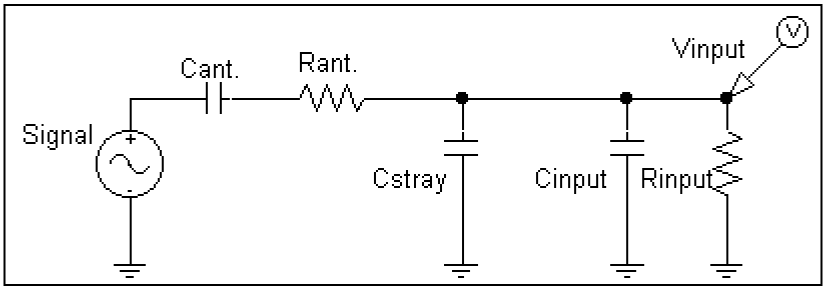
Some Thoughts on E-field Whistler Receiver Design

My introduction to natural radio listening came on a midsummer's eve this past July. The solder was likely still warm on my McGreevy BBB-4[1] as I listened in on the VLF cacophony accompanying the major magnetic storm that raged overhead. Nearly continuous multiple hop, diffuse whistlers mixed with chorusing and tweeks competed with the constant background crackle of strong sferics. I was so taken with these unusual sounds that I began an immediate search for alternative receiver designs incorporating more elaborate filtering. Although hum free locations are plentiful here in Northern Vermont, they all require either a short hike or a long drive to access – not conducive to pre-work sunrise listening. After reviewing the various E-field receiver designs found on the web I settled on one in particular that offered more comprehensive filtering, in addition to higher gain, than the BBB-4. My first tests of this new receiver where disappointing, all signals where greatly attenuated (as compared with the BBB-4). Additionally, what seemed to be a RTTY signal was present, stronger than the barely audible natural signals save the sferics. After unsuccessfully troubleshooting this receiver, I replaced its higher gain front end with the single FET BBB-4 front end – leaving all other filtering, pre and post, intact. Signal strength was depressed even further! But the RTTY signal was no longer present. Intrigued as to why this, apparently, more robust design would not outperform (or even equal) the BBB-4 I began to do a bit of research on E-field VLF/ELF receivers.



Per the literature[2,3] an electrically short E-field antenna (in our case vanishingly short) may be modeled as a voltage source, as given by signal field strength times the equivalent height of the whip, in series with the reactance given by the isotropic capacitance of the whip, the radiation resistance and the loss resistance at the frequencies of interest. For our case I will consider the frequency range from 500 Hz to 20KHz and a 1-meter long vertical whip. Given these parameters, the radiation resistance is almost nil and the loss resistance so many orders of magnitude below the capacitive reactance that the antenna can be modeled as a capacitor in series with the signal source. The isotropic capacitance of a long thin antenna is approximately 10 pF per meter. Given the above criteria, this results in source impedance that ranges from a low of 800KΩ to a high of 32 MΩ across the frequency range of interest. To recover >90% of the signal available at the base of the whip, the input impedance of our receiver needs to be larger than the source impedance by a factor of 10. To prevent loading the 500 Hz signal present at the base of our 1-meter whip, the receivers input impedance needs to be in excess of <u>300 MΩ</u>! Receiver input resistance to ground neatly forms a high pass filter while any input capacitance to earth a straight capacitive voltage divider. Most receiver designs I have seen have a gate resistor no larger than 10 MΩ, many are smaller. More importantly, the input low pass or notch filters often contain 100's of pF in shunting capacitance. You can see where this is leading. A Pspice model of the BBB-4 predicts less than 10% of the available signal appears at the gate of the FET (with a 1-meter whip). In the more elaborate receiver I mentioned above this drops to <1%! In the common source amplifier configuration often encountered, the Miller effect complicates things further by multiplying the capacitance of the FET gate /drain junction roughly by the gain of that stage, further stomping our signal[4].

To further explore this idea, I constructed a "simulated antenna" [2,3] to aid in bench testing and help give evaluations that were more quantitative and less subjective. This antenna consists of nothing more than a small value capacitor housed within a driven shield to mitigate stray capacitance. I choose 12 pF to approximate a ≈ 1-meter whip. Using a 10 mV RMS, 50Ω signal source, I monitored the output of my BBB-4 under three different conditions – signal injected directly into the gate, signal injected prior to low pass filter (normal input) and signal injected at normal input with “simulated antenna” inline. The results are tabulated below:

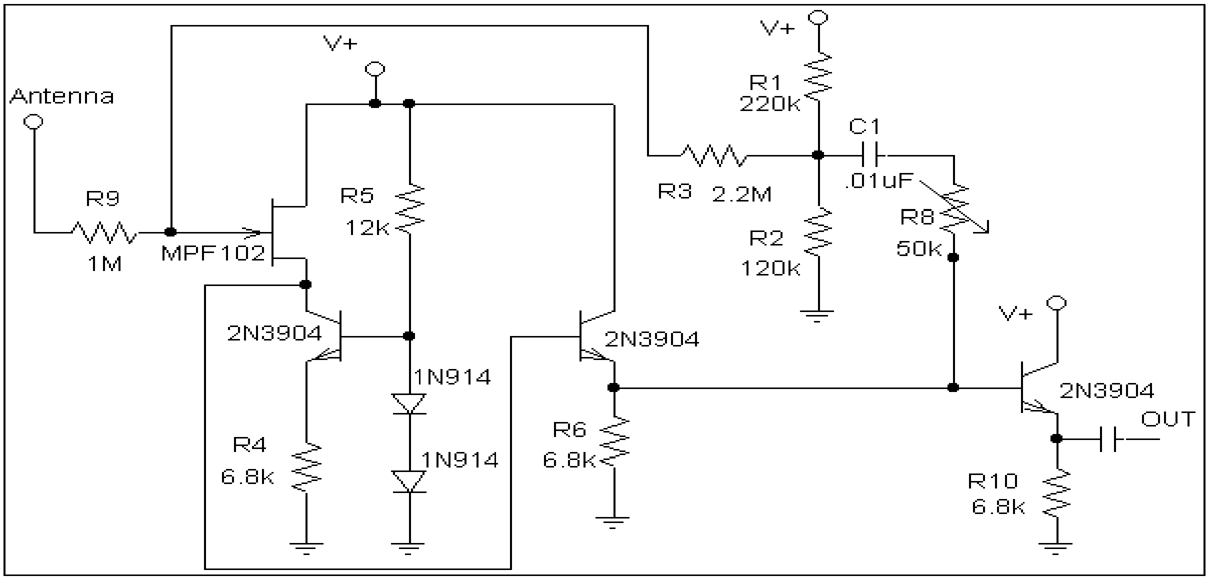
BBB-4 output given 10 mV RMS signal in

Frequency	**Direct** (mV RMS)	**Normal Input** (mV RMS)	**Simulated Antenna** (mV RMS)
50 Hz	5.3	4.7	0
100 Hz	12.6	11.6	0
200 Hz	37.6	33.3	2.5
400 Hz	123	108	9.45
800 Hz	354	306	30.4
1.6 kHz	804	630	70
3.2 kHz	1250	788	109
6.4 kHz	1120	448	86.7
12.8 kHz	624	135	35.5
25.6 kHz	261	28	8.9
51.2 kHz	78.9	4.6	2
102.4 kHz	17.1	1.4	0

At peak frequency response (≈ 3 kHz) my BBB-4 is capable of greater than 40 dB of actual gain. When sourced as it would be in normal use (with a short vertical whip) the effective gain drops to 20 dB at peak. The above is not meant to in any way denigrate Mr. McGreevy’s elegant receiver, but rather to demonstrate that E-field natural radio receivers, designed to be used with short whips, must have extremely high input impedance. 300 MΩ would be a good value to target. Almost any form of input filtering will grossly violate this impedance requirement.

This is starting to sound more like the requirements of an electrometer than a radio receiver! A 300 MΩ input impedance at DC would indeed make a crude electrometer (typical electrometer input impedance is in the Teraohms). This could make the receiver sensitive to charges induced on the antenna by the operator as he / she moves around near it. That in turn may drive the input device out of its linear region and, perhaps, into saturation. Seems an impasse, too low an input impedance and signal is lost, too high and it becomes sensitive to quasi-static fields that we don’t want to see (hear). Additionally, the Johnson noise of a 300 MΩ gate resistor would not be a pretty thing.

My solution to this conundrum has been to use a boot strapped source follower in front of any filtering or voltage gain stages. This allows all manner of filtering to be driven from the low impedance output of the follower **prior** to any voltage gain stages. The front end’s dynamic range can then be made much larger than is normally encountered in natural radio receivers. As the follower has no voltage gain, strong out of band energy does not drive the (follower) FET into a non-linear region – no mixing of NAA down into the audio pass band as occurred above. In fact, tight filtering can now be used to remove the majority of the unwanted crud before so much as a dB of voltage gain is used without killing the desired signal. The following circuit is a modified version of a source follower lifted from the pages of Nuts and Volts magazine. Testing it with the above mentioned simulated antenna yields >85% signal recovery, the 15% being lost to strays and junction capacitance I believe.



At DC, the input impedance is ≈ 3.3 MΩ - no problems with the “electrometer” effect. As frequency rises, increasing amounts of signal are fed back in phase to the gate resistor via C1 and R8, dramatically increasing the apparent resistance of R3 at these frequencies. The apparent value of R3 will become $R3_{actual}$ /(1-gain). The 2N3904 active current source gives the follower a gain of better than .99 so the effective value of R3 can appear huge. This gives the effect we are after, an input impedance that is very high at the frequencies of interest but low enough at DC to prevent sensitivity to the motion of nearby charged objects (which is just about everything).

The only shunting capacitance appearing at the input is that of any strays occurring in the wiring to the gate and the internal junction capacitance of the FET itself. As the source “follows” the gate, the capacitance of this junction does not charge and is therefore not an issue. The drain is fixed, so the Miller effect is also not a problem. This holds the input capacitance of the FET to a couple of pF. There are techniques that will further reduce the apparent junction capacitance[7,8] but I have found the residual capacitance to be more of an aid than a hindrance, as explained shortly. R9 and the MPF102 should have the bare minimum of lead length needed to reach the input connector. I have taken to mounting mine “flying lead” style on the antenna connector, a technique used in ultra high impedance instrumentation (well, in my Keithley electrometer anyway). Alternatively, a piece of coax could be used but the shield must be driven by the output of the follower – not grounded. In short, whatever technique that works [5] should be used to keep any stray capacitive coupling with the gate at a minimum – a few pF here and there is a killer when you are looking at the signal source through only 10 – 20 pF. This is, in my opinion, the major reason that E-field receivers are so sensitive to nearby trees and other vertical conductive items. The world is full objects (including the ground) that are more than willing to be the “other plate” of a capacitive voltage divider. Absorption of the wave front energy by these objects obviously also plays a role, but it is likely minor compared with this loading effect.

Without R8 some peaking will occur just before the corner frequency. This may or may not be desirable depending on your application. I included it, as my intentions were to have as flat a frequency response prior to the -3 dB point as possible. Its exact value will vary depending on the size of your whip. You can use a signal generator and a “simulated antenna” sized to approximate your whip to set it up, or the lower tech, but very effective, cut and try and listen method. Alternatively, it can be left out altogether; the peaking may be desirable. C1 should be between .001 and .1 μF, this gives a -3 dB point that varies from ≈1.5 kHz down to near 300 Hz. Be aware that using the larger values also brings up any hum nicely. Nothing besides care in avoiding stray capacitive coupling to the input gate is at all critical about this circuit. All parts are available at Radio Shack and it will happily run on anything from 6 – 18V.

I live within 1 mile of 2 powerful AM transmitters and as such was pleased to find that auto-rectification was almost non-existent with this circuit, but it was still detectable way down in there. Adding R9 forms a low pass filter with the residual junction capacitance of the FET, neatly taking care of my BCB interference problems. Any other practical method of keeping the BCB energy low enough to prevent self-rectification would lower the input impedance. That last few pFs comes in handy. If strong medium wave signals are not an issue, R9 can be eliminated as it just provides more opportunity for stray shunting capacitance to sneak in.

I have had much success with this little circuit, both as an impedance converter for the front of my BBB-4 and as a front end for my ever-changing home brew receiver. There are obviously other ways to accomplish the same thing, an op-amp will work fine in the boot strapped follower configuration (but much worse auto-rectification in my experience). Should you choose this route, Burr Brown manufactures low input capacitance (1 pF) op amps. Look for electrometer grade devices such as the OPA129. Alternatively the antenna can just be made larger, increasing its isotropic capacitance and lowering its source impedance. This will inevitably lead to long antennas if the rule of keeping the source impedance to 1/10 of the receiver impedance is held. If the input contains just a few hundred pF of shunting capacitance, the antenna must then have a few thousand pF – that’s BIG.

I want to mention that Helliwell [6] reports medium latitude whistler field strengths that range from 4 $\mathrm{mVmeter}^{-1}$ to 5 $\mu\mathrm{Vmeter}^{-1}$ (unfortunately he doesn’t give the distribution). Although not the local BCB station, neither are these really weak signal strengths. I would propose that the idea that hunting whistlers is weak signal work has grown out of the fact that many receiver designs are disposing of the majority of the energy prior to amplification, giving the impression that the signals we are chasing are very weak. I don’t think this is necessarily the case, we just have to keep from squashing them down to nothing prior to trying to detect them.

In conclusion I want to say that I have no particular expertise in this area and am completely prepared to be wrong on all of this. I would welcome any correspondence on the matter and would particularly like to hear from anyone that tries this idea out.

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