A natural radio receiver

Klaus Betke – 30 March 2002

The idea behind this receiver was simply to find out whether atmospheric sounds like tweeks and whistlers [1, 2, 3, 4] can be received in the overdeveloped area I am living in, with electric lines and cables almost everywhere. First tests were quite promising; not in the middle of the city of course, but in suburban areas and on the country side, although even there it may be difficult to find a place that is free of hum. – Although the design is the result of a number of experiments with different circuits, please do not regard this paper as a bullet-proof recipe, but as a "report from the workbench".

Circuit description

Basically a natural radio receiver is little more than a wire antenna connected to a high-impedance audio amplifier. The frontend of this one is made of a FET source follower (T1). This classic approach was used because of its low input noise current. L1, L2, C2, C3 and C4 make a 5th order low-pass filter. It was taken from a design table for 5-element Chebyshev low-pass filters [5], but with the inductors scaled to a standard E12 value. This lead to a filter impedance of approx. 1200 ohms. The filter is mainly for removing signals from VLF radio stations.

Headphone amplifier U1b is biased by the DC output voltage of U1a, which is passed through P1. It provides enough loudness in a 2 x 32 ohms headphone. The recorder output level is relatively low and better suited for microphone than for line level inputs.

A battery indicator is built with T2 and T3. LED D3 flashes when the receiver is turned on, as long as the supply voltage is higher than approx. 3.8 Volts (dry batteries can be considered "empty" when the cell voltage has dropped below 1 V). The receiver still works below this voltage. Supply current at low volumes is a few mA; it is mainly determined by the drain current of T1. U1 quiescent current is less than 0.6 mA.

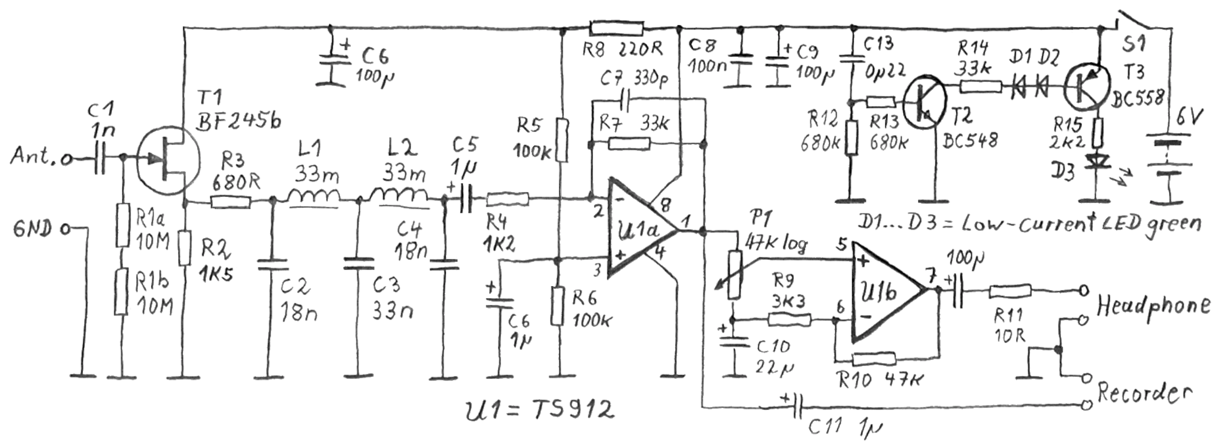

Figure 1. Schematic diagram

The overall frequency response is shown in figure 2. Not included in the diagram is the inherent first-order highpass (6 dB per octave) formed by the antenna capacity plus stray capacitances, and R1. With a one metre whip antenna, a corner frequency of 500 - 1000 Hz can be expected.

Figure 2. Receiver frequency response

Construction details and experiences

The receiver was built on perforated board into a cheap aluminium box (figure 3). The uneven coverage of the PCB results from a number of experiments with an additional amplifier stage, which then was found unnecessary. A telescope whip antenna from an old portable TV set was screwed to the enclosure by means of plastic washers. The prototype was not fitted with a thread for a photo tripod or similar, although this would be a useful feature.

Natural radio receiver circuits are susceptible to oscillation, because the high impedance input easily picks up electric fields from the circuitry itself. A shielding enclosure is mandatory. The connection between the antenna and T1 must be kept very short. The wiring of the volume potentiometer, headphone and record jack should be short and twisted, or shielded. Another common source of feedback – probably the major one – is the headphone cable.

The receiver needs a ground or "counterweight" for optimum sensitivity and to prevent it from ringing (see above). For handheld operation, the hand and body capacitance is usually sufficient.

Filter inductors L1 and L2 must have a low DC resistance, which is an indicator for the achievable filter Q factor. The Fastron 09P-333J type used here has about 70 ohms [6]. 18 nF capacitors were not available in the junkbox, so I used 15n + 3n3 for C1 and C3.

The filter can of course not fully cut off the Russian Alpha navigation signals. Alpha frequency f1 = 11.9 kHz is attenuated by 16 dB, f2 = 12.6 kHz by 19 dB and f3 = 14.9 kHz by 27 dB. But though audible, I did not find the beeps annoying.

A more serious problem was 2nd order intermodulation of T1. At times, frequency shift keying signals could be heard, especially with a BF245a running at a low drain current of I_d = 0.4 mA. It turned out that this was caused by a nearby military VLF transmitter, producing several 10 mV(!) at the T1 source pin. By means of a two-tone generator, it was possible to enhance the linearity through selection of T1 and R2 (I_d should not be too low). The best result was obtained with a BF245c type at I_d = 3 mA, but proper biasing is not possible below 5 V. No doubt further improvements are feasible; I did not yet spend much thought and experiments on this subject.

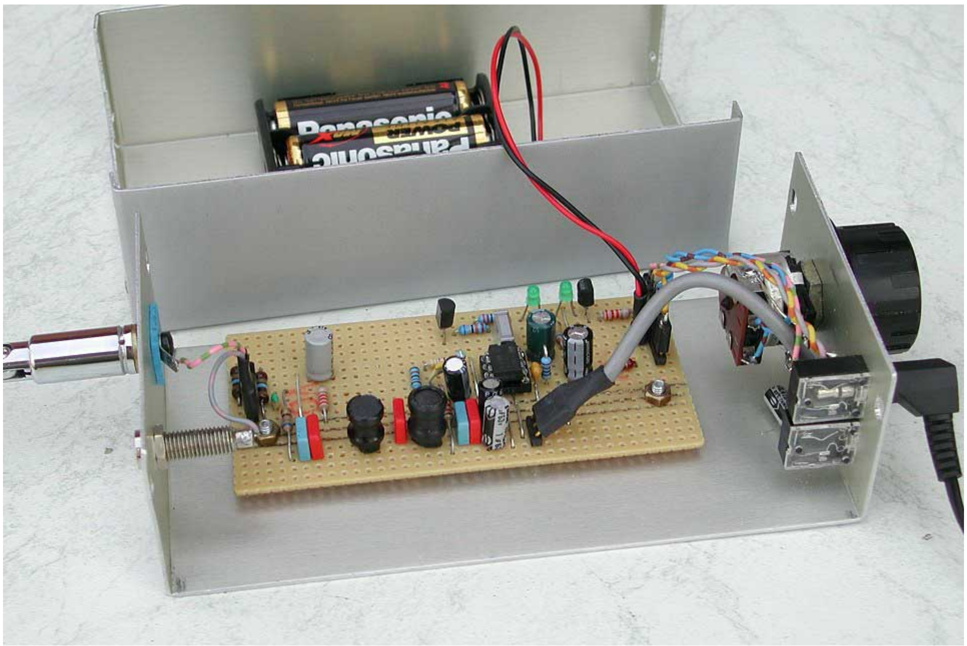

Figure 3. Prototype construction

Notes on the input stage

One design goal for this circuit was operation from a low battery voltage, preferably 6 V or less. For this reason, circuits with the antenna connected to the non-inverting input of an operational amplifier instead of using a FET were tried as well. There are many op-amps with low noise voltage, sufficient bandwidth and suitable for low-voltage operation, but much less are available with a low input noise *current* as well. Noise current an important parameter for high-impedance input amplifiers like this one.

Table 1 lists the major noise sources for an arbitrary selection of amplifiers. Thermal noise across R1 is of course independent of amplifier type and cannot be lowered; therefore it is not necessary to select an op-amp with a lower noise current than, say, the TL07x series. Table 1 also shows that the amplifier's input noise *voltage* is a less important parameter.

Both current-induced and thermal noise in R1 are partly shortened by the antenna, but in receiving tests under real conditions the TLC272 was also found noisier than the TL072. The TS912 (CMOS) was just acceptable.

A discrete JFET like the BF245 can exhibit an extremely low noise current [7]. It has a much higher bandwidth than required, so if there is an amplifier between the FET and the low pass filter, it must not be overloaded[1]. Furthermore the FET itself is subject to nonlinearity, in particular at low operating voltages. Strong radio signals can cause mixing products in the audio range.

Amplifier type	Amplifier input noise current in $fA/\sqrt{Hz}$	R1 noise voltage due to amplifier input noise current, in $nV/\sqrt{Hz}$	R1 thermal noise in $nV/\sqrt{Hz}$	Amplifier input noise voltage in $nV/\sqrt{Hz}$	Minimum supply voltage, in Volts	Remarks
Bipolar op-amp	typ. 1000	(10000)	400	< 5 possible		
TLC27x, TS27x	> 120 *	> 1200		25	3.5	* not specified
TS91x	≈ 60 *	600		30	2.7	* not specified
TL07x	10	100		18	< 8	not specified below ±4.5 V
ICL7611	10	100		100	< 2.5	high low-freq. noise voltage
TLC220x	0.6	6		12	4.6	
LMC6001	0.13	1.3		22	4.5	
Discrete JFET	< 0.1	< 1		very low	< 4 possible	subject to 2nd order IM

Table 1. Noise voltage spectral densities at the input for various amplifier types and a biasing resistor of R1 = 10 Mohms.

References and further reading

[1] Several articles about natural radio are available at *www.vlf.it*

[2] The INSPIRE project: *http://image.gsfc.nasa.gov/poetry/inspire/index.html*

[3] VLF-ELF in NE Holland: *www.da4e.nl*

[4] Long Wave Club of America *www.lwca.org*. Introduction to Natural Radio; links

[5] Standard Value Capacitor Filter Tables. In: The ARRL Handbook For Radio Amateurs, 79th ed. Newington, 2002. The tables also appeared in previous editions

[6] *www.fastron.de*

[7] U. Tietze, Ch. Schenk: Halbleiter-Schaltungstechnik, 11th ed. Springer-Verlag Berlin 1999

---

[1] This amplifier stage turned out to be unnecessary with respect to noise and sensitivity and was thus omitted in the design of figure 1.