APPLIED EMC CONTROL IN A HIGH DYNAMIC RANGE ENVIRONMENT

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Abstract

A homodyne Doppler radar receiver with -148 dBm IF sensitivity required interference free operation in a 40 v/m AM field. Conventional control techniques proved inadequate. A systematic design approach to subassembly testing, shielding evaluation and use of a novel gasket achieved a cost effective design.

1. The Problem

A Doppler radar was required to operate free of radiated susceptibility to specification in a 40 v/m electric field with 100% AM. Additionally, the customer imposed some constraints upon control techniques which included:

- Quick disconnect fasteners for the cover
- Prohibition of integral filter pin connectors
- A high salt spray environment for the housing

Finally, the design had to be produceable to a fixed production budget.

A Doppler radar has several unique factors which require careful consideration in designing out susceptibility:

- The receiver's final signal processing bandwidth is only a few hundred Hz, thus KTB is a very low power level.
- The homodyne receiver noise figure varies inversely with IF (Doppler) frequency from about 30 dB to 12 dB. Owing to mixer conversion loss, the lowest noise floor in the signal bandwidth at the IF input is below -140 dBm (an example is shown on the following page).
- The 0-10 kHz IF bandwidth of the receiver covers the fundamental modulation frequencies of many shipboard and airborne emitters.
- On the other hand, the receiver s narrow bandwidth rejects most of the spectral power of incidentally demodulated signals from pulse modulated sources.
- The Ku-band antenna waveguide cut-off frequency is 9.49 GHz. Hence, signal port conducted interference is not covered herein.

Other susceptibility factors involving the receiver are described below:

a. Both in a test environment and in a real application, structural and cable length resonances create the worst susceptibility problems. These tend to drive Q multiplied currents into finite joint transfer impedances.[1] Similar internal resonances multiply the excitation to susceptible circuits.

   An additional source of resonances is unique to the test environment. This consists of the many resonant modes of the rectangular shielded enclosure.[2]

b. A field strength of 40 v/m corresponds to a far field power density of 4.24 w/m^2.

   The case presents a physical aperture of about 0.4 m^2. Thus, the dynamic range of the problem involves over 170 dB of power. The receiver is responding to out of band signals through an overload mechanism as a square law detector. Its tangential sensitivity in this mode is far less than its in-band sensitivity. However, its very low noise floor owing to narrow bandwidth does lower the tangential sensitivity to narrow band interference. The true tangential sensitivity of an unprotected receiver with a terminated signal port is difficult to measure accurately owing to the resonances cited above. The zero bias Schottky mixer diodes, like back diodes, have low overload tolerance. These and the IF input transistor (2 dB noise figure) probably are the most susceptible demodulators to incidental modulated energy.

c. While the mixers are housed in a bonded teflon stripline circuit board, the outer ground planes have many leak sources. The diode cover plates, while adequate to control local system leakage, suffer from finite transfer impedances aptly described by Madle.[1]. The Polyiron Ku-band absorber used around the IF terminal has only very modest attenuation at UHF frequencies.

d. Dissimilar metal joints (potential detectors) are impractical to eliminate from the input signal path. It is costly to gold plate the entire structure and all receiver parts.

e. The IF amplifier itself presented a close second in susceptibility. Little difference was noted when termination resistors were substituted for the mixer diode signal source.

f. Finally, our product designers wanted to use an economical pop riveted case which inherently has leaky joints. This also provides inherent low mechanical Q owing to friction losses.

2. The Investigation

The general investigative approach was:

a. Identify and rank the susceptible incidental receptors, their critical response modes and thresholds.

b. Apply any local treatment that effectively reduces receptor susceptibility.

c. Initially get rid of housing apertures and penetrations that reduce shielding attenuations (except for the cover). (These can be introduced later in a controlled fashion after the basic housing design is optimized.)

d. Partition the receptors within the structure to optimize protection.

e. Define the basic structural shielding controls.

f. Introduce the necessary apertures, filtering, etc.

g. Guide the product designers and inspect all critical drawings for critical EMC control details.

As was suspected, the susceptible receptors ranked in the following decreasing order:

- Receiver
- Transmitter
- Receiver microwave beam switch
- Transmitter microwave beam switch
- Signal processing and digital logic

It was important to define the critical response criteria for each potential receptor. Any demodulated baseband signal appearing in the receiver output represents excess receiver noise which a desired signal must overcome if a Doppler signal would appear at that frequency. Hence, a wave analyzer was precisely tuned to the emitter's single tone baseband signal. An analyzer bandwidth narrower than the normal frequency tracking bandwidth was used for earlier identification of threshold responses. A 0.4 dB rise in noise in the wiedest tracking bandwidth (450 Hz) was selected as a threshold goal. This is a -10 dB I/N. By using a 30 Hz wave analyzer bandwidth, a 14.7 dB noise reduction enhances the detection capability (at the expense of sweep rate and receiver noise fluctuation).

The transmitter's critical response threshold is a function of modulation frequency. It is established by balanced mixer rejection and the local oscillator bias level. (In a homodyne receiver, the local oscillator frequency offset from the transmitted signal is exactly zero.) Incidental FM is also important but the transfer function is lower.

The transmitter's modulation mechanism is strong signal detection by the current regulator. The demodulated baseband signal is within the current regulator loop's passband. Some of this signal is seen at the summing point from where it presents a small output current ripple component to the IMPATT diode. The latter's small signal ripple transfer function at 80 ma nominal operating current is approximately

$$\frac{0.16 \text{ dB}}{\text{ma (p/p)}} \quad \text{amplitude modulation}$$

The corresponding carrier to side band ratio is 41 dBc/ma p/p ripple (31 dBc/ma rms).[6]

At the susceptibility test modulation frequency of 1 kHz, the allowable c/s ratio is 107 dB (determined by AM rejection and mixer noise figure which varies at an I/F rate at low frequencies). Thus, maximum detected modulation at the regulator output = -76 dB ma or approximately 158 nanoamps rms.

This information gave some insight to the degree of control required as compared to other receptors. However, it is more practical to apply logical control techniques of filtering and shielding of the transmitter module and then directly measuring the new incidental AM. The foregoing current level is interesting to compare to the limit of any allowable demodulated current introduced into the path between the mixer diode and preamplifier.

KT	-174.0 dBm/Hz
B	25.5 dB*
F (1 kHz)	20.0 dB
KTBF	-128.4 dBm = mixer floor

L_c -6,5 dB = -134.9 dBm

Neglecting the 2 dB f_{if} we have 3.21×10^{-17} W. Maximum mixer Z_{IF} = 180 ohms. Hence i_n (min) = $(3.21 \times 10^{-17} \div 180)^{1/2}$ = 420 pa rms noise. To hold loss of sensitivity to 0.4 dB, maximum a -10 dB interference/noise ratio is required. Hence, the allowable baseband signal current at the most sensitive point in the receiver is 140 pa rms.

Thus, the receiver is 20 log $\frac{158}{0.14}$ or 61 dB more sensitive than the transmitter. Actual difference in sensitivity to RF ground current of E fields depends upon physical geometry of the parts (resonant frequencies) and the relative efficiencies of the incidental demodulators.

Analyses such as the foregoing provide some interesting comparisons but one should never get too carried away with them because other real variables which are difficult to quantify may overshadow them. On the other hand, pure empiricism is seldom efficient except for very simple problems.

3. Systematically Solving the Problem

An aspect of EMI control which often dooms a randomly guided empirical solution is that several system contamination points are involved. If three receptors are nearly equal in sensitivity, curing one completely has little apparent effect. Indeed, the results are so susceptible to seemingly innocent changes in geometry that a totally opposite conclusion might be reached when in fact one leak was actually fixed.

In view of this, the lesser receptors were dealt with first. This increased their flexibility and provided more degrees of freedom for controlling the receiver - the real challenge.

A natural division of the structure occurs because two downward illuminating separate 8" x 16" planar arrays form the floor of the box which contains the electronics. In order to stiffen the entity for the vibration environment, the septum which isolates the two arrays is carried up through the box to the cover. A logical approach is to put all of the lesser receptors in one compartment (the transmitter half) and save the other side for the sensitive receiver (Figure 1). This alone would do little good because the receiver compartment requires a removable cover to the outside world and also requires a lot of connections to the rest of the radar. These wires would equalize any difference in the noise fields between compartments if they simply passed through a hole in the septum (more about this later).

*The frequency tracker's acquisition noise bandwidth at a 1 kHz Doppler frequency is 300 Hz.

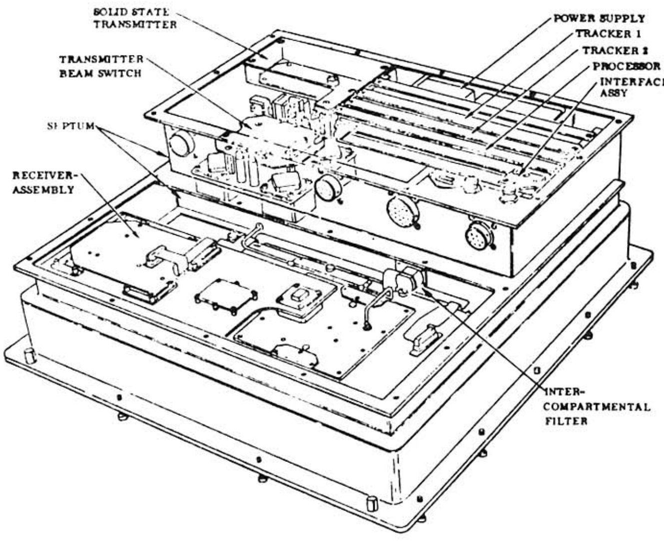

Figure 1. Final Doppler Radar Housing Design Partitioned for Optimum EMC

The next approach was to determine if an economical riveted housing could provide enough control. To this end a riveted aluminum box was constructed approximating the major dimensions of the radar. A battery operated mixer stripline circuit board and preamplifier were then installed in the box. Local oscillator bias and the output signal were fed out of the box and shielded enclosure via two semi-rigid coaxial cables and SMA feedthrough connectors. The box was then illuminated with the highest obtainable modulated field in our own lab over the range of 50-1000 MHz. This field varied from 5 to 40 v/m, as a function of frequency.

A number of very severe and sharp resonant responses were noted. These could be roughly correlated to cable lengths (70 MHz) and several modes of the case and cover. Other responses were caused by rigid waveguide modes within the box. Still other responses were attributed to the shielded room itself. These were dealt with by inverting the test equipment with respect to the room. At the worst resonant points, removing the gasketed box cover made only very modest differences. Sealing the box joints with copper tape having a copper loaded adhesive showed negligible improvement. Next, an inner receiver compartment was brazed to the floor to provide additional shielding to the preamplifier. The stripline ground plane was used as a gasketed cover to this inner box. This also provided little improvement. To determine the relative susceptibility of the mixers and preamplifier, the latter was terminated to the former's ground plane. This showed that the preamplifier alone was about as sensitive as the combination. A 20 dB response attenuation (10 dB lower field susceptibility) resulted from bypassing all three preamplifier transistors from base to emitter with very short lead, 1000 pf capacitors.

In retrospect, much time could have been saved with earlier access to Madle's very useful paper on transfer impedance of gasketed joints.[1] The many box joints were quite long. According to his test fixture curves, the aluminum interfaces just were not going to work very well with conventional monel mesh or oriented wire gaskets. Gasket vendor data which show impressive attenuation figures were obviously not being achieved at resonant points. Madle points out that the main behavior of these gaskets is capacitive and that transfer impedance just wont go below 20 milliohms/cm. Madle also inferred that at resonance, some points in the joints were being driven with current maxima. The very modest case attenuation (measured by removing the cover and retuning to resonance) appeared to be the result of a modest ratio of a very low driving impedance to the finite transfer impedance of metal joints. As a result, E fields were then launched inside the box from these points. These internal fields induced voltages and currents in the "hot" and ground plane portions of the signal loop between the mixer diodes and preamplifier input.

The riveted box was finally discarded for a monolithic structure, but this presented a fabrication problem. Each array consists of a dip brazed assembly of numerically machined aluminum strips. The box sides could also be dip brazed into a subassembly. However, these two subassemblies could not subsequently be dip brazed together. Electron beam welding was possible but was discarded due to cost and logistics problems. The solution was to put flanges on these subassemblies which could then be resistance welded in our own plant. A continuous closure was achieved by overlapping the spot welds. A full size receiver compartment mockup was assembled this way except that a flat plate simulated the array backs. Short open cracks were left in the four corners where the actual waveguide feeds would interfere with the welder head. (Later, it was found necessary to seal these with metalically loaded silicone rubber to prevent interference of several GHz.)

This new mockup showed a big improvement over the riveted box, so the basic design was committed to this approach (Figure 1). Far fewer resonant peaks were seen and these were much lower in amplitude. Now the box was tight enough to provide useful data when probing with a localized stimulus. Two findings became obvious:

- No combination of joint pressure and conventional catalog gasket was adequate (isolations were now around 40 dB at worst resonances).
- No filter provided adequate attenuation to allow bringing the receiver interface wires directly into the stimulating field.

Both problems turned out to be one and the same -- the finite impedance of metal to metal joints. The filter elements themselves were adequate, but the filter case to housing joint was not. Here the attaching external wire would resonate and drive the joint with a high current. At these frequencies the joint failed miserably. Coaxial feedthrough fittings showed the same shortcoming at the flange interface.

Further experiments showed that these filter and flange interface leaks improved by 20 dB if the part was installed on the outside instead of the inner surface of the case. According to Madle's paper, this should not make any difference. Apparently, in addition to propagating an electric field inside, some of the RF interference current which was directly sunk to the inner surface of the box by the feedthrough device was also stimulating the stripline ground plane. This is logical because the stripline is necessarily common to housing ground, owing to the antenna feeds. As a result, the IF signal path is distributed within the ground plane. (The preamplifier's 53 dB gain input stage makes a single point ground to the stripline via its twisted input pair.) Of course it is difficult to separate directly sunk currents on the inner skin from those which flow owing to an electric field propagated by the transfer impedance. Indeed, Madle defines an equivalent transfer impedance due to all causes of leakage.[1]

4. Finalizing the Design

Four external connectors were required by the customer: power, analog signals, digital signals and test points (capped). The transmitter compartment was extended higher than the receiver compartment since more and larger modules were installed therein. This provided two advantages for EMC:

- Two separate covers precluded surface currents from flowing directly across the top of the septum via the inner surface cover skin resistance. A voltage divider would otherwise be created between this skin resistance and the gasket's transfer impedance. Instead, the two covers were totally separated. Now residual currents on the inner surface of the transmitter cover are shunted through separate structure to ground. (The transmitter compartment contains more leak sources to ambient than does the receiver.)
- The external connectors could now all be mounted in the septum wall with their flanges against the relatively noisy transmitter side. (The flanges were gasketed.)

The external cables used the following shields: power - none (twisted pair filtered behind the connector). Analog - one over all shield. Digital - twisted shielded pairs. All shields were terminated within the Kern Engineering backshells with garter springs and tapered glands. (These can easily handle both types of shields.) The primary power filters use a double L configuration with a 110 kHz corner frequency. The connectors thus sunk the shield surface currents and filter currents to the transmitter compartment inner wall rather than the outer septum wall which would have otherwise excited the receiver cover gasket with these currents.

The receiver required 19 interface wires with the noisier transmitter compartment, plus one semirigid coaxial cable for LO bias. However, the only receiver wiring to any external connector went to a capped test connector. The mockup tests conclusively showed that these 19 wires required substantial RF attenuation. (The mockup test required a solid jacketed cable between the mockup and the shielded enclosure wall. Even then, the connectors required silver paint.) Three other design constraints were:

- The customer prohibited filter pin connectors owing to a fear of breaking the ceramic capacitors when mating the connectors.
- Open external connectors could not face upward so as to catch water.
- All internal wiring (except the discrete primary power filter) had to be in a single flat flexible harness with multiple layers. This was soldered to the external receptacles, internal PC board receptacles and plugs for internal non-card modules. The entire assembly, including the multiwire filter block for the receiver interface, had to be removable as an entity with minimal unsoldering.

The external connectors met the second and third criteria by mounting to the inner wall of the transmitter compartment through the septum wall, where they protruded above the receiver (Figure 1). The first criterion was met by modifying a filter pin connector. The vendor supplied it with a larger flange, a fore-shortened shell and protruding male pins on each side. The equivalent circuit of the filter pin is shown in Figure 2. It is equivalent to the Bendix "HF" pin. The receiver interface circuits had to be designed to drive the filter without distorting the desired signals unduly. This required knowledge of the filter model - not just MIL-STD-220 data. The most critical signal criteria was preserving phase and amplitude balance of 7.5 kHz quadrature pairs sufficiently to maintain -15 dB unwanted sideband suppression. (A Doppler shift return is a single sideband signal.) A computer generated envelope of allowable gain and phase unbalance was made. Computer aided circuit modeling was then used to verify worst case performance. This showed that the driving OP amps required a minimum of 2 MHz gain bandwidth. The MIL-STD-220 test attenuation of the "HF" pin is shown in Figure 3. Of course, this attenuation is not necessarily realized in any specific application.[3]

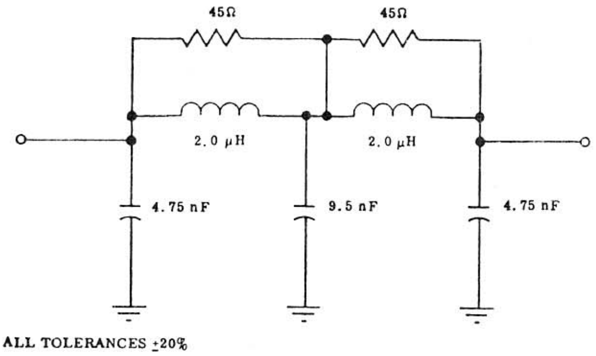

Figure 2. Multipin Filter Model (Bendix HF - Furnished by Bendix Electrical Components Division)

The filter block flange was mounted to the transmitter side of the septum for reasons discussed earlier. The cable going to the receiver and the latter's plug could not be pulled through the hole after unscrewing the filter assembly from the septum wall. The filter flange was gasketed.

The transmitter module was mounted in the noiser side as described earlier. Separate tests were run on this module using -107 dBc AM sideband levels as a susceptibility limit. A monolithic die cast housing for the current regulator provided adequate shielding. The design was constrained to a single interface wire (+135 vdc, 80 ma power). A discrete Pi filter in the housing wall isolated this line. The return was through the structure back to the power supply module. This is practical in a one-box system. Ground interface details are all under the designer's control. This current is by design very pure dc. Unlike a constant voltage source, a current regulator output is hard to contaminate with other ac currents flowing through a common ground resistance. The safety ground wire return was attached to the outside of the transmitter module. EMI filters in ground wires should always be avoided where possible. The low source impedance makes the filter very ineffective.

The case was also used as the receiver module's return for output signals, power and control function. The safety wire again was not filtered. A grounded pin in the filter block was used instead.

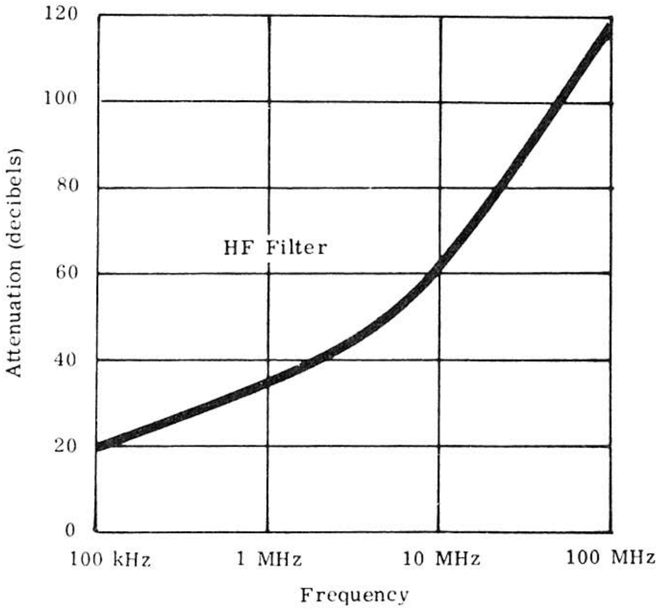

Figure 3. Multipin Filter Attenuation per MIL-STD-220 (50 Ohm) (from Bendix Electrical Components Div. Data Sheet)

5. Selecting a Gasket

The remaining problem, and the most persistant mockup test problem of all, was the inability to seal the lid with any catalog product from either of the two major gasket houses. Small variations were seen between types, but nothing even approached the isolation achievable with a compression lip on the lid of a new, tin plated, one gallon paint can (107 dB at 1 GHz).

This last problem was finally solved when a test technician, upon returning from an EMI shielding course, brought back among his handout literature, references 1, 4 and 5. Kunkel[4] described a new soft berrylium copper spiral gasket with tin plating. Madle's[1] transfer impedance test data showed 20 dB lower transfer impedance using this gasket than the closest competing gasket. Groshart[4] showed that an aluminum/tin interface retained its low impedance after a long humidity soak where other interface pairs typically increased their initial values by a decade. An added bonus was that Madle's model explanation and tests provided insight to earlier test results.

Test results with the Be/Cu/Sn spiral gasket (Table 1) were so dramatic that the test setup was initially suspected as defective. For the first time in three months of iterative investigation, the mockup showed no detectable noise rise in either wave analyzer (Figure 4) at any point in the 50-100 MHz band. The setup was easily verified by cracking loose the cover. Table 1 summarizes the mockup results between gaskets. The listed frequencies correspond to the major resonant bands. Their bandwidth varied from 100 kHz (minimum resolution) to a few MHz. The actual isolation of the final gasket could not be measured. Limited source power precluded driving the test sample hard enough to raise the leakage above receiver noise.

Conclusion

1. The investigative method consisted of:

   a. By analysis, define threshold response limits and rank the potential incidental receptor circuits.

   b. Conduct module level tests to identify the susceptibility levels, using the above response limits.

   c. Build a simple case mockup to identify the degree of controls required for the most susceptible module.

2. Control techniques useful in a high dynamic range situation are:

   a. Minimize wired interfaces: use structural power and signal returns, but do it with care. Critically justify all remaining wires.

   b. Physically isolate the receptors with highest isolation in a separate compartment.

   c. Design a monolithic structure with separate covers for the different class compartments. Use unequal compartment height to separate the covers if required.

   d. Buffer wired interfaces to the most susceptible compartments with intercompartment wall filters - don't go straight outside through a single filter or shielded connector.

   e. Mount filters and connector flanges to the noisy wall surface as opposed to the protected surface.

   f. Shield or additionally filter all external interfaces which must be between the noisier compartment wall and the outside ambient.

   g. Use Be/Cu/Sn spiral gaskets under the covers as a minimum and under connector flanges if needed. Avoid monel, aluminum or brass or conductive elastomer gaskets.

Table 1. Gasket Performance Comparison

Frequency (MHz)	Oriented Al Wire, 1/8" Si Rubber		Oriented Monel Wire, 1/4" Si Rubber		Monel Mesh 1/4" Sq Section		Be/Cu/Sn Spiral	
	Stimulus	Response	Stimulus	Response	Stimulus	Response	Stimulus	Response
65 - 70	Not tested		Not tested <480 MHz		(1) 16	6		Not tested
335 - 360	24	(6) 10				(0)	24	(0)
390 - 540	24	(8) 12	17	(5) 4	21	(10) 13	30	(0)
628 - 680	24	(1) 2	Not tested		27	(2) 4	25	(0)
728 - 765	22	(5) 12	Not tested			(0)	24	(0)
828 - 880	18	(4) 12	Not tested		26	(4) 12	27	(0) (No responses found 300 - 1000 MHz)

Stimulus = dB uv/m (nearest dB) = maximum available power
Response = dB (I+N)/N. Number of responses found are shown ( ) in each listed band. Strongest example indicated. No responses found outside of bands shown except for "not tested" regions.

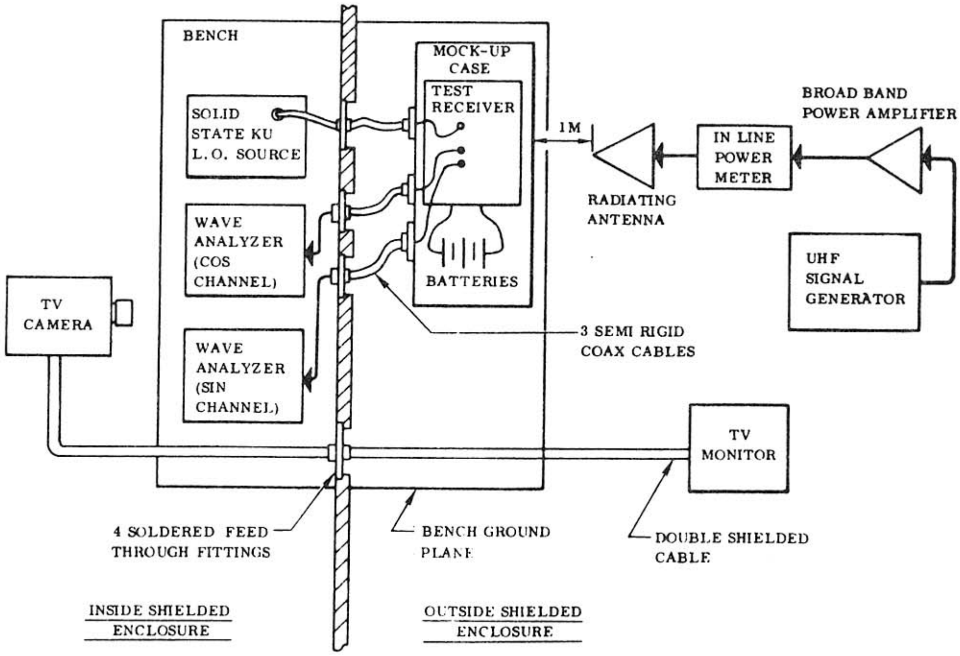

Figure 4. Inverted Test Configuration to Prevent Shielded Enclosure Resonant Modes

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