (IC2), I use ordinary silicon transistors operation as emitter followers. I chose a 4th order Butterworth filter, using 1nF capacitors. The resistors are computed for a 3dB roll-off at 6 kHz from my applet (http://astro.u-strasbg.fr/~koppen/radio/Activee.html). If one had low tolerance capacitors, one could also use 1 percent tolerance resistors and make a filter that behaves very close to theory. I did not go to such trouble, as the filter seems to do its job in several receivers, despite my picking standard values closest to the theoretical ones.



Circuit diagram of input filter, impedance converter, gain stage, and active low pass filter

The filter section can be tested by checking the voltages of the emitters, which should be nearly half the supply voltage. Touching the base of the first stage should give a signal as loud as one had heard from the volume control's 'hot' terminal, however somewhat more 'bassy'.

At this stage of the receiver, the noise from the transistors in the filter does become apparent. Ideally, a filter should be in front of any gain stage, but the noise contribution from the transistors would compromise the receiver's sensitivity. In order to ensure that the noise contribution from the impedance conversion stage is the dominant one, the filter section is preceded by an amplifier whose gain is limited to a moderate factor of 10 (i.e. 20dB). The amplification of this stage is determined by the ratio of the resistors at the collector and the emitter. Thus, by increasing the emitter resistor one can lower the stage gain, in case of need. Under my usual operating conditions I find that the signals at this part of the circuit remain still sufficiently low, so that the presence of the undesired signals does not cause any harm by the unavoidable non-linearity of the transistors, which would cause intermodulation signals to appear in the audible range.

As with the audio section's gain stage, one should expect the collector voltage to be a few volts. The voltage drop across the emitter resistor should be less than one volt. This transistor could draw about 300µA collector current, which would give a emitter voltage of 0.3V and a collector voltage of 4.5V. Any value thereabout would be acceptable. Touching the base lead should now cause a strong hum in the audio output, so that turning down the volume would be needed.

If at any stage of construction the entire circuit would go in howling or a rhythmic behaviour – called motor-boating – make sure that the large smoothing capacitors 1000µ and 470µ are in place as well as the 330Ohm resistor in the supply line whose role is to prevent large variations of the voltage at the audio stage feeding back into the first stages. In case of problems, it is wise to separate the input stages even more by adding such a series resistors and bypass capacitor.

Impedance conversion stage

Finally, the first stage performs the crucial operation of transforming the high input impedance needed for the antenna to the lower impedance of the transistor amplifier stages. Instead of a field effect transistor F1 in the VLF-3 I tried a combination of two normal silicon transistors, known as the cascade or Darlington configuration. The first transistor amplifies its base current, putting out an emitter current at least 100 times higher; this current drives the base of the second transistor and is amplified once again. This results in a very high input impedance, about 100 times 100 times 15kOhm, the value of the emitter resistor, hence at least 150 MOhm. At a frequency of 1kHz, the antenna is extremely short in comparison with the wavelength of 300km. For example, the impedance of a 1m long whip is about 30 MOhm capacitive. Thus, the Darlington pair provides an adequate low loading of the antenna.

Note that there is no voltage gain by this stage. This is done because one does not want to have intermodulation of the desired signals with any undesired signals which are not yet filtered out. The transistors are biased by the three 680kOhm resistors, which will make the voltage at the emitter of the second resistor close to half the supply voltage. As we do not want the 680kOhm resistors spoil the high input impedance, the output audio is fed back to the meeting point of all three resistors. This 'bootstrap' technique makes that point appear to be at the same potential (audio frequency-wise) as the base, hence for audio frequencies, the bias resistors are not present!

This stage can be tested by verifying that the emitter voltage is about half the supply voltage, and one will notice that the receiver has become so sensitive that it picks up any hum, even when one's finger merely comes in the vicinity of the base lead. On the normal worktable with the mains supply for the soldering iron, one should hear a hum noise all the time.

Input low-pass filter

Finally, there is an input low pass filter. This is essential – at least in Europe and also in the area around San Francisco – because it shields the receiver against signals in the LF and MF bands which are AM broadcast stations. In northern Germany, we have the proximity of Kalundborg, a strong long-wave transmitter in Denmark on 243 kHz. Even with s short whip antenna, the signals are so strong that they get rectified on the nonlinear dependence of the transistor's output current on its input voltage. If I do not have a low-pass filter, I can hear the news in two languages as well as a rapid pulse type transmission from near 100 kHz!

To construct a low-pass filter for the high impedances involved, is next to impossible; for example a inductance/capacitance filter would require small values for the capacitors, but a large inductance to ensure a sufficiently low cut-off frequency. This makes such a filter quite unrealizable.

I choose a simple resistance/capacitance filter, which is sufficiently effective, albeit it introduces some loss ahead of the input stage, and thus it limits the sensitivity of the receiver. The two-section low-pass filter gives attenuations of 6dB at 10kHz, 10 dB at 20kHz, and 30 dB at 100kHz. This provides full protection against the local long wave radio stations. In a recent stay in the Silicon Valley area, I noticed that the VLF-2 receiver was picking up AM radio, despite its FET front end. This was easily and completely cured by inserting a single 470kOhm/15pF low-pass filter at its antenna terminal.

For those lucky ones which have an access to very low noise sites and who desire to hunt for very weak signals, this filter may be left out, or – as in the VLF3 – it can be switched in and out. I should also add that in my place operation of the VLF3 is only possible with its filter switched in! Another option would be to be able to select only one RC combination … Some experimentation which can bring the optimum arrangement for your application can be easier than designing a set that fits all cases.

I also tried field effect transistors instead of the Darlington pair. There is indeed a slight improvement in the sensitivity, which does not change the world, mainly because the input low-pass filter remains the main limitation to the sensitivity.

Power consumption

The receiver draws about 5 mA from a 7 V supply. I use 9V block batteries which had been used in, for instance in portable microphones. Since in these applications, the battery drain may be quite high, and the battery has to be replaced while it is still capable of providing a voltage of 6 to 8V. Because of the low consumption of the receiver, such a battery often sees a good service for a couple of months!

Signal strengths

There is not much point trying to reach the ultimate sensitivity, since even if one had a low-hum site, the spherics of a normal day set a limiting level. There may be times and days when I have experienced in Europe days with very faint spherics, for instance before noon before local thunderstorms are built up, or in the winter season, when thunderstorms are absent here. But usually in northern Europe we have a steady spherics background of 1 to 10 mV from a 1.5m long whip antenna. The measured internal noise level of the receiver is about 100µV (with the input low-pass filter) or about 1µV (without the low-pass). If the low-pass was absent, the local AM stations, and a number of VLF/LF stations would be so loud that spherics would be practicable unnoticeable. Whistlers are usually weaker than the crashes of spherics, and often close to the receiver noise level, but their distinct sound makes them still readily picked up by the ear.

Constructional hints

Since all my receivers are individual creations, I never bother to make a printed circuit board and go through all the trouble of etching and drilling etc. Sometime I used Veroboard with has copper islands or strips with already drilled holes. But I really prefer to use an empty copper-clad board as the ground plane of the circuit, soldering all components free-style on the board and to each other, as seen below

Input filter and impedance conversion stage built in 'free-style' using an empty printed circuit board as ground plane

The VLF-3 has a slight disadvantage, by having a plastic enclosure, which leaves it unshielded against picking up the hum and other electromagnetic signals from its surroundings. Putting it into a metal case would improve things. Several receivers I placed inside an empty beer can, with the antenna terminal at its bottom. I removed the lid on its top, replacing it by a piece of printed circuit board, which holds the audio socket, volume control, and the power switch. The board carrying the circuitry is soldered to the face-board or held to it by some stiff copper wire. The pictures below show the top and the bottom of such a can receiver. The mechanical construction is quite tedious, so that recently I use metal cans from tea or sweets that already have a removable plastic lid!

The metal case has not only the advantage of shielding the receiver, but because holding it in the hand automatically provides a good earth connection necessary to avoid whistling and howling due to feed-back. The can's size is ideal to hold in the hand, but while beer or soft drink cans are visually quite nice, their hull is rather thin and it eventually get bumps and cracks from other items in the back-pack. This is another reason for me to prefer more sturdy sweets cans!

The antenna terminal of a beer can VLF receiver

The lid of the beer can is replaced by a printed circuit board which carries the controls

At the very low signal levels, the set becomes sensitive to mechanical perturbations, such as the wind blowing around the antenna, whose vibrations are passed on to the circuit board and its components. While it is impossible to completely avoid this mechanical sensitivity, it does pay off when one pays careful attention to select components which are less prone to pick up mechanical noise than others. For example, ceramic disk capacitors – the ones that come as orange-brown disks – are quite sensitive to mechanical stress. Stroking one of them with a toothpick produces quite a bit of noise, if that capacitor happens to be one of the components of the first stage! Other capacitors – such as the flat rectangular ones encapsulated in green or red shiny plastic (polyester film capacitors) – are much more immune to this effect.