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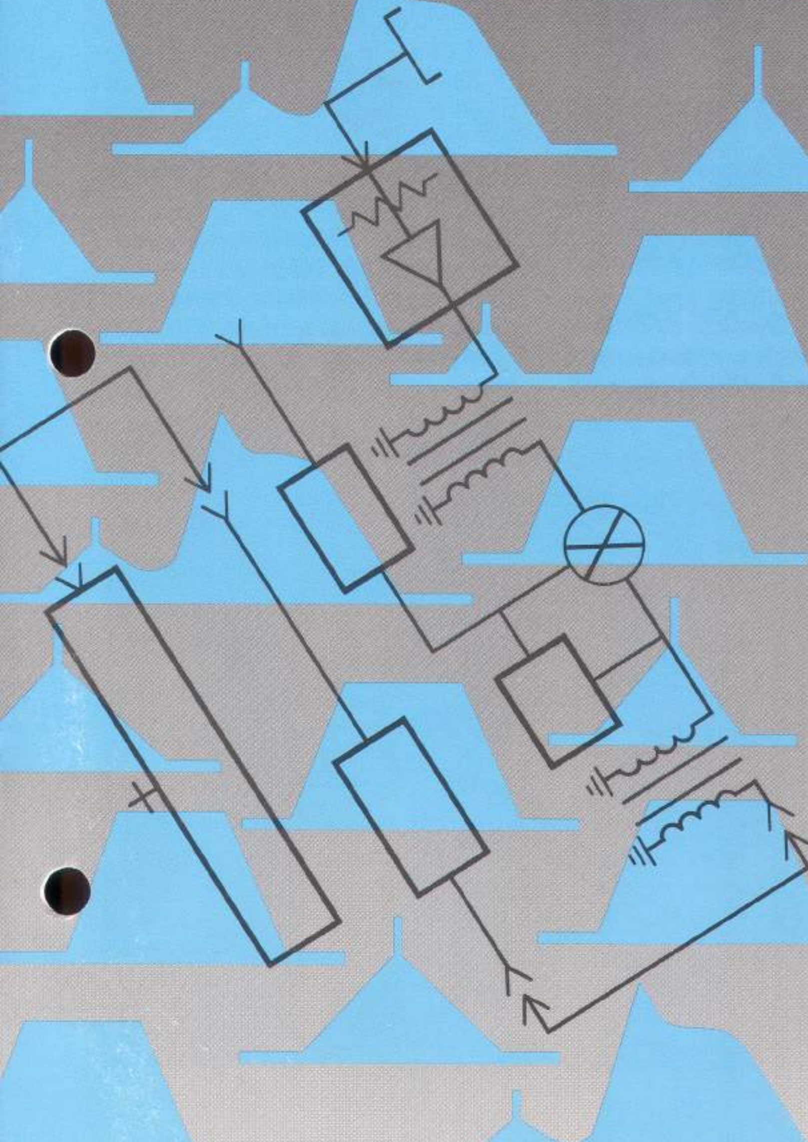
ELF/VLF RECEIVER DESIGN



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Tech-notes

The high standards imposed on military electronics equipment by such requirements as outlined in MIL-STD-462 and other EMC (electromagnetic compatibility) standards have created a need for the development of high-performance, very-low-frequency (VLF) and extremely-low-frequency (ELF) receivers. Military standards require accurate and sensitive measurements of conducted and radiated emissions in the VLF/ELF frequency ranges. Electromechanical and low-frequency clock signals are the emissions of primary concern in the VLF/ELF frequency range.

This article will deal with some of the problems that may be encountered in the development of a 20-Hz to 10-kHz ELF tuner. Specifically, the WJ-8940B ELF tuner, used to detect emissions from other systems in the ELF frequency range, will be used as an example for this discussion (see Figure 1). Some of the problem areas discussed include local oscillator phase noise, low-noise preamplifier design, mixer balance, and power-supply immunity. Narrow-bandwidth, synchronously tuned IF filters will also be discussed briefly.

Phase-Noise Considerations

Local-oscillator phase noise limits the ability of a receiver to recover modulation from a signal. This limitation poses particularly difficult problems because the local oscillator must tune within 20 Hz of the IF frequency. Also, the ELF tuner is designed to allow for IF bandwidths of 100 percent of the tuned frequency, which further limits the amount of phase noise the local oscillator can have before degrading the system's performance.

A Fluke 6160B frequency synthesizer is part of the main WJ-8940B system. A 100-kHz local oscillator frequency is obtained by setting the synthesizer at 10 MHz and engaging a divide-by-100 circuit.

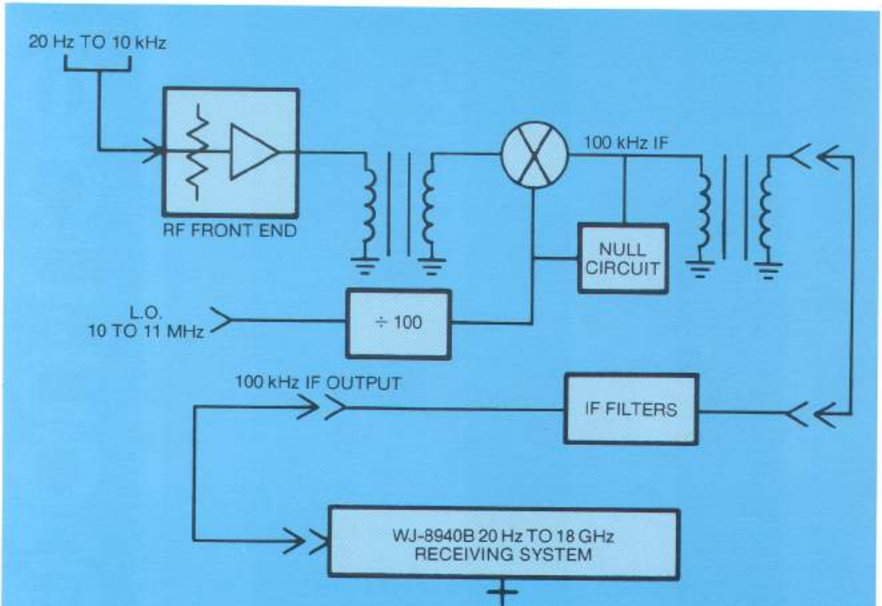

Figure 1. WJ-8940B/ELF system block diagram.

Ideally, frequency division will improve phase noise performance by $20 \log_{10} N$, (dBc), where, N is the division integer (100 in our case). All divide circuits used should be synchronous dividers, as opposed to ripple counters. Phase noise introduced into the signal by the TTL dividers is due to the narrow window of threshold uncertainty where the divider must decide if the signal is a 1 or a 0.

In a ripple counter (divider), the uncertainty effect is additive. Each divider stage has a fixed amount of uncertainty which is related to the logic family the divider is from. As the frequency lowers after each division, the uncertainty jitter from each successive stage is added to the jitter of the previous stage, adding to the phase noise. The phase noise of a signal using a ripple counter will improve, but not at the rate of 20-dB/decade, due to the addition of the uncertainty effects of each divider stage.

Using synchronous dividers, each division stage is clocked at the same time and at the same rate as the input stage. This restricts the time uncertainty to that of one divider stage. Since the time uncertainty is constant while the period of the waveform is increasing, the phase uncertainty will decrease at the rate of 20-dB/decade (i.e., the phase uncertainty becomes a smaller percentage of the waveform period).

Experimentally, it has been found that low-power Schottky TTL dividers offer the lowest phase noise. Typically, these dividers have a noise floor of -142 dBc at a 10-Hz offset from the carrier.

The 10-MHz signal from the Fluke synthesizer has a phase-noise specification of -120 dBc at a 10-Hz offset (see Figure 2). The designer would expect to acquire an additional 40 dB ($20 \log_{10} 100 = 40$ dB, N = dividing integer) of phase noise improvement through frequency division. The phase noise on the 100-kHz signal at a 10-Hz offset would then be, -120 dBc + (-40 dB) = -160 dBc. Since the TTL dividers' noise floor is only -142 dBc at a 10-Hz offset, the phase noise characteristics of the 100-kHz waveform will be limited to -142 dBc. The absolute level of the phase noise at a 10-Hz offset is +17 dBm + (-142 dBc) = -125 dBm, at the local oscillator mixer input (where +17 dBm is the mixer drive level). Whether this phase noise level is sufficient to prevent system degradation (see Figure 3A and 3B) will depend on mixer balance and IF filter selectivity, both of which will be discussed later.

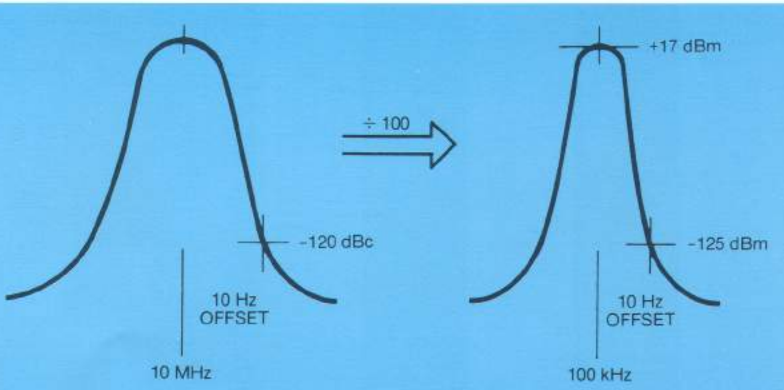

Figure 2. Improvement of phase noise due to frequency division.

Preamplifier Considerations

Gain, noise figure, and dynamic range specifications must be considered in the design of any receiver. Careful selection of, and design for these specifications will yield a higher-performance receiver capable of high sensitivity, low distortion, and wide, instantaneous dynamic range.

Enough gain must be designed into the preamplifier to determine and maintain the noise figure for the receiver. The higher the gain of the preamplifier, the lower the 1-dB compression point of the receiver will be; therefore, one must strive for the best compromise in using the minimum possible gain in the preamplifier to set the noise figure of the receiver, and still have the best possible 1-dB compression point for the required dynamic range.

In determining preamplifier gain, the following must be considered: the ultimate noise figure of the receiver, the phase noise of the local oscillator, the mixer LO-to-IF balance, the mixer conversion loss, and the noise figure of the remainder of the system following the first mixer (see Figure 4).

The following is an example of a preamplifier gain calculation using the system specifications listed below:

1. Noise figure for the remainder of the system following the mixer = 20 dB.
2. Mixer specification:
   LO-to-IF isolation = 60 dB
   (This is a conservative number, higher isolation mixers are available, plus extra mixer balance can be obtained using null circuits.)
   Conversion loss = 6 dB
3. Phase noise of the local oscillator at a 10-Hz offset = –125 dBm.
4. Receiver noise figure design goal = 10 dB.

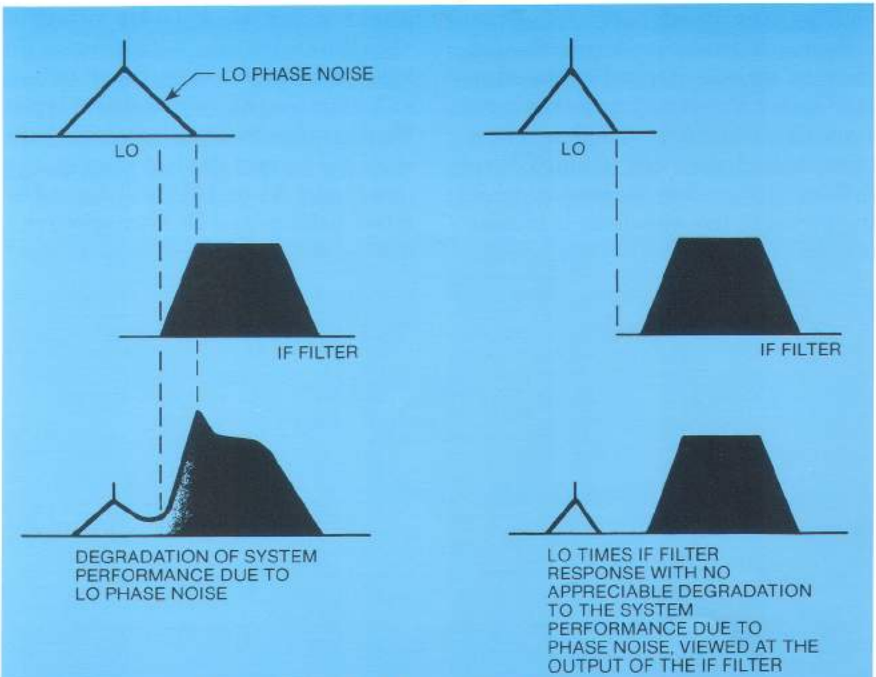

Figure 3. Phase noise problems.

A 20-dB noise figure for the remainder of the system is equivalent to a noise level of -154 dBm, referenced to a 1-Hz bandwidth (-154 dBm/Hz). Compare this level to the noise created by the local oscillator, transferred to the IF port of the mixer. The local oscillator has phase noise of -125 dBm/Hz at the LO port of the mixer. The LO-to-IF isolation of the mixer reduces this level to -185 dBm/Hz (-125 dBm/Hz - 60 dB = -185 dBm/Hz). However, this level will be limited to -174 dBm (the thermal noise of any system at 25°C in a 1-Hz bandwidth). This level is negligible when compared to the equivalent input noise of the remainder of the system (-154 dBm/Hz). Working backwards through the mixer, the noise at the RF port of the mixer will be, -154 dBm/Hz + 6 dB = -148 dBm/Hz. Since a 10-dB noise figure (-164 dBm/Hz) is desired, the gain needed to match the noise for the rest of the system will be:

$$-148\ \text{dBm/Hz} - (-164\ \text{dBm/Hz}) = 16\ \text{dB}.$$

To maintain the 10-dB noise figure in the receiver, the preamplifier must override the noise of everything which follows it by about 10 dB; therefore, the gain of the preamplifier should be 16 dB + 10 dB = 26 dB. If the calculated minimum gain above is used, the receiver will be optimized for noise figure and 1-dB compression point. The noise figure of the receiver will be approximately 11 dB. To obtain a final noise figure of 10 dB or less, the designer would have had to start with a preamplifier noise figure of less than 10 dB.

Obtaining a 10-dB noise figure and 20 dB of gain over the 20-Hz to 10-kHz frequency range in a 50-Ω system is difficult because conventional RF amplifiers are not readily available to meet these specifications. The approach W-J has taken is to use a Precision Monolithics OP-27 operational amplifier, whose noise voltage and noise current specifications are very low. Calculation of noise figure using noise voltage, noise current, and resistance requires the following equation:

$$NF_{dB} = 10\log_{10}\frac{V_n^2 + I_n^2 R_s^2 + 4kTR_s}{4kTR_s}$$

V_n = input noise voltage density | R_s = Thevenin source resistance in ohms

I_n = input noise current density | k = Boltzman's constant $1.374 \times 10^{-23}/°K$

T = temperature in degrees Kelvin (298°K = room temperature)

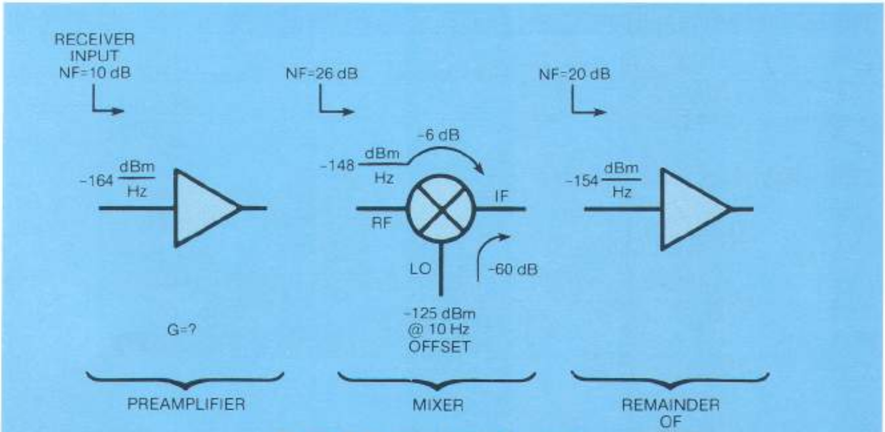

Figure 4. Receiver system blocks.

The designer must remember that what is important in its final analysis is the output signal-to-noise ratio. By choosing a high R_s, the noise figure can be reduced to near zero if I_n is small. In this case, the dominant noise source will be, V_{R_s}, ($V_{R_s}^2 = 4KTBR_s$, the noise of the source resistance) which overshadows V_n completely. The design results in a very low noise figure, but very low S/N as well, because of high noise.

The optimum source resistance, which is the value that will yield the lowest noise figure in a system, is calculated as,

$$R_{s_{opt}} = \frac{V_n}{I_n}$$

(Note that this does not mean the lowest noise.)

The designer should not add series resistance in an attempt to make $R_s = R_{s_{opt}}$, unless transformer coupling is used. Adding series resistance adds noise and reduces the signal level in the circuit, while using transformer coupling implements an efficient impedance transform. In the W-J receiver, the optimum impedance would have been 2000Ω, as determined by our V_n and I_n numbers (see Figure 5).

$$R_{s_{opt}} = \frac{V_n}{I_n} = \frac{8n\ V/\sqrt{Hz}}{4\ pA/\sqrt{Hz}} = 2000\Omega$$

Due to the poor noise performance of the operational amplifier at 2000Ω and the poor availability of 2000Ω:50Ω transformers, a 600Ω source impedance is used, since 600Ω:50Ω transformers are readily available. V_n is the dominant noise contributor, so a transformation from a source impedance of 50Ω to 600Ω will improve the noise figure by about 10 dB.

$$NF_{improvement} = 20\ \log_{10} \sqrt{\frac{600}{50}} = 10.79\ dB$$

The operational amplifier chosen has,

$$V_n = 8nV/\sqrt{Hz} \text{ and } I_n = 4\ pA/\sqrt{Hz}$$

(worst case at 10 Hz).

This will yield a noise figure of:

$$NF_{dB} = 10\ \log_{10} A$$

$$A = \frac{(8x10^{-9})^2 + (4x10^{-12})^2\ (1200)^2 + 4\ (1.374x10^{-23})\ (298)\ (1200)}{4\ (1.374x10^{-23})\ (298)\ (1200)}$$

$$NF_{dB} = 7.35\ dB$$

To obtain the full output voltage swing of the operational amplifier, the amplifier's output needs to drive an impedance higher than 50Ω. A 600Ω:50Ω transformer is

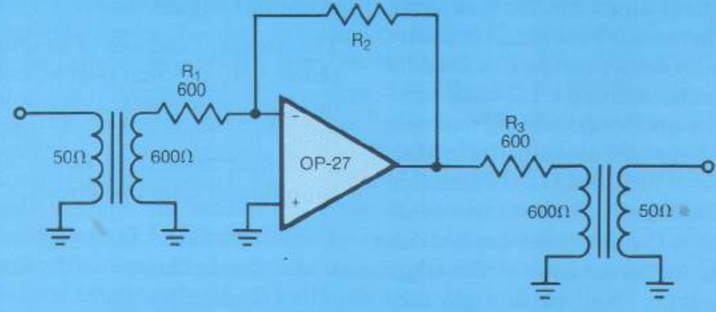

Figure 5. Preamplifier circuit.

used to accomplish this, while also transforming back to a 50Ω system impedance.

Low-noise operational amplifiers, which are readily available at fairly low cost, now enable one to obtain low noise figures, reasonable gains, and a wide, instanteous dynamic range for front-end preamplifier designs in ELF receivers.

Mixer Balance

In an ELF receiver whose local oscillator frequency comes very close to the IF frequency, noise-figure degradation can occur due to the local oscillator riding up on the skirt of the IF filters, as shown in Figure 6.

There are three possible solutions to this problem:

1. Improve IF filter selectivity, i.e., shape factor.
2. Improve phase noise of the local oscillator.
3. Improve mixer balance and null out the local oscillator.

The first solution has proven to be very costly and impractical. The second solution has been discussed in the phase-noise considerations section of

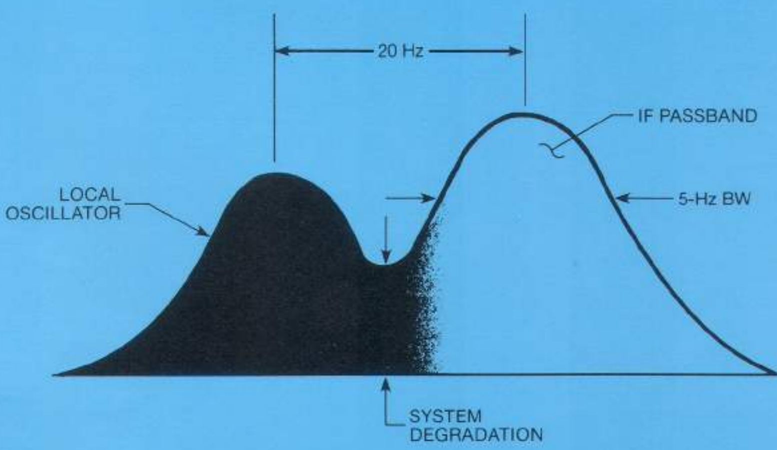

Figure 6. System degradation due to insufficient mixer balance.

this paper, and it has been shown what the practical limits are for restricting the phase noise for the local oscillator. The third solution can be obtained by carefully specifying the LO-to-IF rejection of the mixer and adding a simple R-C null circuit around the mixer. Mixers with 70 dB of LO-to-IF isolation at the frequency of interest are available. The R-C null circuit can provide as much as an additional 60 dB of mixer balance. Null circuits are very unstable because of variation of inductance and resistance in the mixer transformers, due to temperature changes. A perfect null could be obtained by feeding a portion of the LO signal, equal in amplitude to the output leakage signal and 180° out of phase with the output leakage signal, back to a summing node at the IF port of the mixer (see Figure 7).

The smallest change of amplitude or phase will, to some degree, cause the local oscillator signal to come out of its null. This makes it very difficult to guarantee more than about 20 dB of cancellation from this circuit.

The effect of the LO on system performance can be determined by first calculating the local oscillator level at the IF filter using the following equation:

$P = P_{LO} - I_{Mix} - N - T_F$ = level of LO at IF filter (in dBm), where,

P_{LO} = Power of the LO spectrum (in dBm) at the mixer input

I_{Mix} = LO-to-IF isolation of the mixer (in dB)

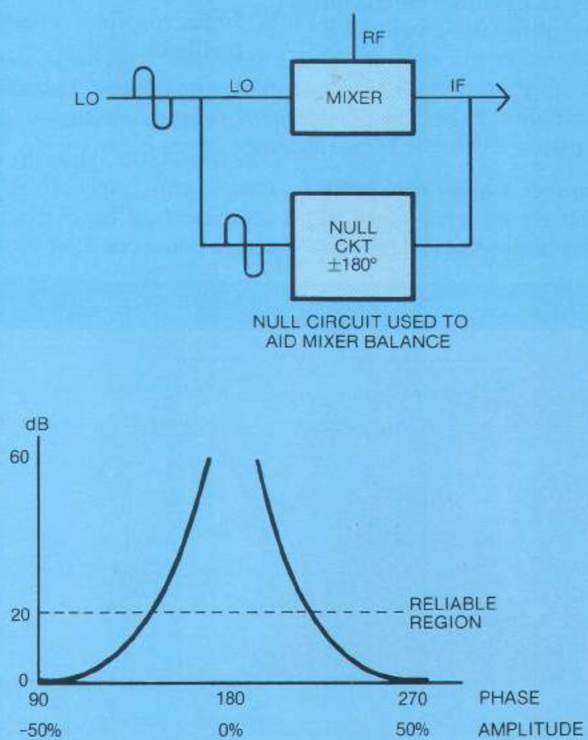

Figure 7. Additional mixer balance.

N = The extra isolation the null circuit provides (in dB)

T_F = Transfer function of the IF filter

Next, using the receiver's noise figure and bandwidth, the noise floor of the system is calculated by,

$$S = KTB + NF + 10 \log_{10} B$$

where,

S = Sensitivity (in dBm)

KTB = Thermal (KTB) noise power (–174 dBm) in a one-Hz bandwidth at room temperature (25°C)

NF = Noise figure (in dB)

B = Predetected IF noise bandwidth (in Hz)

Using a 5-Hz bandwidth and a design goal of a 10-dB noise figure:

$$s = -174 \text{ dBm} + 10 \text{ dB} + 10 \log_{10} 5 = -157 \text{ dBm}$$

If no degradation to system noise figure is to occur, the total local oscillator power, including AM and FM noise that passes through the IF filter, must be below the level of the noise floor (see Figure 8). Therefore, if the local oscillator signal rides up on the skirt of the IF filter, the receiver's minimum-discernible-signal capability is reduced, and the system performance is degraded.

Power-Line Immunity

Rejection of powerline sidebands within an ELF receiver must be carefully considered. The operator would like to be able to tune through 60 Hz and its higher harmonics, receive signals which are externally generated, and picked up only by the sensor connected to the receiver. Problems occur with an ELF receiver where 60-Hz sidebands are introduced into the system through power supplies and ambient 60-Hz pick-up.

The method employed to minimize this problem is to totally float the front end

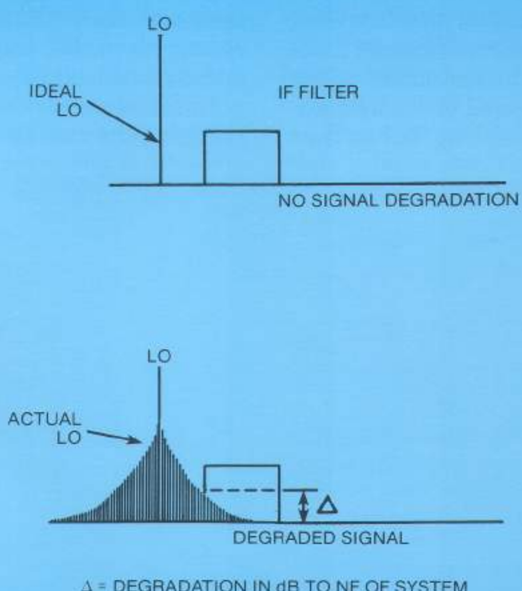

Figure 8. System performance due to L.O. feed through.

of the radio. Referencing the front end of the receiver to its own ground, through a transformer, will float the receiver in relation to the ground of the rest of the system (see Figure 9). All ambient 60-Hz powerline signals are now induced on both sides of the primary winding of the transformer (common-mode rejection).

The amount of power-line isolation obtained depends on:

1. The amount of common-mode isolation of the transformer.
2. Power-supply immunity of the operational amplifier used as a preamplifier.
3. The isolation of the digital lines (via opto-couplers) into, and out of the front end.

All grounds connected to the front-end module must be isolated from the rest of the system, or the front end will not be floating with respect to the rest of the system.

All power supplies used in the front end must be dedicated to the front-end module to ensure proper ground isolation. Low-noise, high-isolation power supplies must be used to ensure good, low-frequency sensitivity. It has been found that power supplies using LM723 voltage regulators yield very low ripple and good noise performance at a reasonable cost.

If 60-Hz powerline sidebands are not minimized through proper front-end and power-supply design, the receiver's sensitivity will be degraded. By use of low-noise, high-isolation power supplies, and the floating of the receiver's front-end RF module, immunity can be maximized without going to a battery-powered system.

IF Filters

Tuning signals in the ELF frequency range requires very narrow bandwidths. The WJ-8940B/ELF receiver has IF bandwidths of 5, 10, 20, 50 and 100 Hz, in addition to the existing bandwidths the WJ-8940B has available.

Since the final IF of the ELF receiver is at 100 kHz, a synchronously tuned filter employing crystal resonators has been chosen. This design reduces the required resonator Q needed to achieve these very narrow bandwidths by cascading nine low-Q stages together. In addition, this type of filter design permits multiple bandwidths by changing the loading (varying the Q)

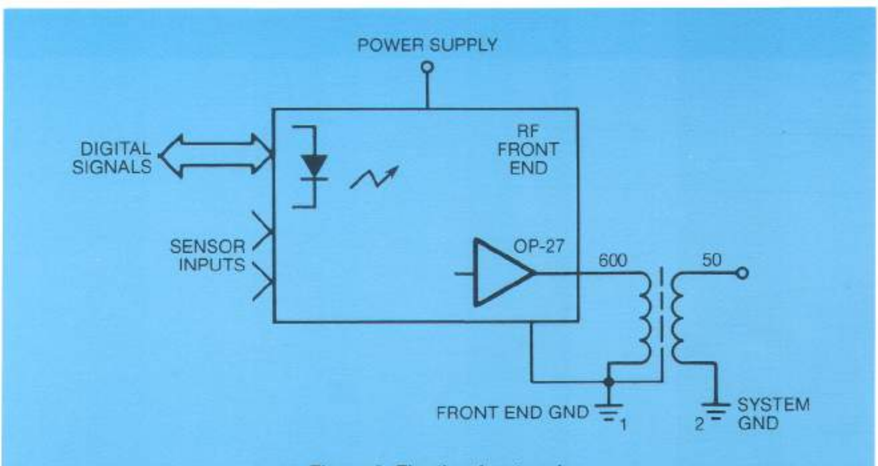

Figure 9. Floating front end.

on each crystal stage, while still maintaining the same crystals and amplifier blocks for each bandwidth. Using 9 crystal stages, these filters have approximately a 4.7:1 shape factor, and about 100 dB of instantaneous dynamic range. Synchronously tuned filters also have very good impulse bandwidth characteristics, which is important in EMC work.

Conclusion

Meticulous attention must be paid to the design of a VLF/ELF receiver if high-quality performance is to be attained. Local oscillator phase noise, mixer balance, and preamplifier gain are critical parameters of the design. If the phase noise is too high, the local oscillator not sufficiently nulled out, or the preamplifier gain not set properly, system noise-figure degradation will result. Since an ELF radio tunes in the frequency range of the power line, the designer must also take the proper steps to maximize power-line immunity.

Acknowledgement

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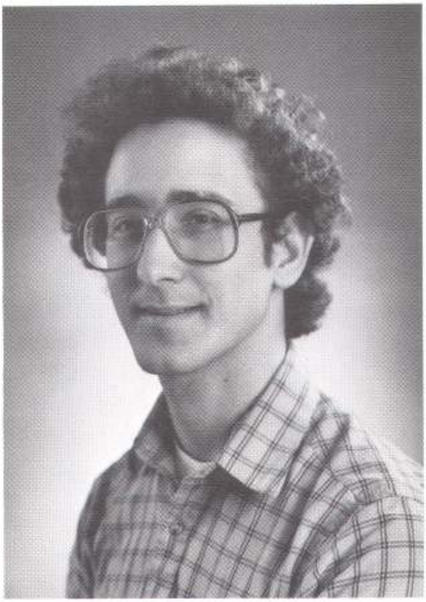

Warren K. Gruber

Mr. Gruber is currently a Member of the Technical Staff, Special Products Department of the CEI Division.

He has worked on the design, development and production of the WJ-8940B/MX and WJ-8940B/ELF. He is presently involved in designing the WJ-8940B Wideband Demodulator and new Portable Tempest Receiving System.

Previously, Mr. Gruber was a co-op for the Federal Government in Washington, D.C. His work experience there included analog and digital designs.

Mr. Gruber graduated with a Bachelor of Electrical Engineering degree from Georgia Institute of Technology in 1980.

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