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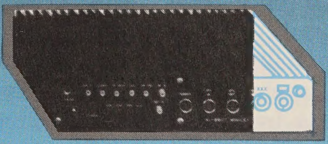
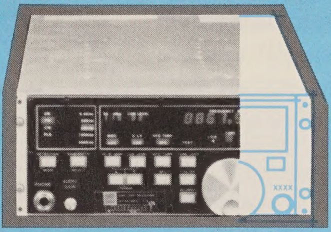
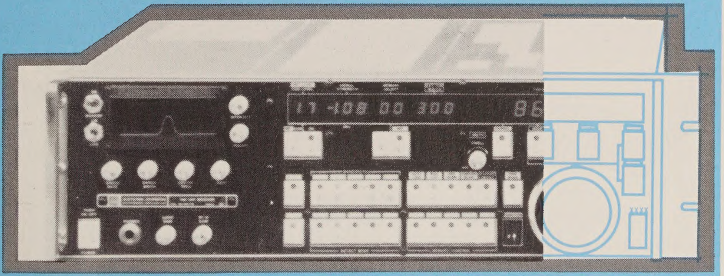
Design Considerations for Miniaturized Receivers







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Tech-notes

The size and weight of VHF/UHF receivers are prime concerns when designing for a surveillance environment where mobility is paramount and space is at a premium. Smaller VHF/UHF receivers would reduce the size of surveillance systems, increase mobility, and allow the addition of more receivers to existing sites. To make such improvements worth the development effort, receivers should be at least one-third the size of today's half-rack receivers without sacrificing performance or price. To complicate matters, our airwaves are becoming cluttered with more and stronger signals, putting greater demands on surveillance receivers to handle smaller signals in the presence of larger ones. Important operating features such as scan, step, and frequency lockouts that aid in signal logging should also be a part of this receiver. To illustrate the design considerations in the miniaturization of a receiver, reference will be made to a recently completed project at Watkins-Johnson Company (see Figure 1).

Special Design Considerations

There are four familiar design problems that must be addressed in producing a receiver: availability of components, electrical isolation between components, heat dissipation, and intermodulation distortion (IMD). All of these become more difficult in the design of miniaturized receivers.

Today's receivers contain over 3,000 components, which have been packed as densely as possible using through-hole technology. Many components of high complexity and performance are available in TO-8 style cans. Others, such as crystal oscillators, cannot be miniaturized because of the intrinsic nature of the device. Furthermore, when

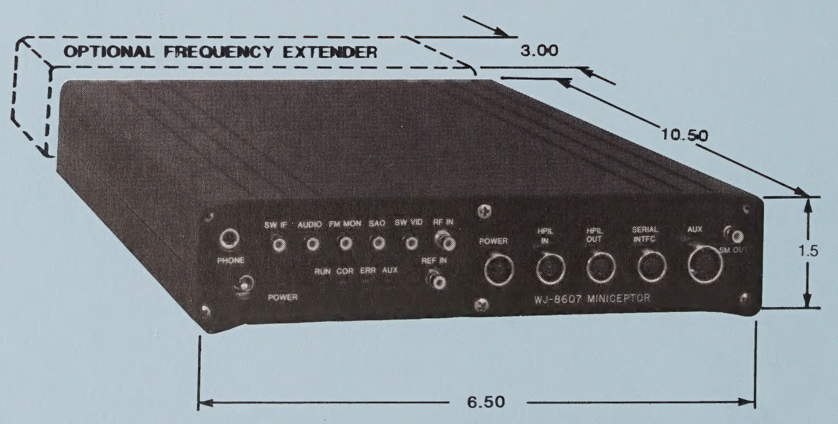

Figure 1. WJ-8607 Miniceptor VHF/UHF Surveillance Receiver.

components are too closely spaced, they are not as easily serviced, creating maintenance problems.

The tighter placement of components to each other for size reduction can lead to increased signal interchange, giving rise to the need for better isolation. Because parasitic inductances are reduced, transistors may now produce higher harmonics. Resultant signals, known as internally generated spurious responses or spurs, are sensed as real signals from the antenna.

Heat dissipation presents an increasing problem as receiver size decreases and power requirements increase or remain the same. The reduction of air space between components greatly decreases heat dissipation through air-flow convection. Space considerations also eliminate the use of blower fans to solve the cooling problem.

The fourth design consideration is freedom from intermodulation distortion. Intermodulation distortion occurs when two strong unwanted signals are applied to the receiver's antenna input and are mixed in the rf stages to create intermodulation products. If the frequency of an intermodulation product is sufficiently close to the tuned frequency, it will be processed by the receiver as if it were the real signal of interest. Second and third-order intermodulation distortion products are the most common, and are defined below:

$$F_1 \pm F_2 = F_T$$

Second-order intermodulation distortion

and

$$2F_1 \pm F_2 = F_T$$

Third-order intermodulation distortion.

Where, F_1 and F_2 = strong unwanted signals and F_T = the intermodulation product.

Second-order intermodulation distortion is reduced to a minimal level by using suboctave bandpass filters. Third-order intermodulation distortion is not as easily managed. The measure of a receiver's ability to reject third-order intermodulation is specified as its minimum third-order intercept, a definition, expressed in dBm, of the system's nonlinear processing of signals due to its creation of spurious signals. The higher the third-order intercept point of a receiver, the less susceptible it will be to third-order intermodulation distortion. This requires more power. A receiver requiring higher intercept-point performance will require RF/IF amplifiers having higher intercept levels, which is usually accomplished only by raising the 1-dB compression point of the amplifiers. These higher power amplifiers will have higher noise figures, which reduce sensitivity. They also consume more power than lower intercept-point devices. Higher intercept receivers will also require mixers with higher local oscillator power levels, which gives rise to increased LO radiation and prime power consumption. Therefore, designs which optimize intermodulation distortion degrade these other design criteria—power consumption, rf isolation and sensitivity.

Other criteria for the design of a small receiver are high dynamic range, selectivity, sensitivity, and built-in smart scan and step features. Dynamic range refers to the ratio in dB of the minimum detectable signal compared to the largest detectable signal that does not overload the receiver. Sensitivity is a measure in dBm of the lowest signal level that can be detected by a receiver. Selectivity refers to the degree to which a receiver can detect a low-level signal, while rejecting a high-level signal at a nearby frequency. Table 1 shows the basic specifications of one such receiver.

Specifications:	
Frequency Range	2–512 MHz (2–2000 MHz with FE option)
Frequency Resolution	100 Hz, synthesized
Noise Figure	12 dB, maximum (15 dB, 512-2000 MHz, with FE option)
Intermodulation:	
2nd-Order Intercept Point	+45 dBm, typical
3rd-Order Intercept Point	+8 dBm, minimum (+0 dBm 512-2000 MHz)
L.O. Phase Noise	100 dBc/Hz at 20 kHz from the carrier
Tuning Speed	10 millisecond maximum to within 10 kHz.
Internally Generated Spurious	Less than 110-dBm equivalent input
Demodulation Modes	AM, FM, CW, Pulse, and SSB
Dimensions	1.5″ x 10.5″ x 6.5″ (excluding frequency extender)
Power Consumption	16 Watts, nominal

Table 1. Critical specifications highlights of a miniature receiver

Approaches To The Problem

Component size reduction or packing components tighter can be achieved using a choice of three techniques: hybridization, surface-mount technology, or tighter packing of through-hole components. Figure 2 depicts these packaging techniques.

Hybrids (which consist of active devices in unpackaged form that are enclosed along with the required elements of resistance, inductance, and capacitance on an insulating substrate) have made possible dramatic reductions in both size and weight. While hybrids are widely available, they also substantially increase the cost of the receiver. Size reduction by tighter packaging of components makes assembly and repair more difficult.

A third alternative is surface-mount technology or SMT, which has come of age in the last few years. Table 2 shows the typical pad area in square tenths of an inch required for some common SMT components used to construct a synthesizer board, the most densely-packed receiver board. The total board area equals the total pad area times 1.5. As an example, one loop of the synthesizer required 69 components using a total pad area of 153 tenths of an inch. The total PC board area was $153 \times 1.5 \simeq 230$ tenths or 2.3 square inches, which translates to 30 components per square inch. Figure 3 compares the size, power consumption, weight, module count, PC board area, and component density of two receivers—one designed using conventional through-hole assembly and the other using SMT. Research shows

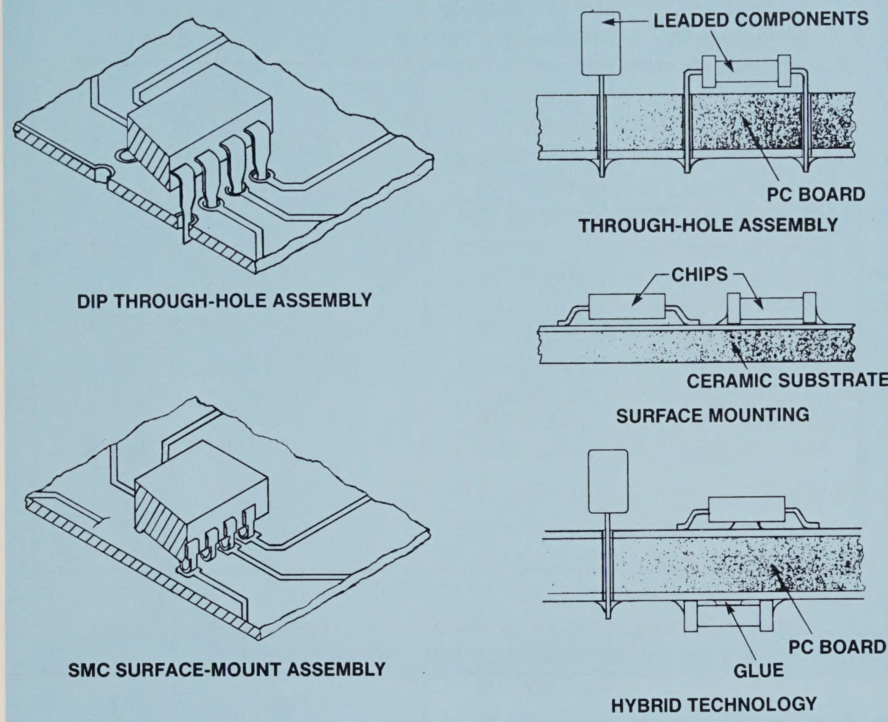

Figure 2. Packaging techniques.

that 80 to 90 percent of the components used in a receiver are available as surface-mount devices, eliminating one problem quickly. Current costs of surface-mount devices are 20 percent higher than their conventional counterparts, but these costs should drop with wider acceptance of SMT. Industry forecasters predict that the use of SMT worldwide will exceed 50 percent in all electronics products by 1990. Furthermore, SMT lends itself to automation very well. Solder-paste screening, pick and place, and infrared reflow machines are cutting assembly costs as much as 60 percent over conventional assembly. Surprisingly, by using proper tools, changing a surface-mount device is far easier than replacing a through-hole component.

Smart SMT Packaging Alleviates Isolation Problems

Because of its very nature, rf converter circuitry requires rf isolation. For example, refer to the typical dual mixer rf converter shown in Figure 4. The first mixer converts the antenna input to an IF frequency of 555 MHz, and the second mixer converts the first IF to the final IF of 21.4 MHz. The first LO tunes from 555 MHz to 1055 MHz, and the second LO tunes from 530.6 to

Component	Surface-Mount Device (Square Tenths)	Through-Hole Component (Square Tenths)
Resistor	2.0	4.0
Capacitor (1206)	2.5	3.0 (.01 μf)
Inductor	3.0	11.0
Tantalum Capacitor	4.5	9.0
SOT 23 Device	1.5	5.0 (Transistor)
8 Pin SOIC	6.0	14.0
20 Pin PLCC	16.0	35.0 (20 pin DIP)
MICRO X	3.0	4.0
16 Pin SOIC	12.0	32.0
SMT Mixer	7.5	16.0 (XTAL Can)
POTS	5.0	7.0
Variable Capacitors	5.5	8.0

Table 2. A comparison of typical pad areas (surface-mount devices versus through-hole components).

535.5 MHz. A mixer that converts well at the fundamental frequency also converts well at the harmonics of the two local oscillators. These harmonics can range in any order and cause spurious response in the receiver on all combinations that produce a first or second IF frequency. An example of a spurious frequency would be as follows:

7 x 2nd LO (533) = 3731 MHz
4 x 1st LO (794) = 3176 MHz
3731 - 3176 = 555 MHz,
the 1st IF Frequency.

These LO harmonics can be generated well above 8 GHz and spurious signals can number in the thousands.

The first IF filter will reject most of these combinations by not allowing the first LO or the second LO frequencies to recombine in either the first or second mixer. In conventional designs, rf isolation is achieved by using a brass chassis with multiple compartments for PC boards that are interconnected using feedthrough capacitors and hand wiring. The brass chassis and partitions prevent local oscillator harmonic-frequency combinations from bypassing the filter.

Unfortunately, heavy reliance on brass and space isolation is not feasible in a small receiver. However, smart packaging provides solutions for rf isolation problems without excess metal and distance between components. Multilayer PC boards with two ground planes were tested with good results. Figure 5 depicts the experimental isolation model. Three 50-ohm tracks were buried between the two ground planes. Isolation was controlled by ground intercon-

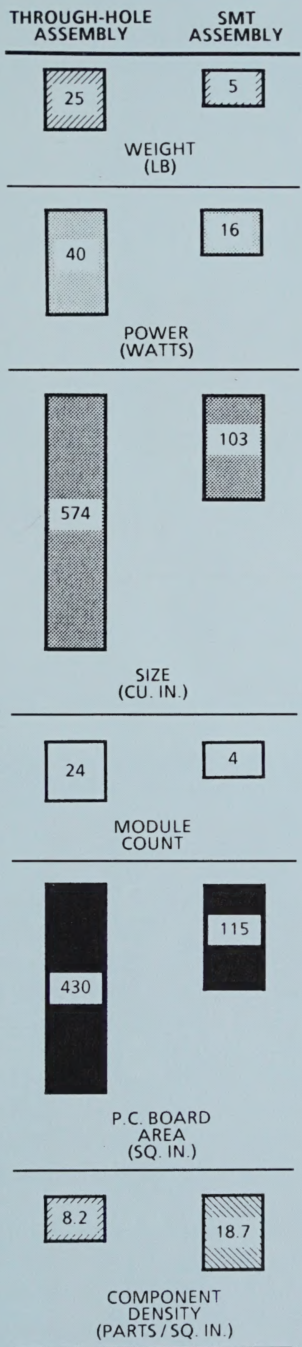

Figure 3. Through-hole versus SMT comparisons.

nections between the tracks called vias. These vias were spaced 0.1 inch apart. Tracks 1 and 2 were isolated with a single row of vias, while track 2 and 3 were separated with a double row. Another track was placed on the edge of the board to measure emissions when no ground vias were used. A ferrite chip with a bypass capacitor was placed across the ground vias to the third track to duplicate the functions of the feed-through capacitor in a brass plate. This test showed how well power supply and control lines are isolated. The board was evaluated by sweeping the frequency from 20 MHz to 8 GHz, while monitoring the adjacent track. Figure 6 shows the results, upon which the following conclusions were drawn:

1) The single row of 0.1-inch spaced vias provided adequate attenuation for all known frequency harmonics to 8 GHz.

2) RF emissions from the edge of the PC board (no ground vias) must be controlled by either edge plating or more ground vias.

3) DC inputs or control lines into the rf areas can be isolated using surface-mount components. As more than one partition is crossed, changes in value of the chokes and bypass components will avoid the self-resonant problems indicated by the upper trace.

The design of the rf converter PC board and the synthesizer PC board took advantage of this knowledge. For instance, notice the placement of the components for the multilayer rf converter PC board shown in Figure 7. They follow the block diagram and are separated by rows of ground vias. At least three rows separate the first and second LO from each other. Figure 8 is a side view of the rf converter and shows how all of the components are interconnected. All through-hole components, such as the TO-8 style amplifiers and mixers and IF filters, are mounted on

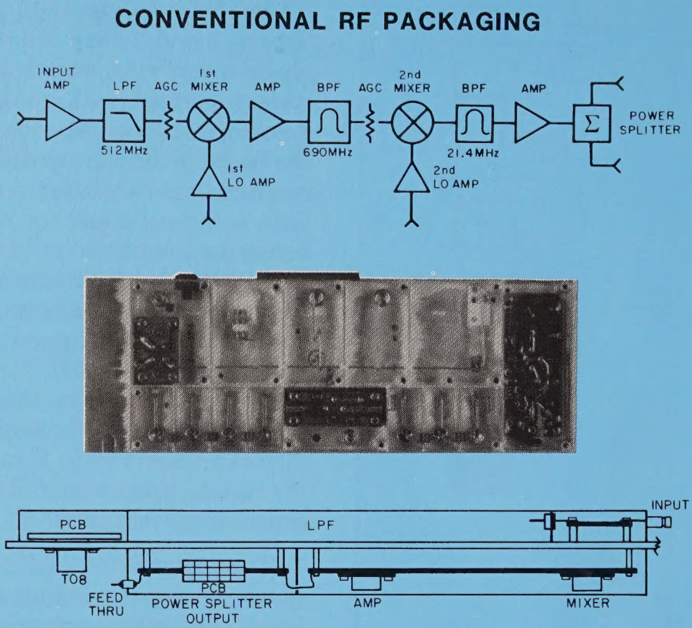

Figure 4. Conventional rf packaging.

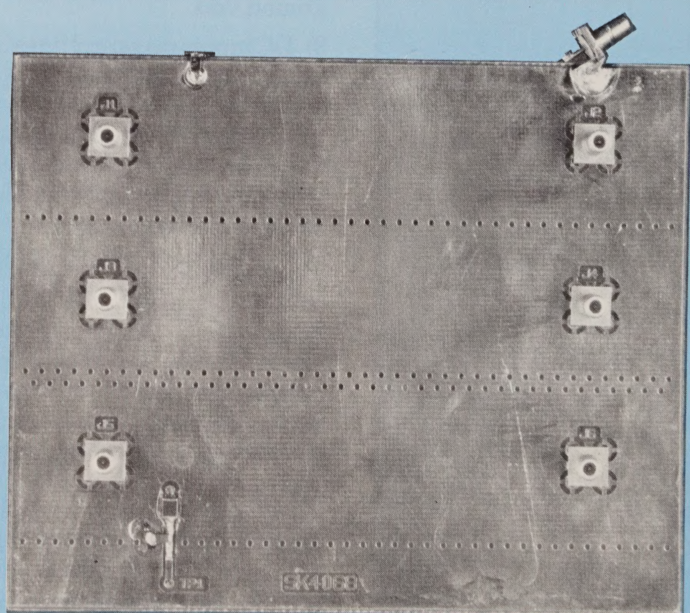

Figure 5. Experimental isolation model.

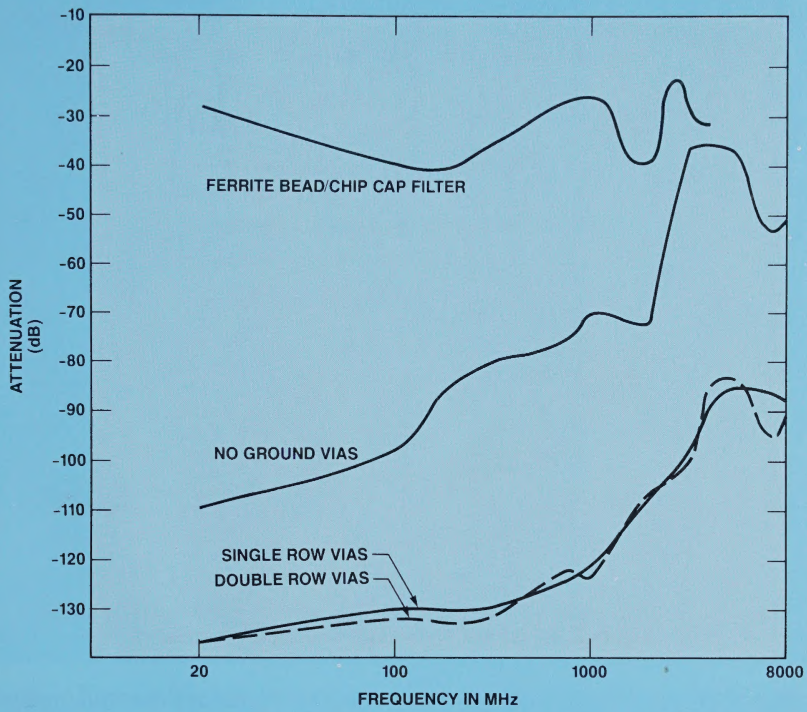

Figure 6. Test board isolation results.

the top side. The leads are connected to the middle layers through sockets built into the plated throughholes. These sockets provide test points for trouble-shooting. The sensitive 50-ohm signal lines are sandwiched between ground layers. The bottom layer is for all of the surface-mounted components, which consist of rf chokes, bypass capacitors, and control integrated circuits. An aluminum back plate is milled out around the surface-mount components and the bottom side tracks to provide additional shielding.

The rf converter module was designed and built on a 3-inch by 10-inch four-layer PC board that included a 10-percent bandwidth tracking preselector and five plug-in IF bandwidths. Of particular interest was the grounding pattern and the milled out sockets in the back plate. When tested, the rf converter had no spurious responses that were attributed to a PC board isolation problem. Also, the skirt selectivity of the IF filters was down to the actual filters' ultimate rejection. Two-layer PC boards have never achieved this. The gain, flatness, noise figure, and third intercept point are all shown in Figure 9.

These techniques apply directly to isolation of the five phase-locked loops and oscillators on the synthesizer board, shown in Figure 10, where no local oscillator must ever cross another oscillator or any of its respective harmonics to prevent crossover spurious responses from occurring. These types of spurs

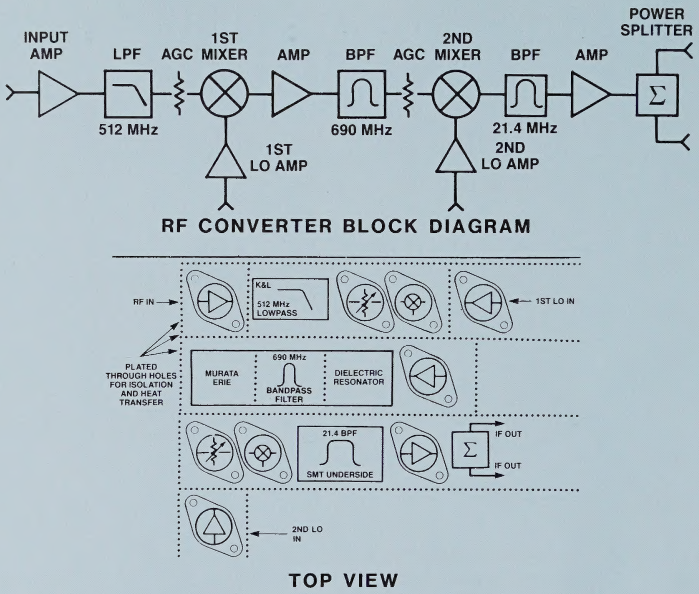

Figure 7. RF converter in about 13.5 square inches.

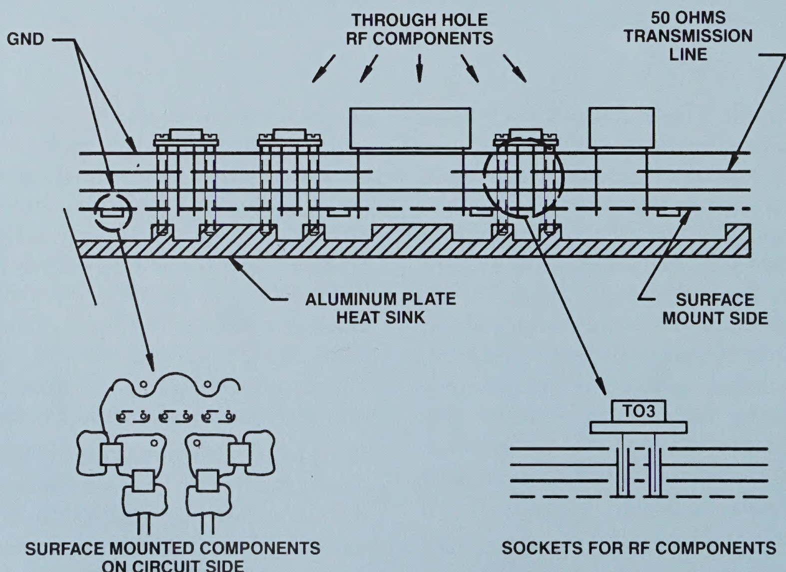

Figure 8. Surface-mounted rf packaging.

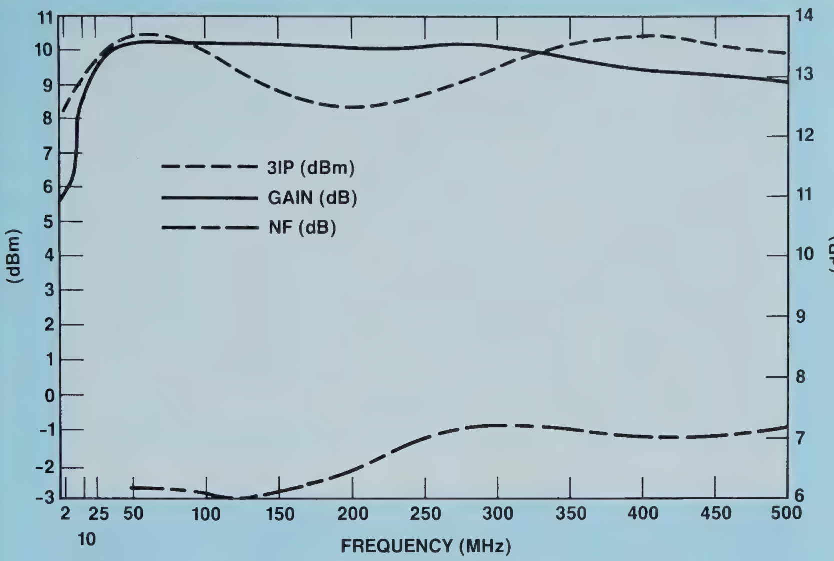

Figure 9. Third-order intercept point, noise figure, and gain versus frequency.

differ from harmonic mixing spurs and are harder to detect because a signal must be present at the rf input.

Miniaturization gives rise to a second problem in the design of the synthesizer. To maintain low phase noise, oscillator resonant circuits must have high-Q characteristics. However, all coils suffer a drastic loss in Q when miniaturized. For this reason, the use of coils have been abandoned in favor of the transmission line oscillator depicted in Figure 11. The high-Q capacitor, at one end of the quarter-wave transmission line, turns into a high-Q inductor at the opposite end. The transmission line is buried between the ground layers of the four-layer PC board. To increase the resonant circuit Q and decrease the frequency shift versus voltage of the voltage-controlled oscillator, we reduced the varactor diode coupling in the resonant circuit and, therefore, the tuning range. Four oscillator bands are used in the first LO and one in each of the other four loops. Each oscillator, built with surface-mount devices and a buried transmission line, occupies less than one square inch. The overall phase noise through the receiver is shown in Figure 12. The phase noise, 20 kHz away from the carrier, easily meets specifications.

Smart SMT Packaging Alleviates Thermal Management Problems

The milled-out aluminum back plate that is used to isolate surface-mount components and bottom side tracks also acts as a heat sink (See Figure 13). Heat is conducted away from the power amplifiers using the mounting screws which pass through the plated through holes directly into the back plate. The flat packaging of the receiver maximizes the amount of heat that escapes from the outer cover because of the increased surface area.

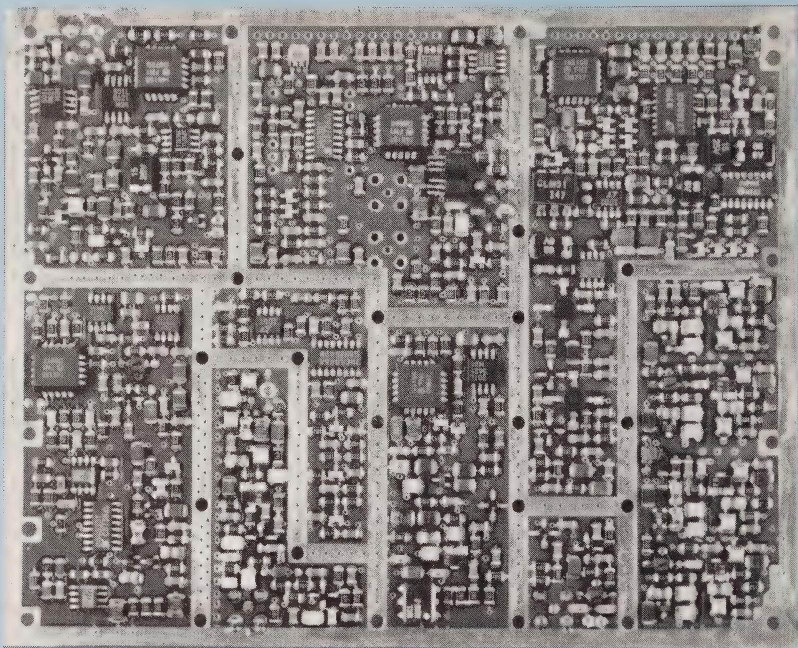

Figure 10. Synthesizer module (SMD side).

Other Thermal Management Solutions

To ensure good thermal management, power consumption becomes an important component selection criterion that rivals performance and size. For instance, a Hewlett-Packard Interface Loop (HPIL) was selected for the digital control module over an IEEE-488 interface, in part because it provides reduced size and power consumption.

In the demodulator module, diode detectors that require large, power-hungry signals (on the order of 7 volts peak-to-peak) were abandoned in favor of a synchronous detector that uses an active mixer that needs only -27dBm drive.

Another way to manage heat is to make compromises in the receiver performance, where acceptable. For instance, the video response must be maintained for wideband signals out to at least 5 MHz. Video responses of this width require considerable power from most operational amplifiers. These wideband video operational amplifiers normally require large power dissipation. The compromise of reducing output voltage swing from ±1.0 Vpp to ±0.5 Vpp into 50 ohms reduces amplifier power by 75%. The video output is filtered at one-half the IF bandwidth in order to roll off the out-of-band noise caused by the large amplification after the IF filters. Post-filtering is provided before the AM and FM detectors to prevent reduction in sensitivity. However, the FM monitor output usually supplied simultaneously with the switched video output was left unfiltered. Since additional video low-

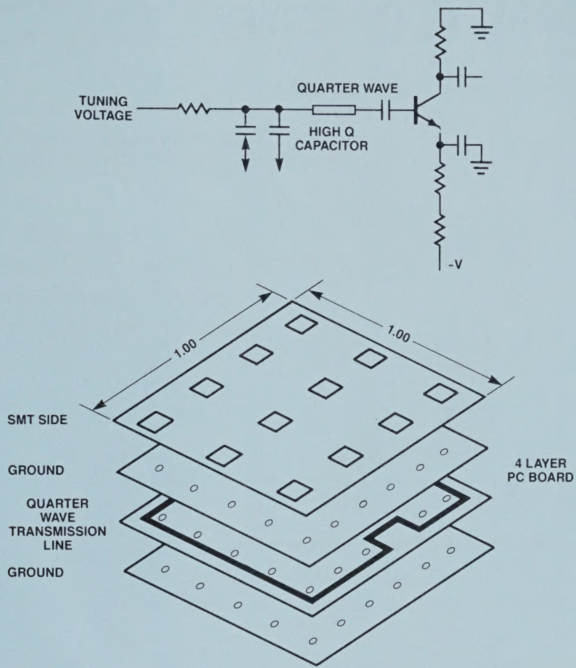

Figure 11. SMD transmission-line oscillator.

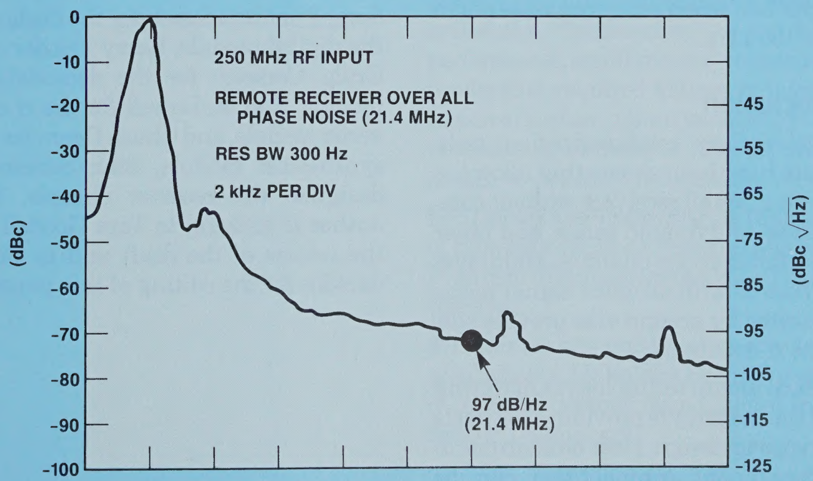

Figure 12. LO phase noise.

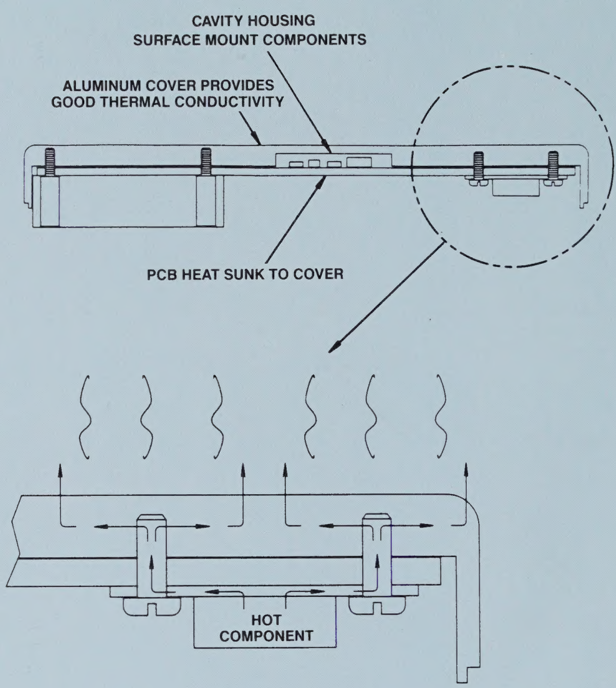

Figure 13. Heat-sinking path to outside cover.

pass filters could not fit in the space allotted, the FM monitor video at this output has a frequency response out to only 100 kHz.

Conclusion

New receiver miniaturization techniques have been shown that allow the design of small receivers without compromise to dynamic range and other important receiver qualities. Multilayer PC boards with stripline signal paths separated by ground vias provide adequate rf isolation.

Surface-mount technology is maturing and the industry is providing the parts for receiver design. Heat buildup due to surface-mount compactness can be removed by careful construction of the case that houses the multilayer boards.

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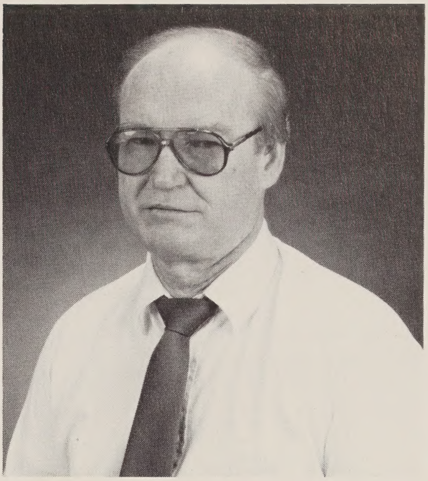

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Mr. Dexter is a Staff Scientist, in the Watkins-Johnson Company Communication Electronics Technology Division, Gaithersburg, Maryland, where he currently manages the Hybrid Laboratory and directs the investigation of new techniques in electronic assembly using thick film on ceramic, SMT and chip-and-wire.

He formerly managed the development of the VHF/UHF surveillance receiver called the "Miniceptor," whose high performance, small size and voluminous production required extensive investigation of surface-mount technology and methods of multilayer printed-circuit design to preserve rf isolation.

Mr. Dexter has also served as Manager of Surveillance Receivers and has been Program Manager for the WJ-8718 HF Receiver.

Mr. Dexter has published many technical articles. He holds a B.S.E.T. degree in Applied Science from Capitol Institute of Technology.

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