EMC Engineering

Top Ten EMC Problems & EMC Troubleshooting Techniques

by Kenneth Wyatt, DVD, Colorado Springs

Rev. 5, June 19, 2007

Agilent Technologies

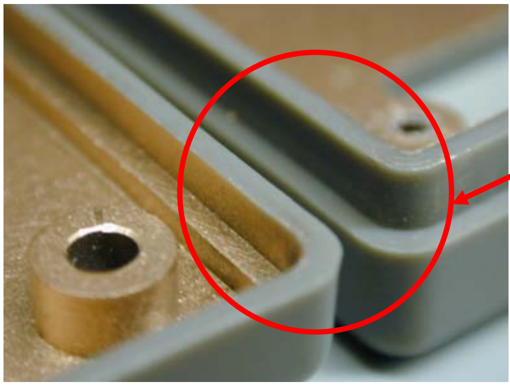
1a. Ground Impedance

The overwhelming majority of high-frequency problems, whether related to emissions, immunity or self-compatibility have high ground return impedance as a root cause.

- **Wires and traces have a high impedance. *This is why a ground return plane should be used at high frequencies***
- **High-frequency effects start occurring at 1 MHz**
- **The inductance of a wire in free space is about 20 nH/inch**
- **A one-inch wire (or trace) has an impedance of $2\pi fl \approx 12\Omega$ at 100 MHz**

1b. Slot caught during a design review

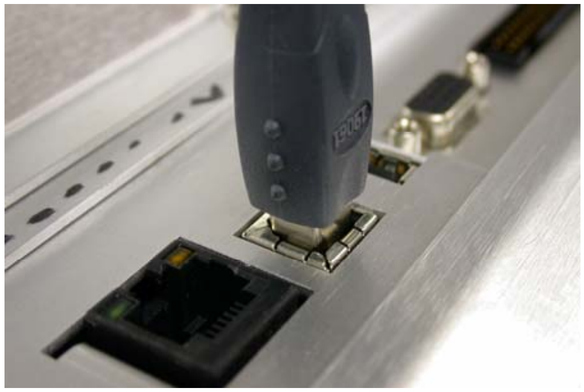
1c. Poor shield integrity



Attempt at shielding module failed to connect halves!

Module halves copper-plated

2a. Poor Cable Grounding



RF Immunity problems almost always involves a cable.

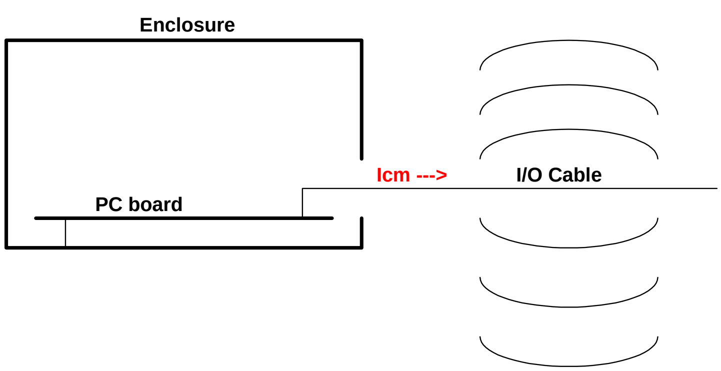
➢ **Shield "pigtails" are bad – circumferential (360 degrees) are best.**

2b. Poor Cable Grounding (continued)

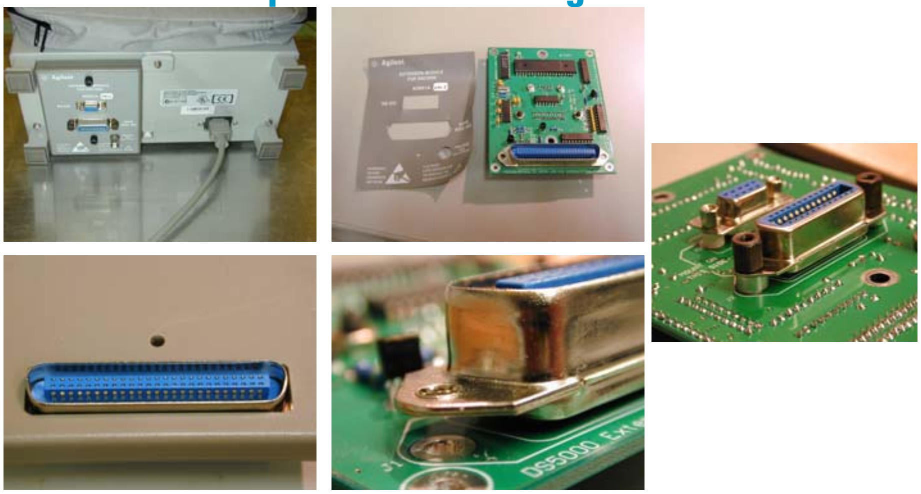
Divert the current back to the shielded enclosure

- Proper termination of the cable shield back to the enclosure is the key

Block the current with a high-impedance ferrite choke

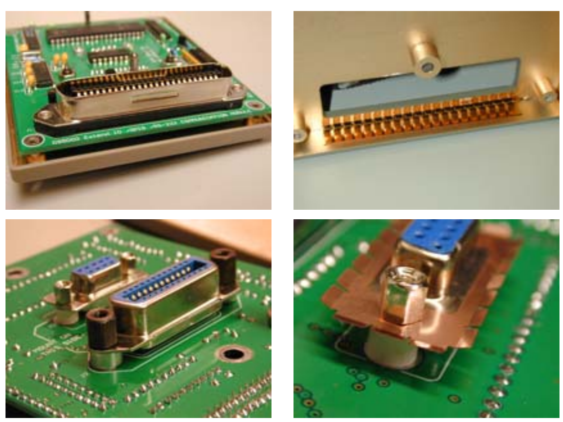


2c. Connector penetration through shield



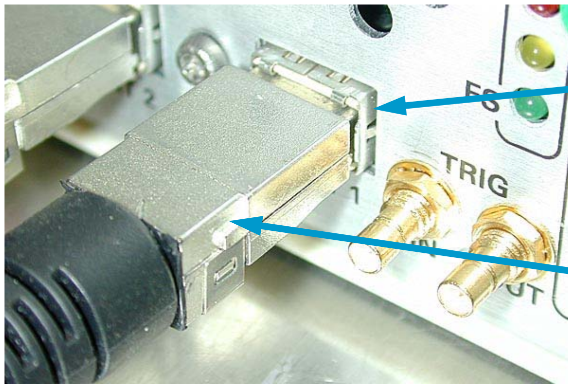
Module was unshielded, main connector ground shells had no connection with mate, connectors penetrated enclosure

2d. Connector penetration through shield (cont.)



Module halves copper-plated, finger stock added to connectors and ribbed main connector ground shell connects with mate

2e. Good Cable Grounding



Ideal I/O connector:

- **Notice the design incorporates an integrated grounding connection, which solidly connects shielded enclosure with connector ground shell in multiple locations.**
- **The connector ground shell then connects to the cable shield.**

Good cable grounding design – cable shield properly connected to metal enclosure.

2f. Improved Cable/Connector Grounding

Shim with fingers added to shunt internal noise currents

3. Emissions From Switching Devices

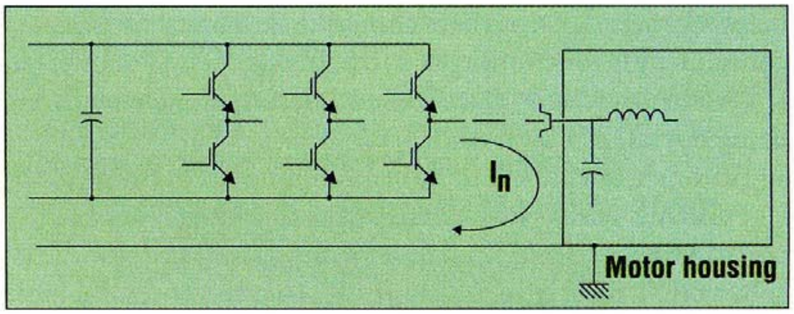


Figure 2. The switched-power noise path in a motor drive.

Switched high-voltages couple to heat sinks and radiate

➢Use bypassing and ground the heatsink (multiple points)

4a. LCD Emissions

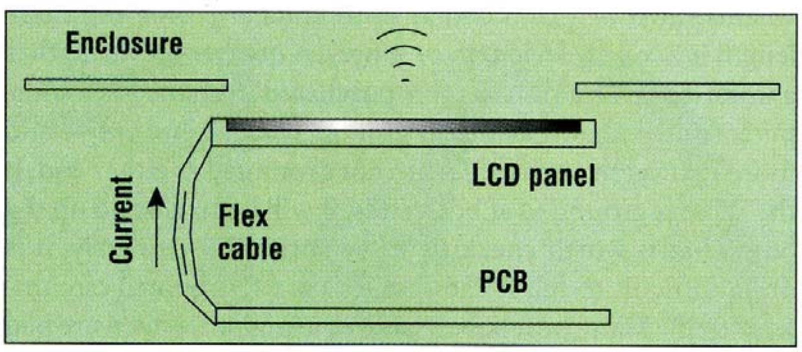


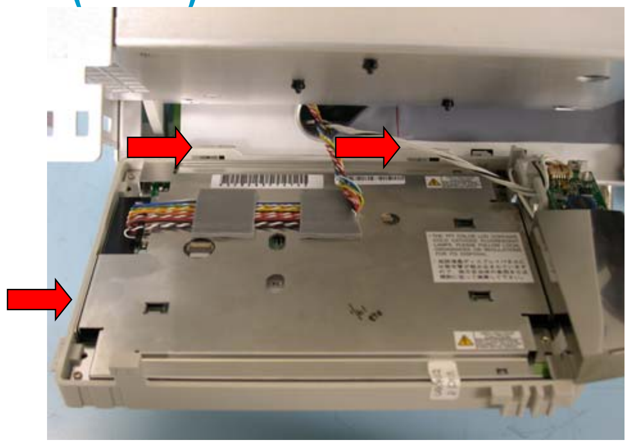
Figure 3. Emissions from an LCD.

Display cable radiates and excites the metal LCD housing

➢Ground the LCD housing to the enclosure in multiple points

4b. LCD Emissions (Oscar)

added



>Display cable radiates and excites the metal LCD housing at the display “dot” clock frequency (437.5 MHz).

>One more ground at the LCD housing reduced emissions 8 dB.

5a. Stray Internal Coupling Paths

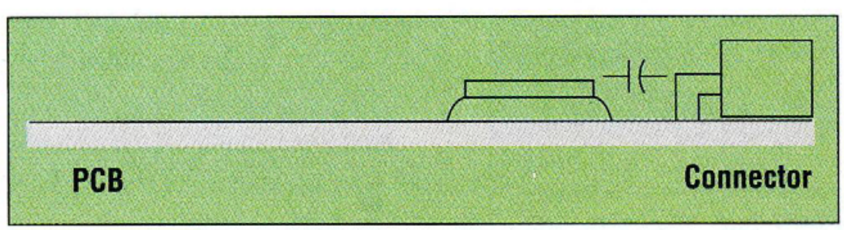
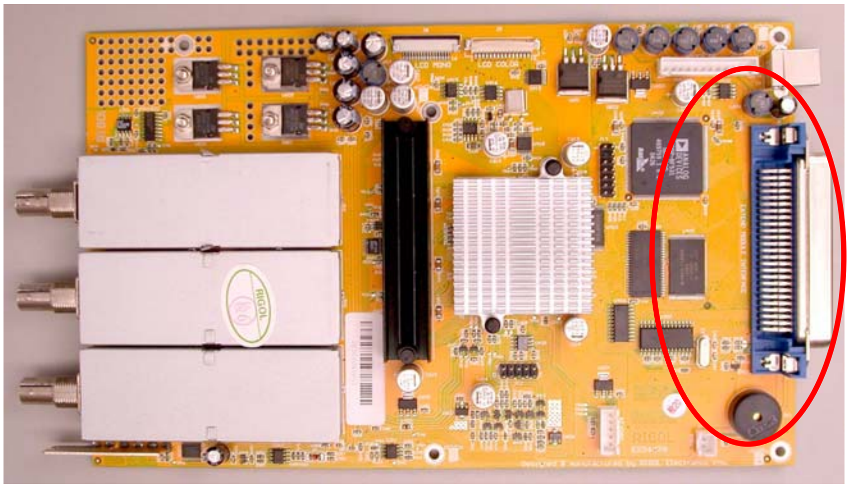


Figure 4. Stray capacitance between the chip and connector can bypass on-board filters.

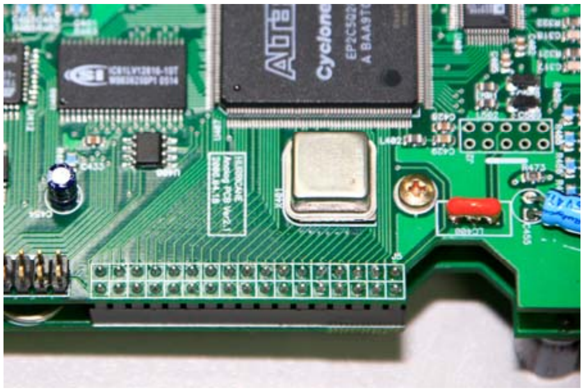
- Adding an external ferrite choke on the I/O cable often works best.
- Interrupt the coupling path with a Faraday shield.

DSO3000 acquisition board



Loop area on signal pins of connector coupling noisy signals.

5b. Data lines running underneath xtal oscillator



Data lines couple 100 MHz (and harmonics) through I/O connector to second PC board; which in that area, is referenced to the power plane (with gaps).

7a. Crosstalk

Most often due to a self-compatibility problem that occurs when noisy source currents come into close proximity to sensitive analog, or low-level digital, signals

- **Route power and signals in separate cables**
- **Use shielded cables**
- **For circuit trace couplings, use additional separation or grounded “guard” traces in between the source and receptor traces**

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7b. Crosstalk in Solid Ground Planes

Crosstalk between two conductors depends on their mutual inductance and capacitance. Usually, the inductive crosstalk is dominant.

$$\text{Crosstalk} \approx \frac{K}{1+(D/H)^2} \qquad [5.2]$$

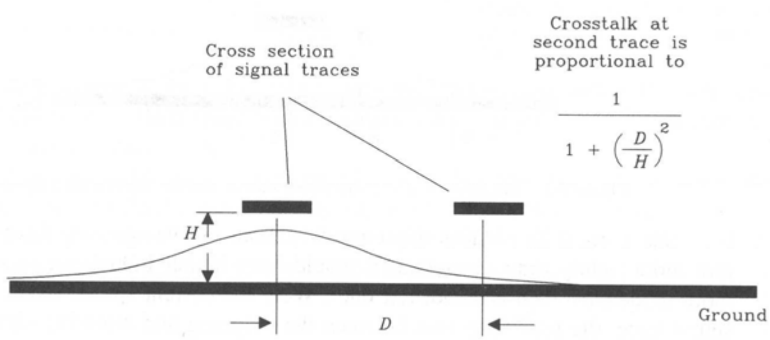

Figure 5.4 Cross section of two traces showing crosstalk.

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7c. Reducing Crosstalk With A Guard Trace

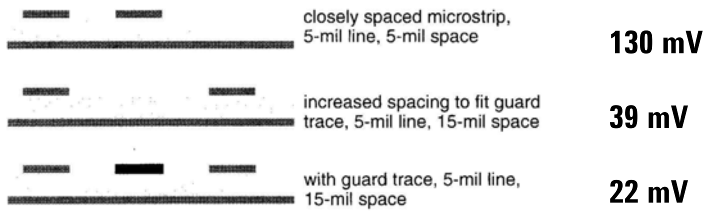


Figure 10-42 Three different microstrip structures evaluated for noise at the receiver of the victim line.

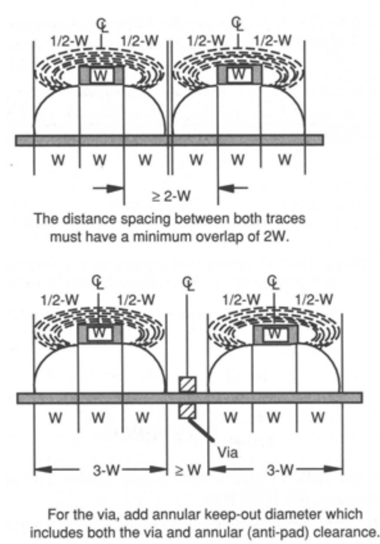
Ref: Signal Integrity – Simplified, Bogatin

7d. Use the “3W” Rule During Layout

Clocks and periodic signals have the greatest chance of causing crosstalk in other traces.

Minimize crosstalk effects by using the “3W” rule; that is, ensure that all critical traces are “buffered” by at least 3 “trace-widths surrounding each potential source and victim trace.

Increasing the spacing from 1W to 3W will decrease far-end crosstalk by 65%.



7e. Differential Pairs and the "3W" Rule

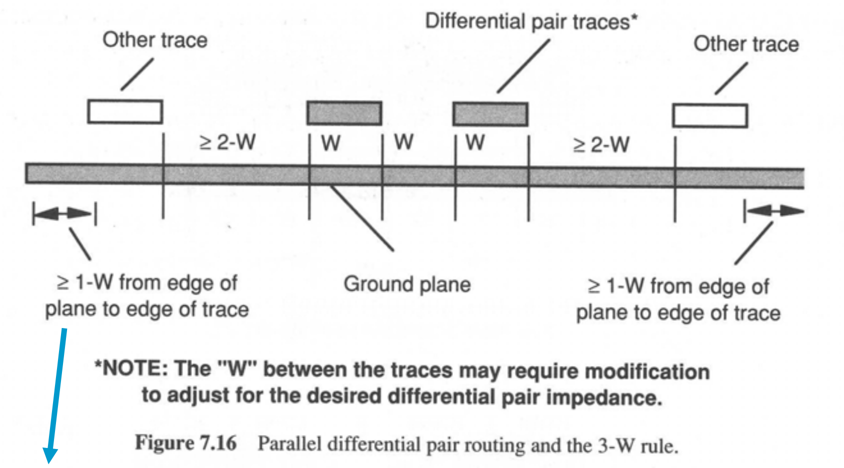


Figure 7.16 Parallel differential pair routing and the 3-W rule.

I usually consider 3-5W the minimum spacing for any critical trace to board edge spacing.

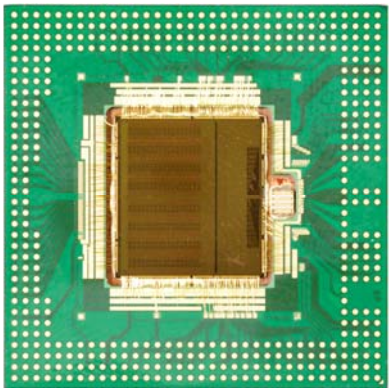
8a. Inadequate Signal Returns

A common situation with cables, as well as pin out designs in ASICs or other LSI devices is lack of adequate signal return wires (or pins).

Unless the return path impedance is zero, a fraction of the current will likely return on a stray path, creating large loop currents.

- Route power and signals in separate cables.
- Use shielded cables.
- Add more ground return pins to ASIC/FPGA definitions (50-50% is ideal).

8b. Inadequate Signal Returns



Ensure adequate number and position of signal return pins (approaching 50-50%).

9a. Discontinuous Return Paths

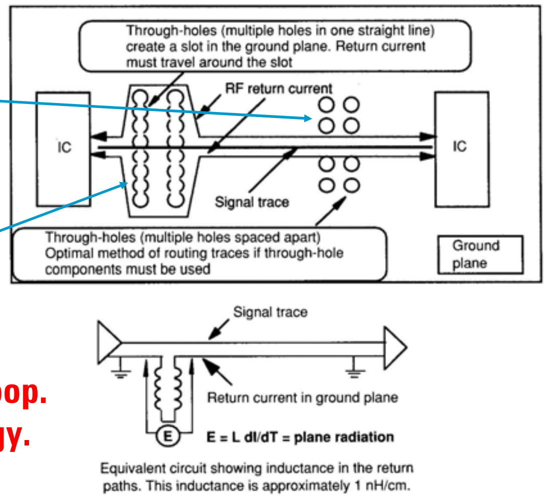
Most PC board problems can be traced to discontinuous signal return paths. This is becoming more of an issue with increasing clock frequencies used today.

- **Ideally, the signal travels out a trace and returns immediately under that trace**
- **All to often, the return path is broken by a discontinuity, such as a gap or slot in the ground plane or the signal trace passes through a via and changes reference planes**
- **Examine ground (and power) plane layers for gaps and slots**
- **Add extra vias for return currents when switching reference planes**

9b. Generation of differential-mode emission

YES!

NO!

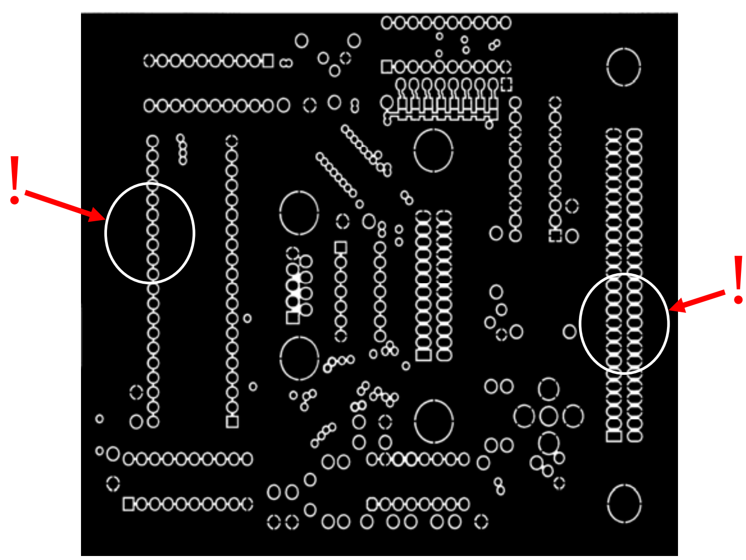


DM current flows in a loop. The loop radiates energy.

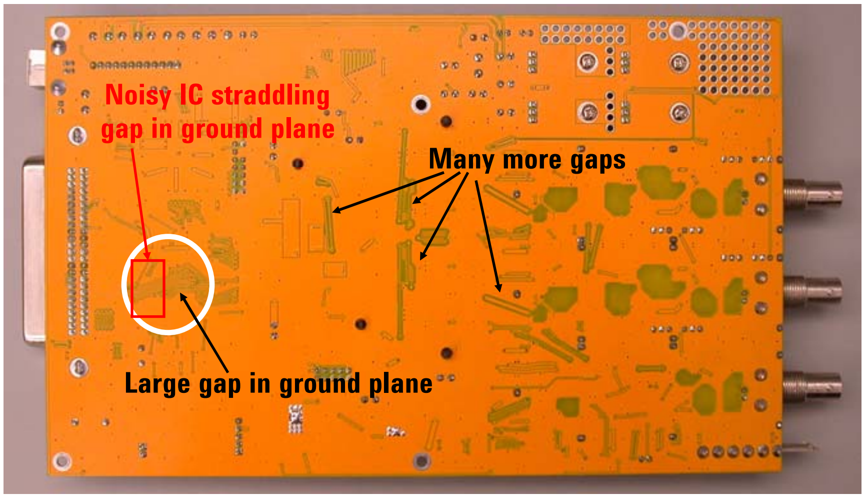
Figure 4.15 Ground loops when using through-hole components (slots in the plane).

Montrose, EMC and the Printed Circuit Board, IEEE Press, 1999

9c. Discontinuous Return Paths (examples)



9d. Slots in acquisition board signal return plane



Temporary bridge with copper tape reduced emissions 17 dB!

9e. Discontinuous Return Paths (examples)

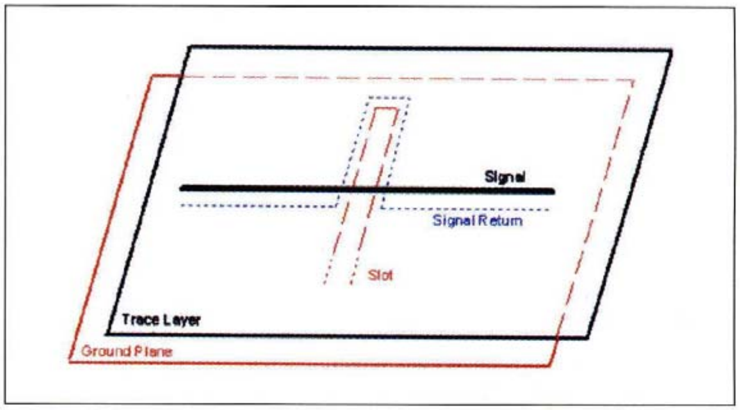


Figure 3: Routing a trace over a slot in a plane can cause a large loop area

9f. Discontinuous Return Paths (examples)

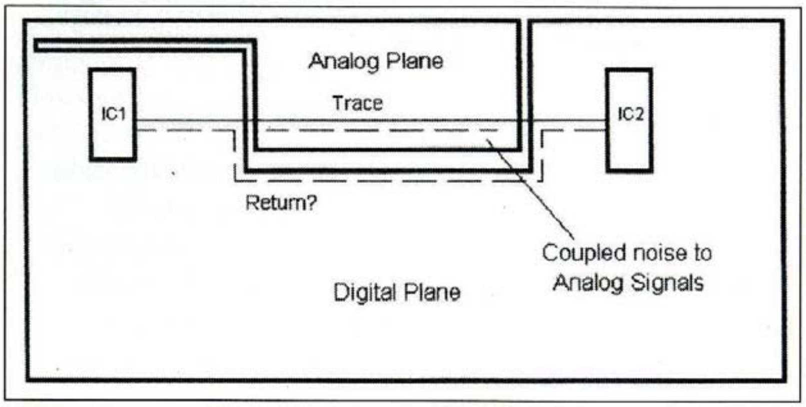
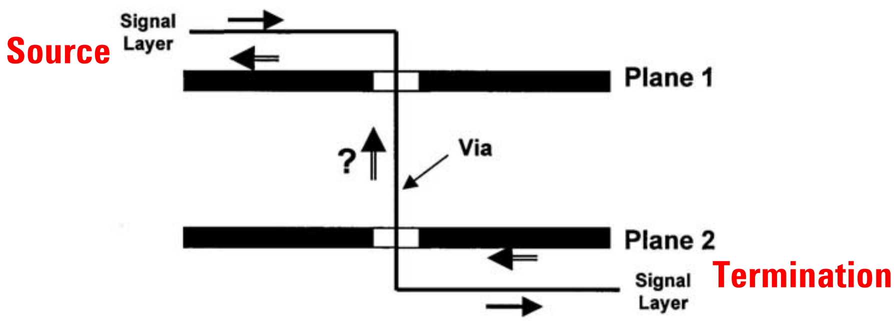


Figure 7: Routing a trace over an unrelated plane can cause several types of problems

9g. Trace passing through two planes with via



Signal Traces Adjacent to Different Planes

Question: where does the return signal current flow?

Ref: Ott, EMC Aspects of Future High Speed Digital Designs, PCB-01049

10a. ESD In Metal Enclosures

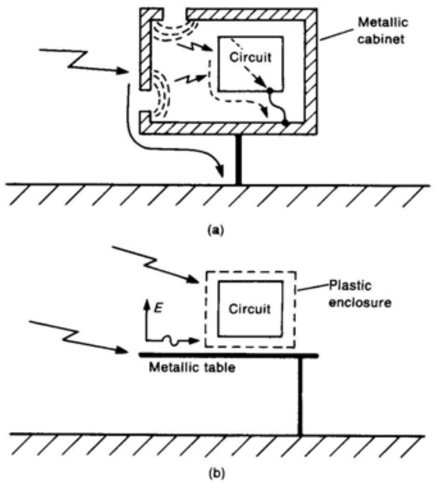


FIGURE 12.3 Illustration of the coupling of an ESD discharge to an electronic circuit for (a) a metal enclosure with apertures and (b) a plastic enclosure.

10b. Failure Modes Caused by ESD

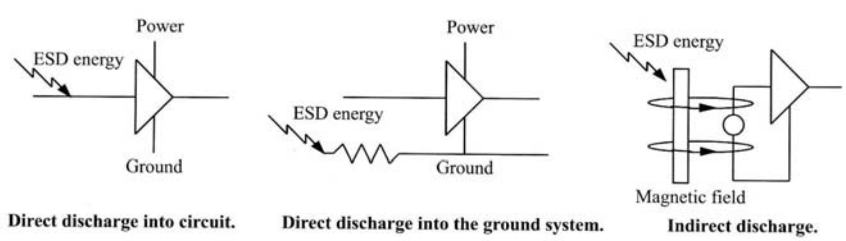


Figure 2.16 Failure modes caused by an ESD event.

- Typical failure modes include a change of instrument state (front panel control), CPU reset, instrument lockup, loss of data
- Fix by shielding, rerouting cables, separation of receptor circuits

Electromagnetic Compatibility Engineering

EMC Pre-Compliance Testing & Troubleshooting

by Kenneth Wyatt, DVD, Colorado Springs

Rev 3, June 19, 2007

Agilent Technologies

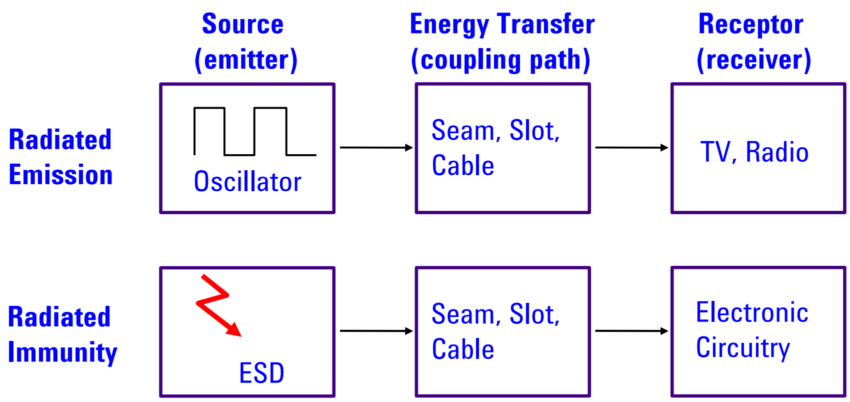
Five Key Threats

These comprise 95% of all EMC problems
(EDN Magazine)

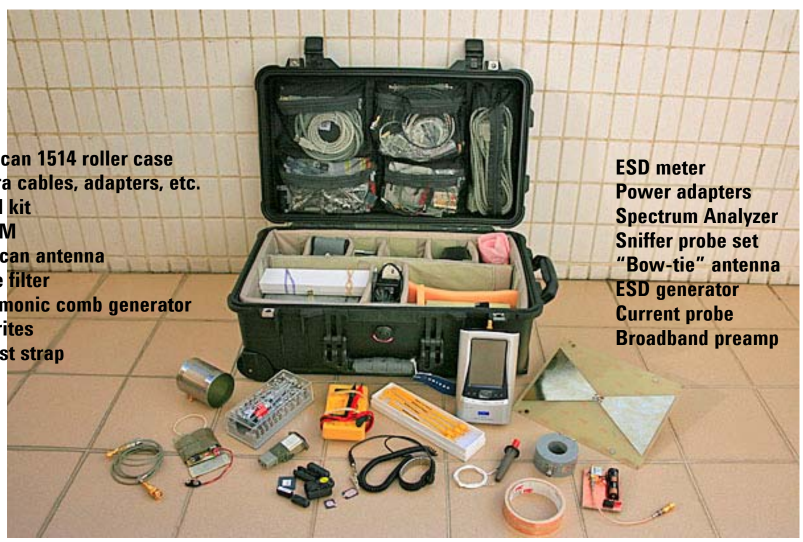
1. **Radiated Emissions**
2. **ESD (susceptibility)**
3. **RF Fields (susceptibility)**
4. **Power disturbances**
5. **Internal compatibility (crosstalk, etc.)**

The solution to most EMC problems is to *CONTROL THE PATH OF CURRENT*.

"Source-Path-Receptor" Model



EMC Troubleshooting Kit



- Pelican 1514 roller case
- Extra cables, adapters, etc.
- Tool kit
- DMM
- Tin can antenna
- Line filter
- Harmonic comb generator
- Ferrites
- Wrist strap

- ESD meter
- Power adapters
- Spectrum Analyzer
- Sniffer probe set
- "Bow-tie" antenna
- ESD generator
- Current probe
- Broadband preamp

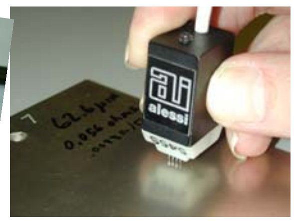
Major Contents

Current Probe
FCC F-33-1

Spectrum Analyzer
TTi PSA1301T

E- and H-Field probes
Beehive Electronics

Wideband Preamp
Mini-Circuits 2X60-3018G-S



Resistivity Probe

Small FRS Transmitter

EMC Troubleshooting Kit

What can you do with it?

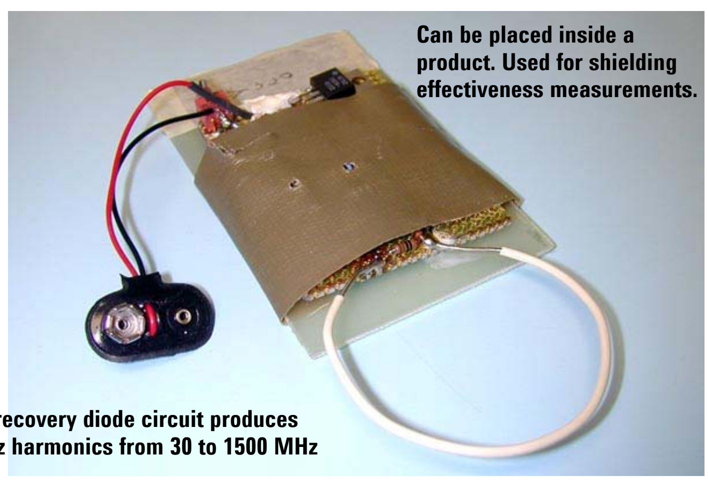
The EMC troubleshooting kit may be used for the following:

1. Identifying radiated emission sources on PC boards
2. Discovering leaky seams in enclosures
3. Measuring cable common-mode currents / radiation
4. Making quick “A-B” comparisons for proposed design changes
5. Testing for radiated and ESD immunity
6. Highly portable – may be used as a mini “EMC crash cart”

Simple Pre-Compliance Tests & Troubleshooting

- Shielding tests
- Analyze/measure crystal oscillator harmonics
- E- and H-field probing
  - PC Boards (E- and H-field probes)
  - Cables (current probes)
  - Shields (surface current and 4-point probes)
- Measure bare PC board emissions
- Measure conducted emissions in cables

"Mini" Harmonic Comb Generator Used For Shielding Effectiveness Test



Wyatt/Chaney, RFI Measurements Using a Harmonic Comb Generator, RF Design Magazine, Jan. 1991

Harmonic comb generator design

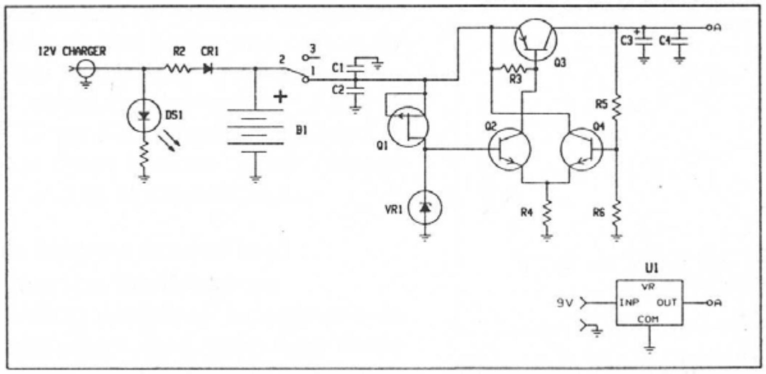


Figure 4a. Schematic diagram of the power supply and battery charging circuit. U1 is an optional voltage regulator used for the 9V battery operated miniature comb generator.

Wyatt/Chaney, RFI Measurements Using a Harmonic Comb Generator, RF Design Magazine, Jan. 1991

Harmonic comb generator design

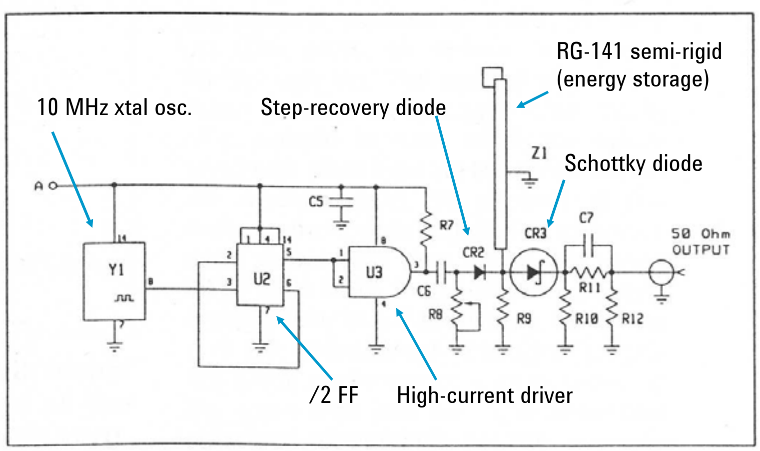


Figure 4b. Schematic diagram of the comb generator circuit.

Wyatt/Chaney, RFI Measurements Using a Harmonic Comb Generator, RF Design Magazine, Jan. 1991

Harmonic comb generator design

Capacitors

C1	470 pF
C2	2.2 μF/35V
C3	10 μF/35V
C4,5	0.1 μF
C6	0.01 μF
C7	6.8 pF

Resistors

R1	390
R2	56/2W
R3	1K
R4,6	178
R5	261
R7	23.7/0.5W
R8	50 ohm trimpot
R9,11	51.1
R10,12	110

Diodes

CR1	1N4001 rectifier
CR2	HP 5082-0180 step recovery
CR3	HP 5082-2810 hot carrier
DS1	LED panel light
VR1	2.4V/400mW zener

Transistors

Q1	P channel JFET (select for I_{dss}=3mA)
Q2,4	2N3904
Q3	TIP42A

Integrated Circuits

U1	3-terminal 5V regulator (used only for "mini" comb generator)
U2	74LS74
U3	75451

Miscellaneous

B1	6V/2.6AH battery (Yuasa NP2.6-6 sealed lead acid 5.25"L × 2.375"H × 1.25"W
S1	SPDT power switch
Y1	10 MHz crystal oscillator
Z1	2.0" long 0.085" diameter semi-rigid coax (shorted at one end)

BNC antenna connector

Charger jack 1/8" miniature phone jack

Charger - 12V/300 mA (International Components Corp. Model ICC-3-750-1015)

Enclosure - Bud CU-247 Econobox 7.375" × 4.6875"W × 2.25"H

Table 1. Parts list for the comb generator.

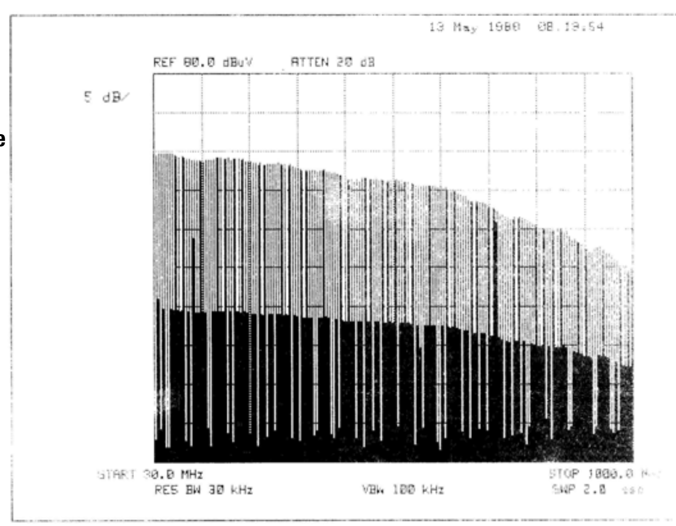
Note: Substitutions will have to be made for the Schottky and step-recovery diodes, as they are no longer available from HP/Agilent.

Wyatt/Chaney, RFI Measurements Using a Harmonic Comb Generator, RF Design Magazine, Jan. 1991

Comb generator output

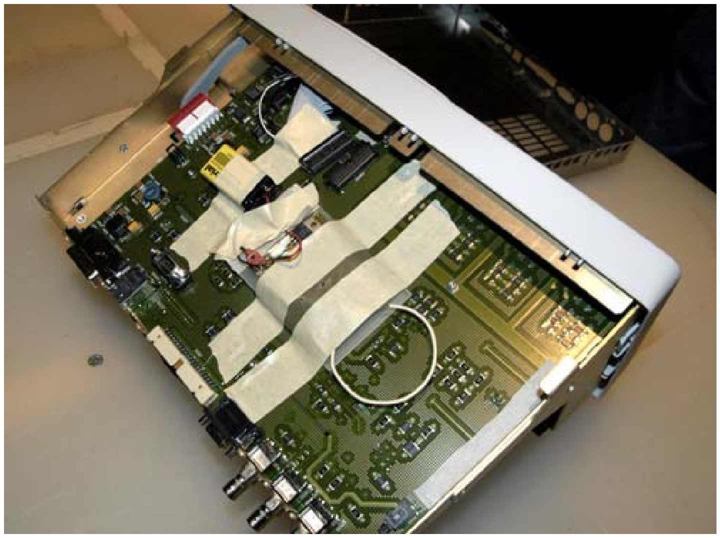
Direct output of the harmonic comb generator into a spectrum analyzer

30 to 1000 MHz
15 dB down @ 1000 MHz



Wyatt/Chaney, RFI Measurements Using a Harmonic Comb Generator, RF Design Magazine, Jan. 1991

Comb Generator Taped To Prototype Product



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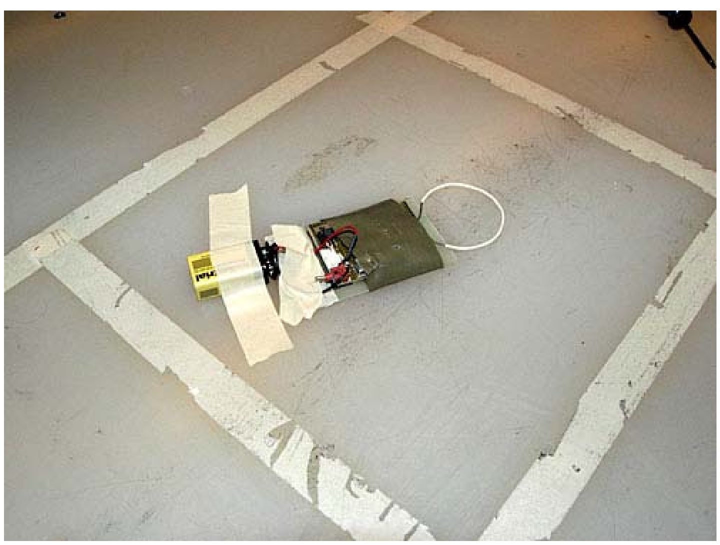
Then Comb Generator Is Measured Alone



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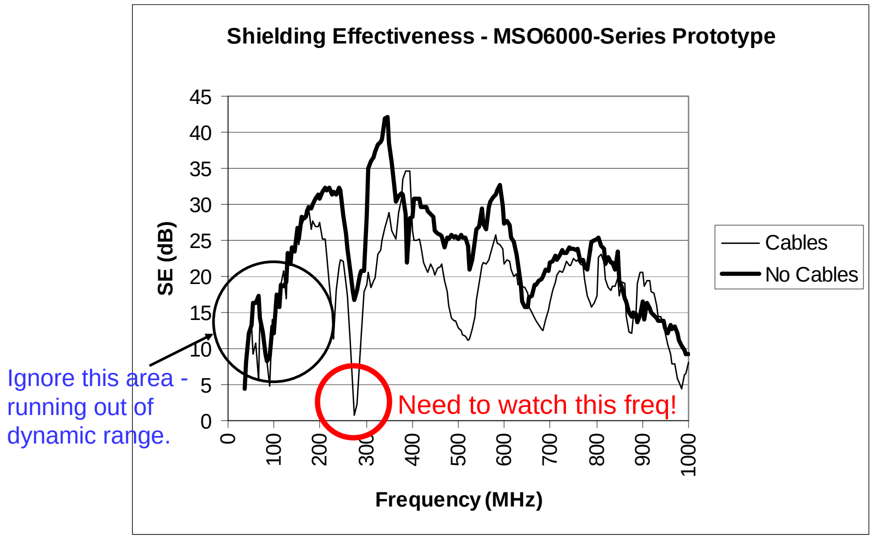
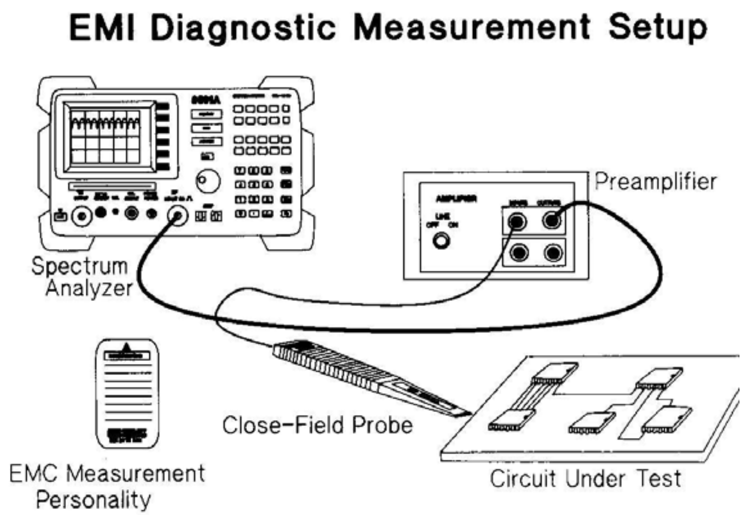
Shielding Effectiveness Plot Is The Difference!



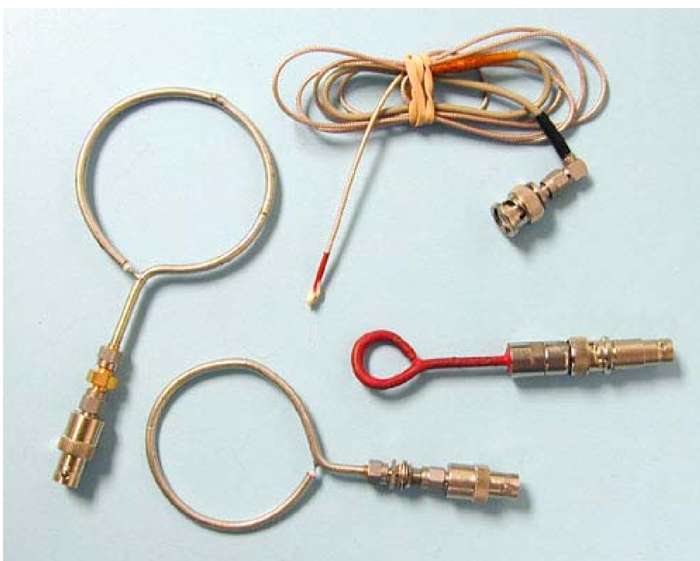
Use of a Basting Pan To Isolate Emissions From Product or Cables

Typical EMI Diagnostic Setup



Wilcox, A Design Process for Achieving Electromagnetic Compatibility, Compliance Engineering

Examples Of Home Made Loop (H-Field) Probes



Constructing a simple loop probe

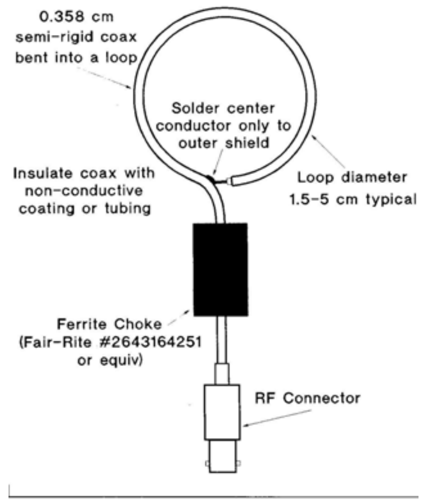
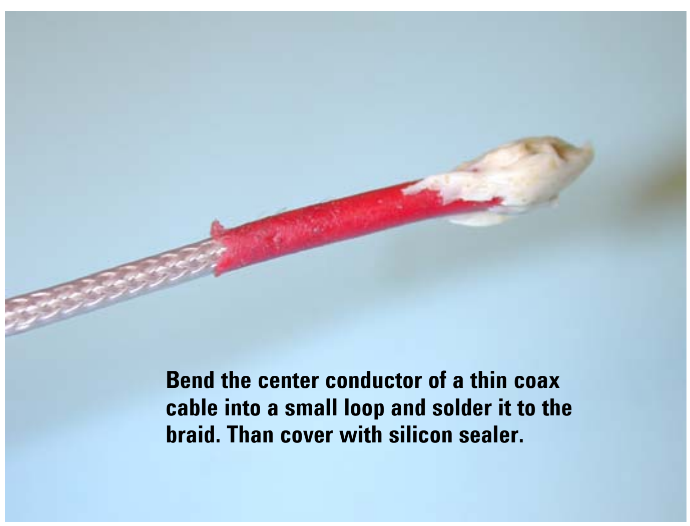


Figure 3. Simple, easy-to-make magnetic field probe.

Roleson, Finding EMI Resonances in Structures, EMC Test & Design, Jan/Feb 1992

"Mini" loop probe



Commercial Loop Probes

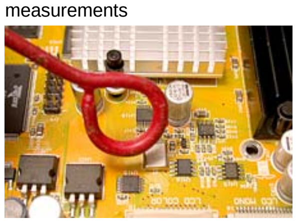
Commercial probes are available from several sources:

Beehive Electronics probes pictured...

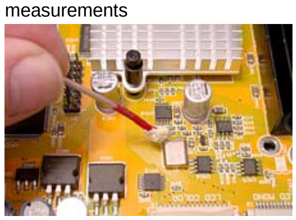
www.beehive-electronics.com

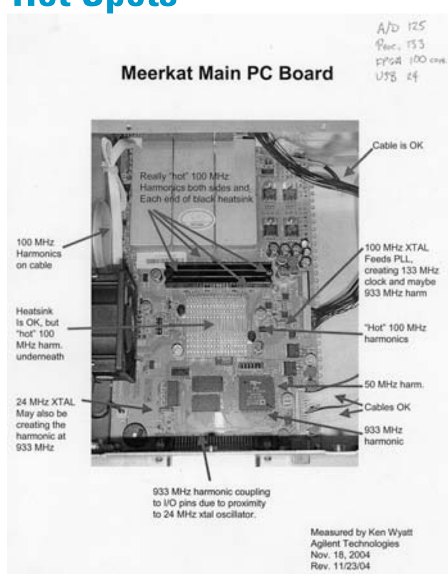
Mapping Of PC Board "Hot Spots"

½" Magnetic field probe for course measurements



"Micro" magnetic field probe for fine measurements

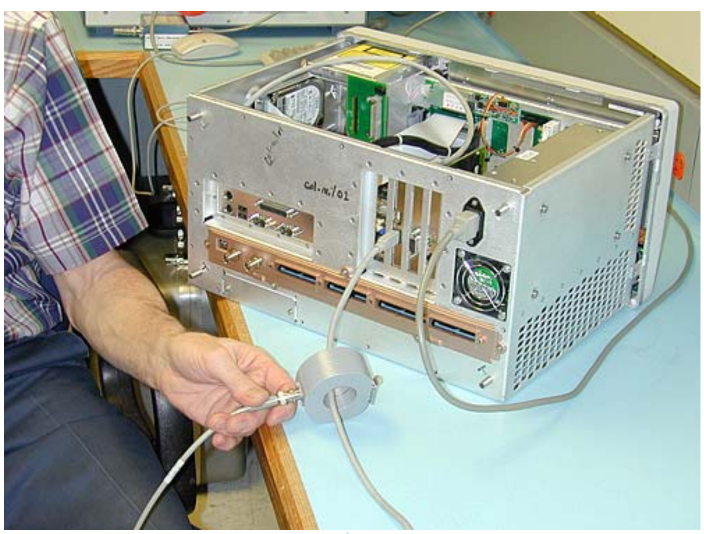




Examples of current probes

These may be used to measure high-frequency (common-mode) currents in cables

Using A Current Probe To Measure Cable Common-Mode Currents



Current Probe Transfer Impedance

Rather than carrying out a precise calculation, it is sufficient to measure the voltage with a known current and frequency passing through the probe.

This measurement is usually expressed as "transfer impedance" (Z_T).

$$\hat{Z}_T = \frac{\hat{V}}{\hat{I}}$$

Or, expressed in dB:

$$|\hat{Z}_T|_{\text{dB}\,\Omega} = |\hat{V}|_{\text{dB}\mu\text{V}} - |\hat{I}|_{\text{dB}\mu\text{A}}$$

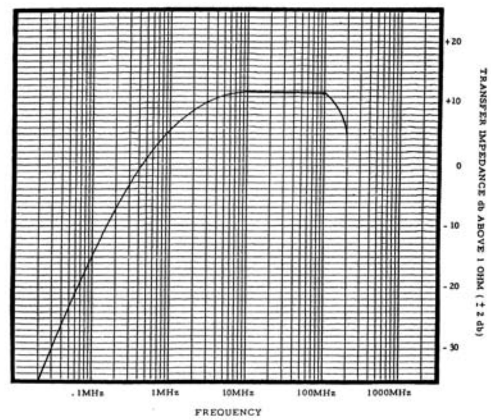


FIGURE 8.10 A typical measured current probe transfer impedance (courtesy of Fischer Custom Communications, Inc.)

Application Of The Current Probe - Example

For example, consider the problem of determining the level of probe voltage that will correspond to a CM current on a cable that would just meet the radiated emission regulatory limit.

Clamping the probe around a cable and lumping the net CM current into one wire of length L gives the net radiated emission a distance d away. Note we must divide Eq. 8.16 by 2, since that result was for *two* wires carrying a current of I_C. Assuming FCC-B limit at 30 MHz (100 uV/m) and 1m cable.

$$|\hat{E}_C|_{\max} = 6.28 \times 10^{-7} \frac{|\hat{I}_{C,\text{net}}| f \mathcal{L}}{d} \qquad (8.21)$$

$$|\hat{V}_{SA}|_{\text{dB}\mu\text{V}} = |\hat{I}|_{\text{dB}\mu\text{A}} + |\hat{Z}_T|_{\text{dB}\Omega} \qquad (8.22)$$

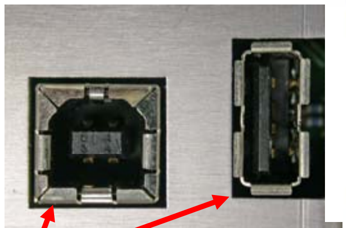
$$= 24\ \text{dB}\mu\text{A} + 15\ \text{dB}\Omega$$

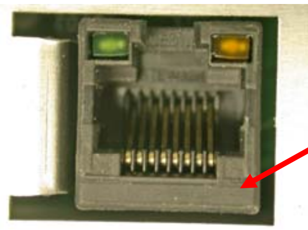
$$= 39\ \text{dB}\mu\text{V}$$

$$= 89\ \mu\text{V}$$

From: *Introduction to Electromagnetic Compatibility*, Paul

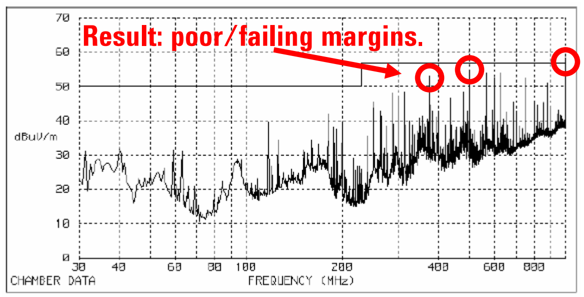
Importance of I/O Connector Grounds





LAN conn needs gnd shell.

Note a lack of good connection between chassis enclosure and connector ground.

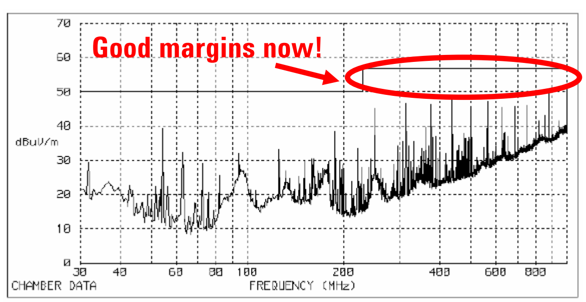


Results With I/O Cables Removed

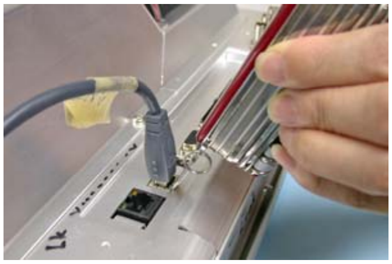
I/O and video cables removed.

Ferrite on fan cable (reduced 1 GHz).

Margins are improved by 10+ dB.



Result After Simple Connection to Chassis



Looking from 500 to 1000 MHz

Before **After**

Test setup:
Current probe on USB cable. Connection between connector ground shell and chassis enclosure made with screwdriver blade.

Some harmonics dropped by 10-15 dB!

Ferrite Chokes Block Common-Mode Currents

Often used on keyboard, mouse or video cables

Very useful for troubleshooting

Manufactures often provide free evaluation kits

Best used on low-Z cables

The Concept of the Image Plane

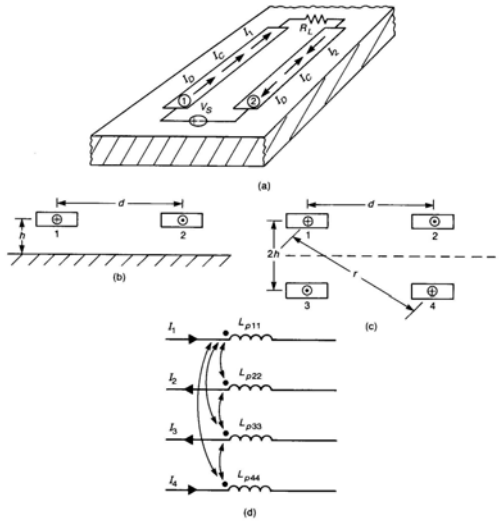


FIGURE 13.31 Use of an image plane to reduce the radiated emissions and ground drop of a PCB: (a) the board schematic; (b) the board cross section; (c) replacement of the image plane with images; (d) the partial inductance model.

The Concept of the Image Plane

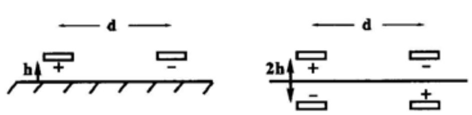


Figure 13 - Use of an image plane to cancel differential- and common-mode currents.

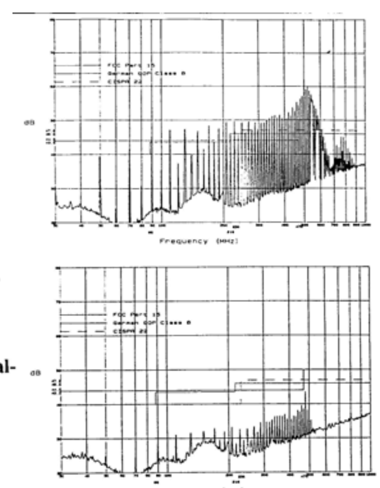
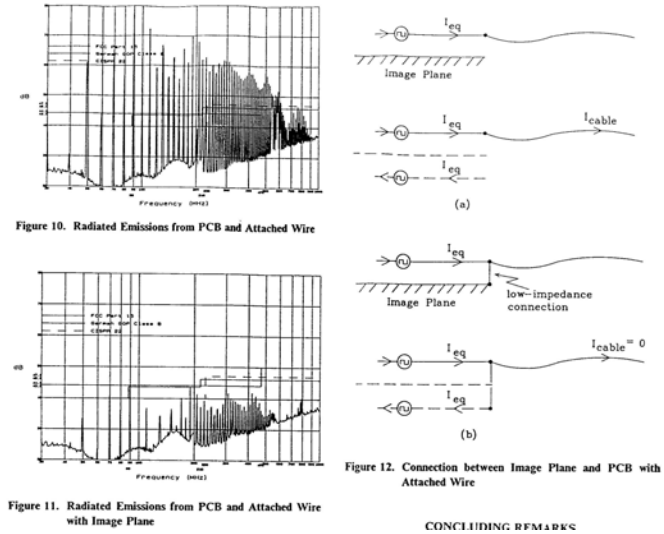


Figure 8. Radiated Emissions from PCB with Image Plane

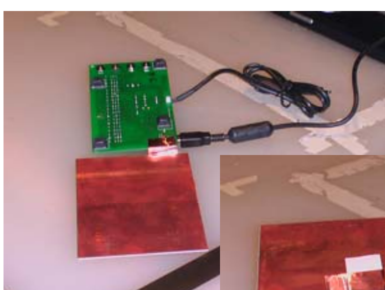
Ott/Paul/German, Effect of an Image Plane on Printed Circuit Board Radiation, International Symposium on EMC, 1990

The Concept of the Image Plane



Ott/Paul/German, Effect of an Image Plane on Printed Circuit Board Radiation, International Symposium on EMC, 1990

Use Of an Image Plane (IP) to Reduce Emissions



For troubleshooting purposes, attach IP near I/O connector ground and fold under PC board.

Ultimately, for this project, we only needed a ferrite on the USB cable.

An IP can reduce radiated emissions from PC boards by 8 to 15 dB. In practice, the IP can be the bottom layer of the PC board.

Line Cord Emissions

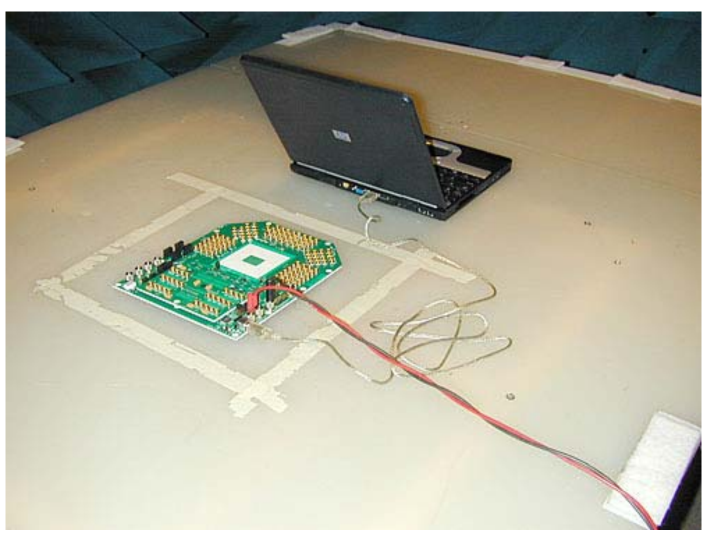
If the line cord is suspected of emitting HF harmonics, insert an external line filter in series

If the emission level (or measured common-mode current) drops, then you need to design in better line filtering

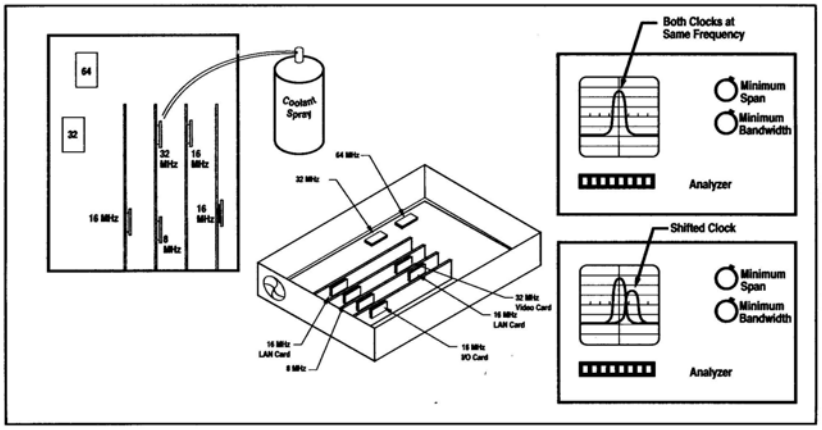
An external filter may be made with an extra power line filter module and spare line cord

Cut the cord down to minimal size and carefully solder the stripped ends to the filter, observing the correct connections. Wrap with electrical tape.

Testing A Bare PC Board For Radiated Emissions



Use coolant spray to determine which oscillator is contributing the most to the harmonic of concern

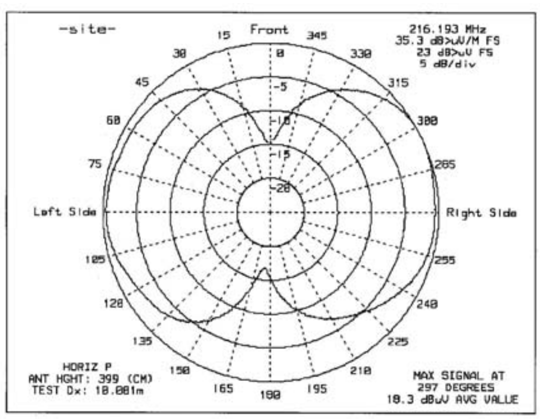


Example Of A Polar Plot - Wide Lobes

Emissions are coming from the sides of the product.

Single- or double-lobed plot is typical behavior at the lower frequencies (<300 MHz).

Probably due to cable radiation.



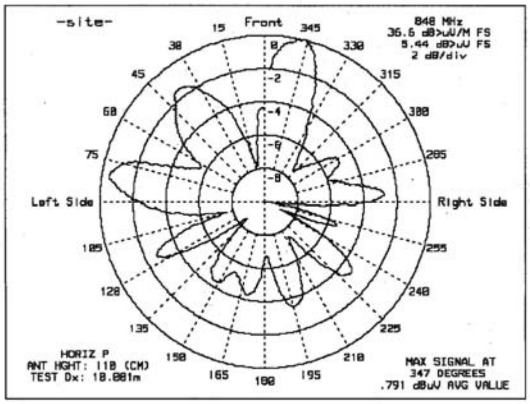
Polar plot at 216 MHz. Shape indicates a half-wave dipole antenna pattern.

Typical Polar Plot At Higher Frequencies - Narrow Lobes

Emissions are coming from all around the product

Typical behavior at the higher frequencies (>300 MHz)

Probably due to slot radiation.



Polar plot at 848 MHz. Pattern probably indicates slot radiation and multiple reflections.

Using a loop probe to measure resonances

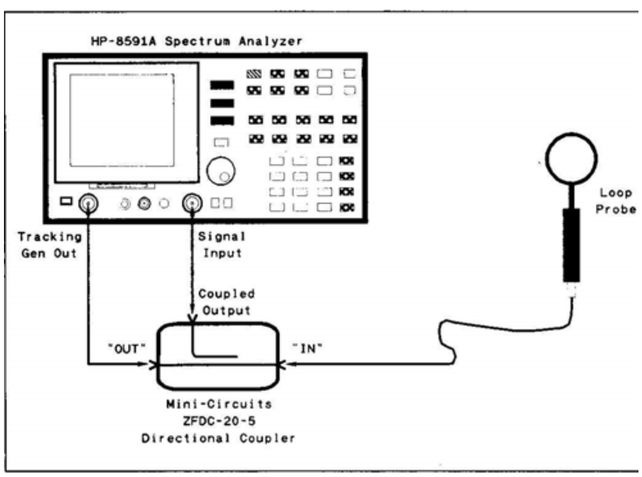


Figure 1. Setup for finding structural resonances.

Roleson, Finding EMI Resonances in Structures, EMC Test & Design, Jan/Feb 1992

Resonance measurement

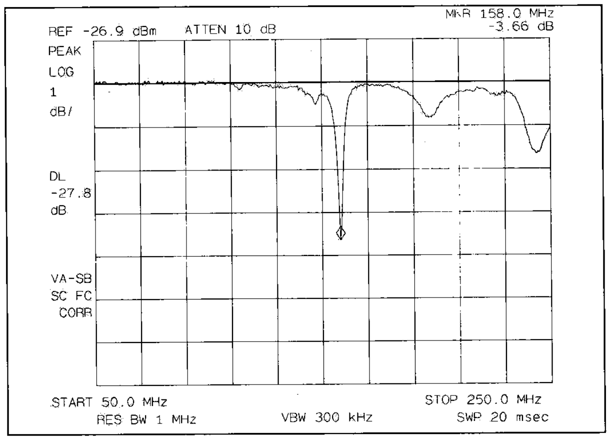


Figure 2. Structural resonances are shown as dips in normalized trace on spectrum analyzer display.

Roleson, Finding EMI Resonances in Structures, EMC Test & Design, Jan/Feb 1992

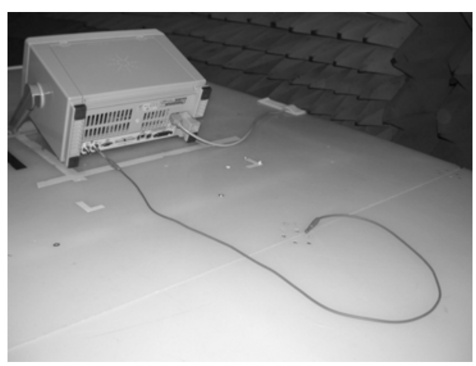
External clip lead

Useful for assessing proper signal return (or shield) connection back to enclosure

Connect 1m-long clip lead to various shield connection points on all I/O cable ports

Clamp a current probe around the cable (or measure the amount of radiated emissions)

If no current is detected or the clip lead has no effect on radiated emissions, that specific shield connection point is connected back to enclosure shielding OK

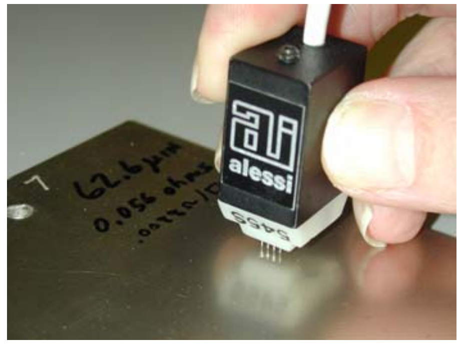


Plated shield resistivity measurement

Use of a "four-point" probe allows you to verify the sheet resistance, and hence the thickness of vapor-deposited (or plated) metallic shields.

A four-terminal DMM, such as the Agilent 34420A, is required.

By knowing the thickness, you can calculate the shielding effectiveness, given the manufacturer's equation.



Alessi 545S probe shown

Four Point Probe Method

Assuming a 4-pin collinear array with equidistant pins and a "thin" sample.

F2 = geometric correction factor (= 4.53 for probe << sample and a thin layer).

A "thin" conductive layer is defined as W << S.

Sheet Resistance (Rs) = 4.53 (V/I) (Ohms/square)

Resistivity (ρ) = 2 π s (V/I) (Ohm-cm, where s = point spacing in cm)

t = ρ/ Rs (cm)

Use Of A Differential Probe To Assess Seam Integrity

Connect a differential probe to a low-cost oscilloscope or spectrum analyzer

Place a probe tip on each side of an enclosure seam

If you measure an appreciable voltage difference, the seam connection is poor and may be a possible source of radiated emissions (*if seam length is greater than 1/20th of wavelength at frequency of interest*)

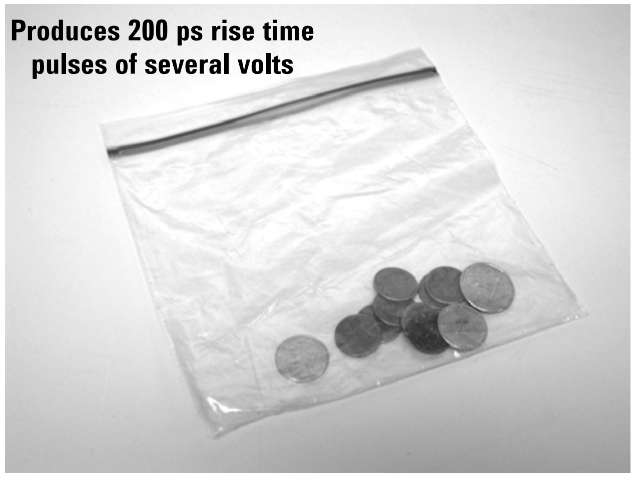
Use Of A Differential Probe To Assess PC Board "Noise"

Connect a differential probe to a low-cost oscilloscope or spectrum analyzer

To measure ground plane noise, probe different points on the ground plane

To measure the effectivity of your bypass caps, probe from V*source* to V*return* at some distance from each high-risk IC.

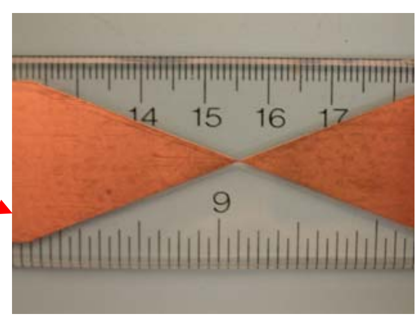
Simple ESD Source – Coins In ZipLok Bag (Simulates Pocket Change)



Idea, courtesy of Doug Smith (www.emcesd.com)

Simple ESD Source – Spark Gap Ruler

Produces 200 - 500 ps rise time pulses of several volts



Idea, courtesy of Doug Smith (www.emcesd.com)

EMC Management Recommendations

- Identify a regulatory point of contact within the design team
- Develop EMC design goals (6 dB margin for sample of five)
- Perform margin testing, rather than testing to limits
- EMC engineer is a part of the project management team
- Make early design reviews part of the product generation process