Troubleshooting Today's EMI Issues

presented by:

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 TodaysEMI:1

You might be an EMC engineer if…

- You expect your child's grades to always be 6 dB better than last years…
- You are asked to leave Best Buy because you turn over all the products to check the labels…
- Your home TV has the worst reception in the neighborhood…

 TodaysEMI:2

Today's EMC issues

- ✓ Radiated emissions (RE)
- ✓ Radiated immunity (RI)
- ✓ Electrostatic discharge (ESD)

Why?

- Violation of best engineering practices for EMC
- Lower IC supply voltages: 5 > 3.3 > 1.8 > etc.
- More low cost mobile devices
- Proliferation of wireless and high power transmitters

Troubleshooting radiated immunity

Why do products radiate?

- Energy + Coupling Path + Antenna = EMI

Take away any of the three elements and no EMI…

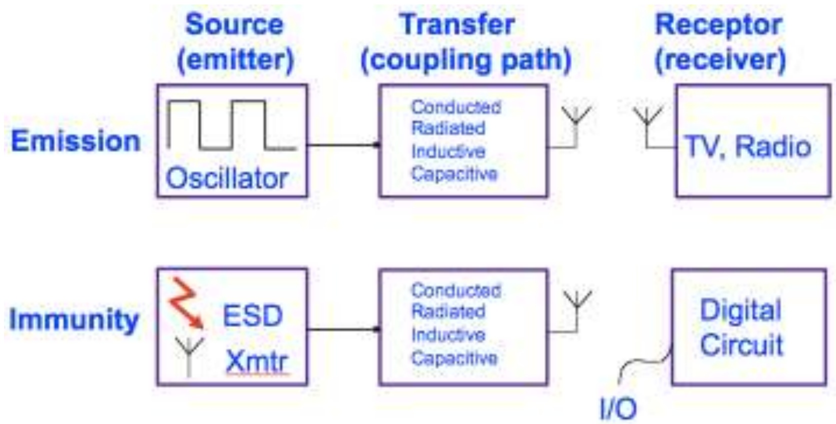
- No energy >>> No EMI
- No coupling path >>> No EMI
- No antenna >>> No EMI

Common issues leading to radiated emissions

- Discontinuous current return paths
- Poorly-terminated I/O cable shields
- Slot radiation from shields

All the above can cause radiated emissions and allow susceptibility from radiated sources and ESD

Source - path - receptor model



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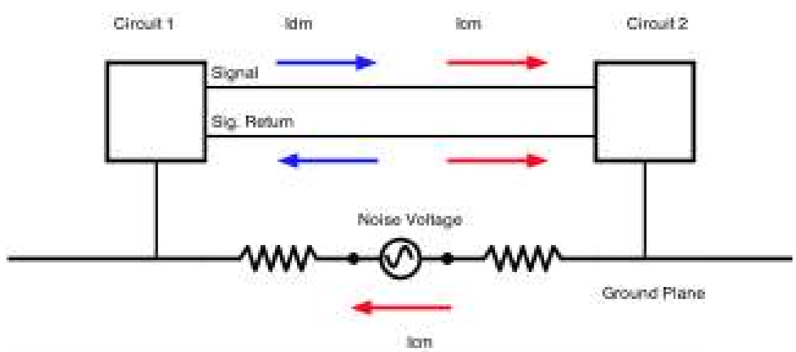
Differential versus common-mode currents



Any voltage difference between two circuit reference points ("grounds") will drive common-mode currents between the signal and return wires.

 TodaysEMI:8

Differential-mode emission equation (over a reflecting surface)

$$\left|E_{D,\max}\right| = 2.63 \times 10^{-14} \frac{\left|I_D\right| f^2 L s}{d}$$

High frequency currents in a LOOP

Assuming electrically short lengths, (*L< half wavelength)*.

To reduce E_D, we can:

1. Reduce the current level (also by slowing rise times)
2. Reduce the loop area

Note the relatively small factor 1x10^{-14}

Common-mode emission equation

$$\left|E_{C,\max}\right| = 1.257 \times 10^{-6} \frac{\left|I_C\right| f L}{d}$$

High frequency currents in a WIRE

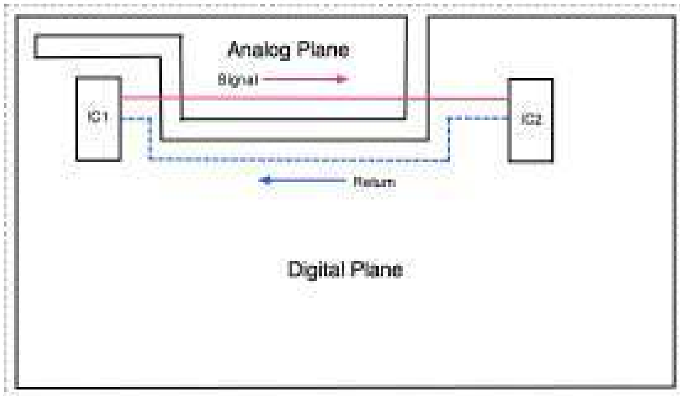
Assuming electrically short length, *(L< half wavelength)*.

To reduce E_C, we can:

1. Reduce the current level (also by slowing rise times)
2. Reduce the line length (shorter PC traces)
3. Diverting or blocking the current

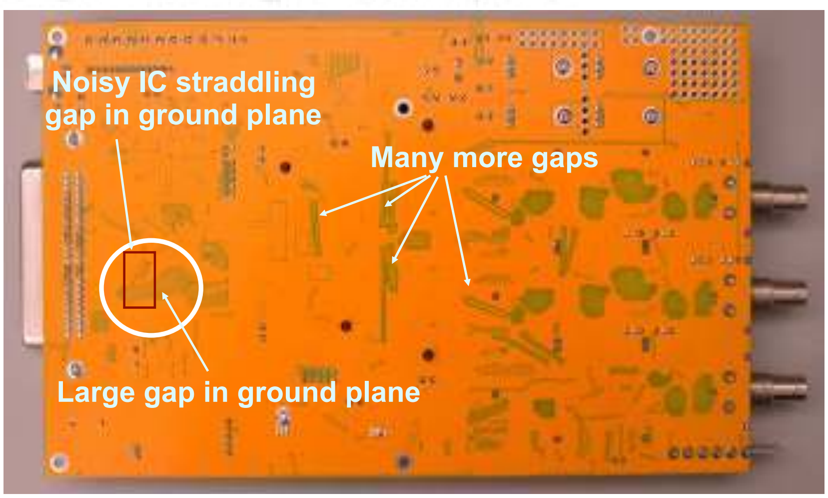
Note the relatively larger factor, 1x10^{-6}

Discontinuous current return paths



Routing a trace over an unrelated (e.g. analog) plane can cause noise coupling to other circuitry. Digital traces should never cross analog planes or gaps in the signal return plane.

Gaps in the signal return plane



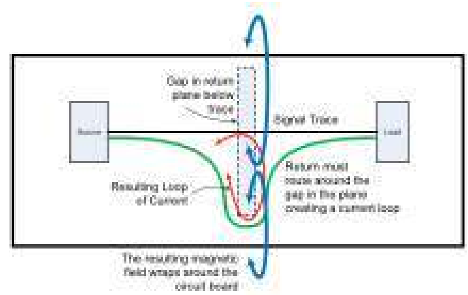
Temporary bridge with copper tape reduced emissions 17 dB!

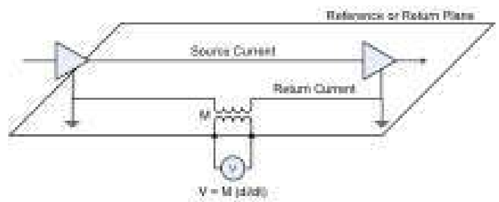
Generation of common-mode emissions

Differential-mode (signal) current always flows in a loop.

Any gap in the return plane forces the return current to create a “loop antenna” effect, creating a mutual inductance (M), which induces a potential, V, thereby creating an on-board common-mode source.

This voltage source “pushes” common-mode currents throughout the PC board and onto I/O cables causing them to radiate, PLUS, the magnetic fields wrap around large sections of the board inducing noise into other circuit traces.



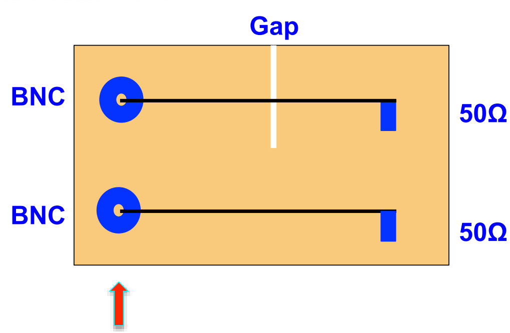


Demo - gap in return plane

High-frequency traces crossing gaps in the return plane can lead to:

- An increase in radiated emissions
- An increase in radiated susceptibility
- An increase in ESD susceptibility

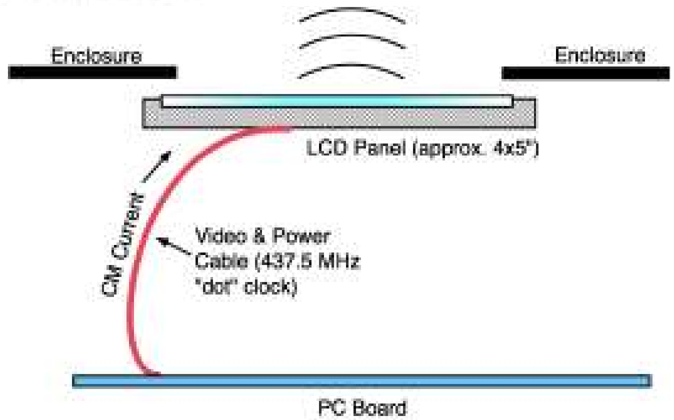
We’ll use a loop probe to measure & compare the signal level along a transmission line with- and without a slot cut in the signal return plane.



Injecting 3V, 2ns pulse train into either the gapped or un-gapped trace. Simulation of a high speed digital signal. The gap is 5 cm long.

Idea courtesy, Doug Smith, http://www.emcesd.com

LCD emissions



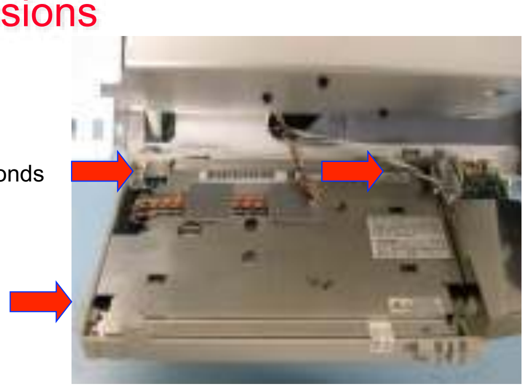
Display cable radiates and excites the metal LCD housing.

Solution: bond the LCD housing to the enclosure in multiple points.

LCD emissions

Existing bonds

Bond 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.

CM currents get returned to the enclosure. Could also be resonance of the LCD panel.

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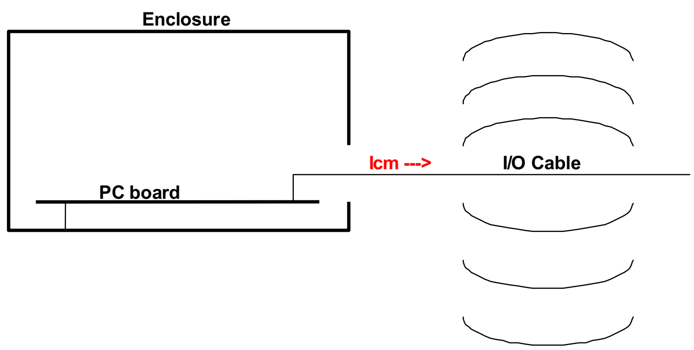
Never penetrate a shield with a wire or cable



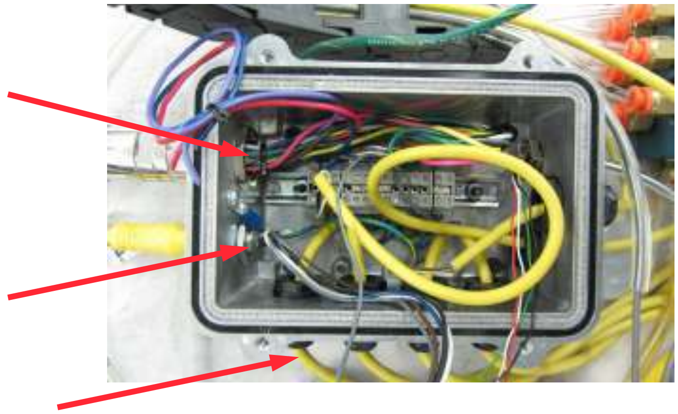
Penetrating a shield with a wire defeats the shield!
Noise currents on the inside will couple to the wire and travel outside the shield, causing radiated emissions. Transmitters on the outside may interfere with circuits.

Poor cable shield bonding to enclosure

Poor cable shield bonding – cable shield disconnected.

Good cable shield bonding – cable shield connected to chassis.

Poor cable shield bonding to enclosure



Poor cable shield bonding – cable penetrating through metal enclosure.

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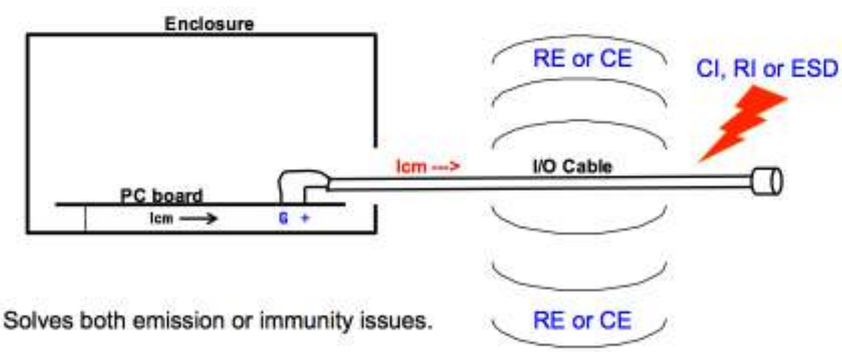
Poor cable bonding – pigtail 1

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



Solves both emission or immunity issues.

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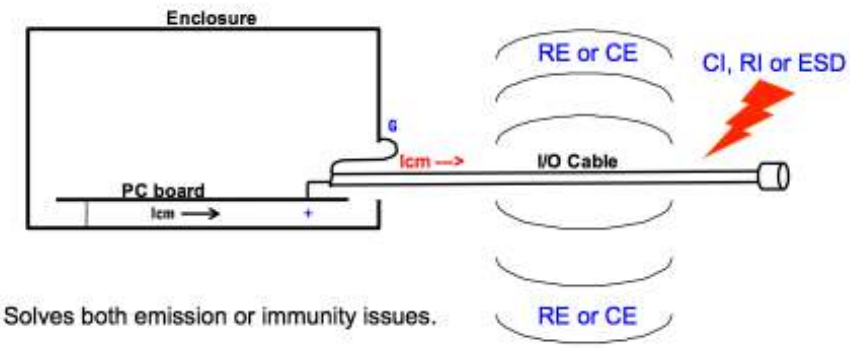
Poor cable bonding – pigtail 2

Divert the current back to the shielded enclosure

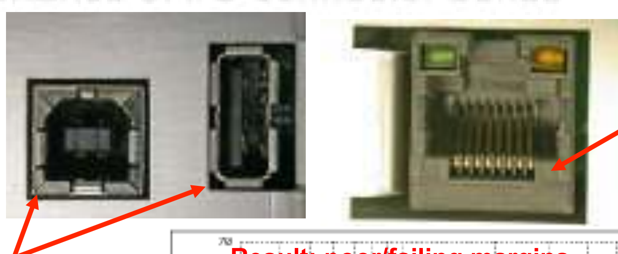
- Proper termination of the cable shield back to the enclosure is the key

Block the current with a high-impedance ferrite choke



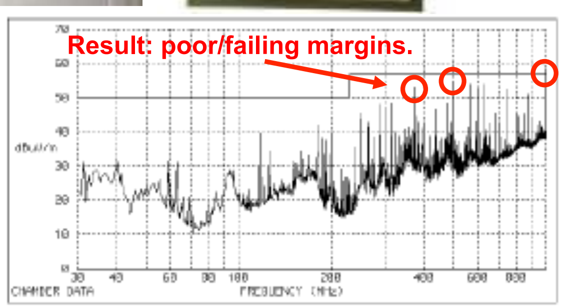
Solves both emission or immunity issues.

Importance of I/O connector bonds



Ethernet connector needs gnd shell.

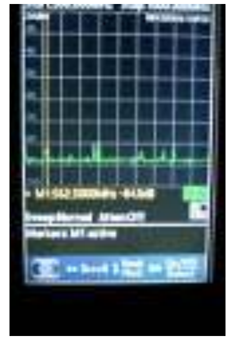
Note a lack of good connection between chassis enclosure and connector ground shell.



Result after simple connection to chassis

Looking from 500 to 1000 MHz

Before

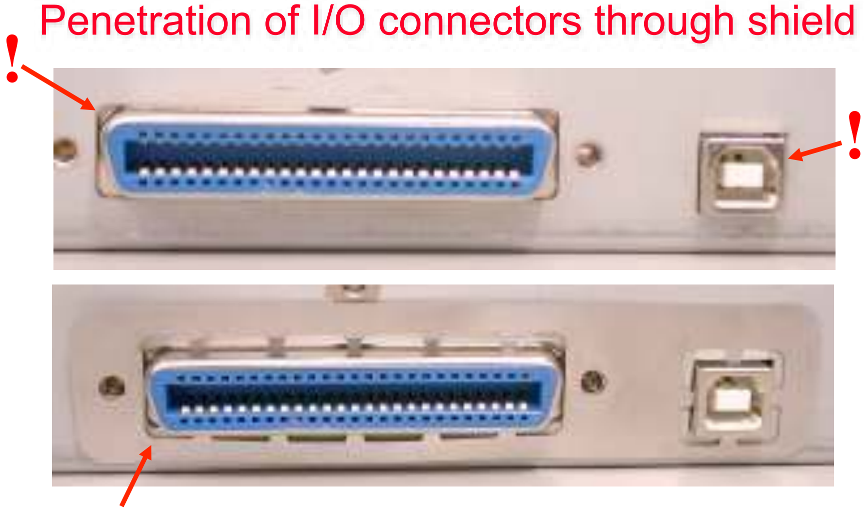


After

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!

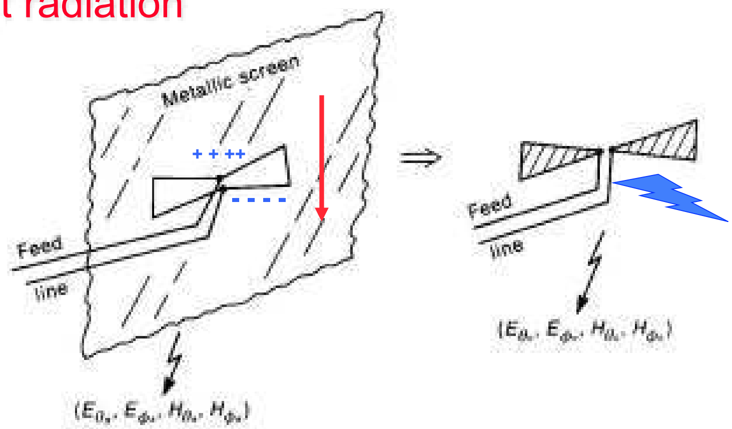
Penetration of I/O connectors through shield



Shim with fingers added to shunt internal noise currents.

Slot radiation

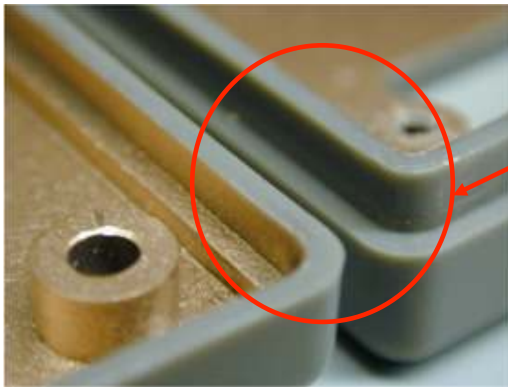
Babinet's Principle states a slot or seam can be modeled as a dipole antenna.



Currents perpendicular to slots will excite the slot the same as a dipole antenna.

Shielding - slot caught during design review

Shielding - poor shield integrity



Attempt at shielding module failed to connect halves!

Module halves copper-plated

Troubleshooting radiated emissions

1. Near-field probes (E and H-field)
2. Current probes
3. Simple antennas

May be used to help pinpoint emission sources and assist in the troubleshooting process.

However, not all sources located are propagating structures (antennas)!

Use near field probes to identify possible sources

Not all potential sources will be radiating structures – depends on wavelength.

http://www.edn.com/electronics-blogs/the-emc-blog/4414975/Identifying-emission-sources-and-propagating-structures

DIY loop probes

DIY H-field probes made from semi-rigid coax. Bend into a round (or square) shape and solder center conductor to outer shield. A ferrite choke around the handle helps block common-mode currents.

An E-field probe may be made by simply stripping off a little of the shield, allowing the center conductor to be exposed.

Commercial near-field probes

Commercial probes are available from several sources:
Beehive Electronics probes pictured…($295/set of four).
www.beehive-electronics.com

DIY current probes

Cores used were Würth Elektronik #74270097 (material 4W620, useful from 10 to 1000 MHz).

14 turns #22 Teflon insulated.

Shield with copper or aluminum foil – split around inside of core for e-field shielding. Wrap with insulating tape.

Homemade current probes work well from 10 to 1000 MHz
(shown prior to E-field shielding with copper tape and insulation).

More info: http://www.interferencetechnology.com/the-hf-current-probe-theory-and-application/

DIY current probes

Cores used were older Steward clamp-on ferrite chokes, but other brands should work as well.

7 turns #22 Teflon insulated.

Use epoxy to hold the turns tight and to mount the BNC connector.

Homemade current probes work well from 10 to 250 MHz.

More info: http://www.interferencetechnology.com/the-hf-current-probe-theory-and-application/

Commercial current probes

Use a current probe to measure common mode currents on cables.

This may be used to estimate the E-field at some distance from the cable.

For more information, refer to the article.

Commercial current probe from Fischer Custom Communications (1 to 250 MHz).

More info: http://www.interferencetechnology.com/the-hf-current-probe-theory-and-application/

Current probe transfer impedance

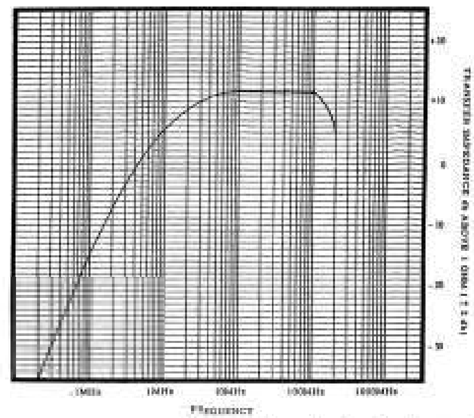
Rather than carrying out a precise calculation, it is sufficient to measure the voltage with a known current and frequency passing through the probe.

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

$$Z_T = \frac{V}{I}$$

Or, expressed in dB:

$$|Z_T|_{dB\Omega} = |V|_{dB\mu V} - |I|_{dB\mu A}$$



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

EMI antennas made from TV antennas

“Bow Tie” UHF antenna
(300 to 800 MHz)

Note: solder in a TV-grade balun assembly to ~match 50 ohms

Adjustable “precision” dipole
(65 to 200 MHz)

Note: BNC connector is soldered directly to the dipole elements.

PC board antennas

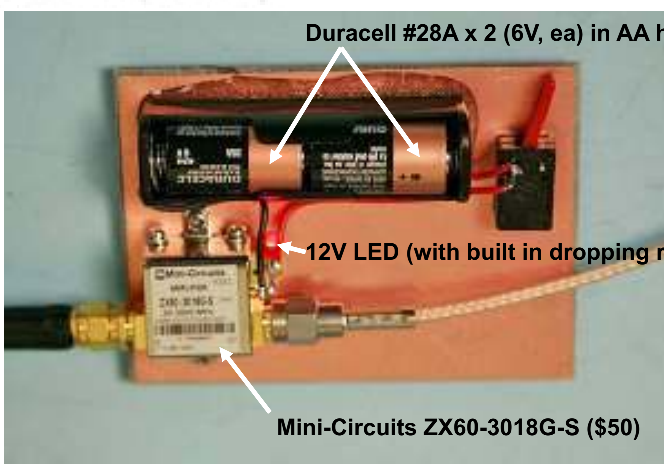
PC board log periodic antennas (ranging from 400 MHz to 11 GHz shown). Approximate gain is 6 dB. Available from www.wa5vjb.com/.

400 to 1000 MHz LP antenna on DIY mount and table-top tripod ($40).

Cost ranges from $7 to $28.

http://www.edn.com/electronics-blogs/the-emc-blog/4403451/PC-board-log-periodic-antennas

Broadband preamp



Broadband preamplifier for close-field probes (if needed)

Commercial Preamplifier

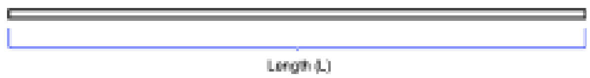
Beehive preamplifier, gain 30 dB, 4-5 dB NF, $525.
Courtesy, Beehive Electronics.

Commercial Preamplifier

Com-Power preamplifier, gain 21 dB, 10 – 1000 MHz, $475
(Measured range was 3 MHz to 1.5 GHz+).

http://www.edn.com/electronics-blogs/the-emc-blog/4403427/Review--Com-Power-PAP-501-broadband-preamp

Resonance effects - cables & structures

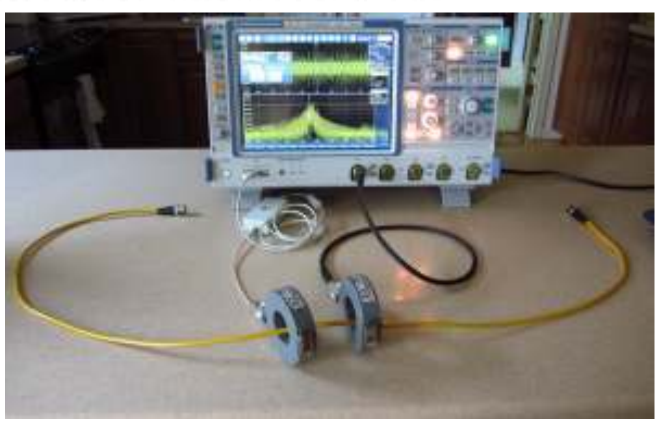


In free space: $\lambda(m) = {}^{v}/_{f(Hz)} = {}^{3\times10^{8}}/_{f(Hz)}$

Metal structures or lengths of cable may resonate efficiently in multiples of 1/2 wavelength.

GHz clocked processors can induce resonances (in the range 1 to 3 GHz) on the tines of large heat sinks. Bonding to the signal return plane (in multiple points) is the typical fix.

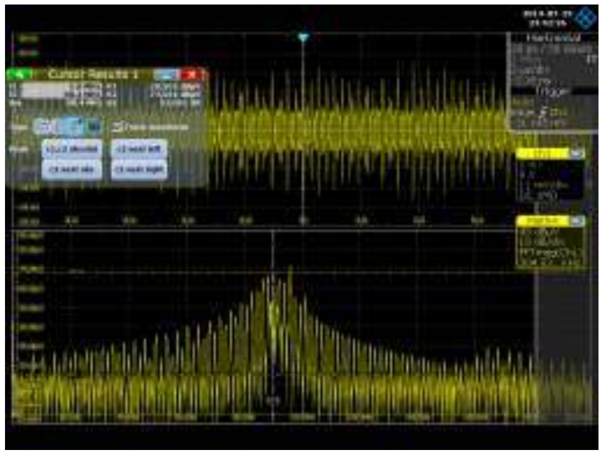
Measuring cable resonance



Use a harmonic comb generator and current probes to measure cable resonance.

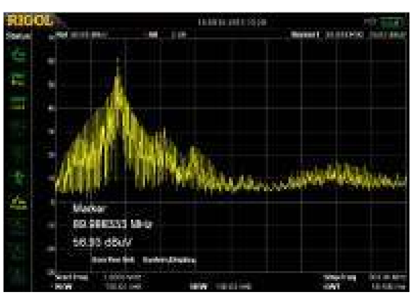
Ref: http://edn.com/electronics-blogs/the-emc-blog/4423597/Measuring-resonance-in-cables

1.3m cable (88.4 MHz resonance)



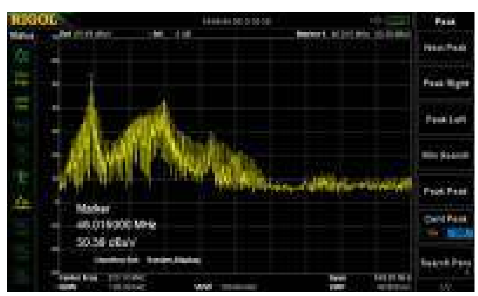
Resonance effects - cables & structures

Half-wave resonance of 90 MHz.



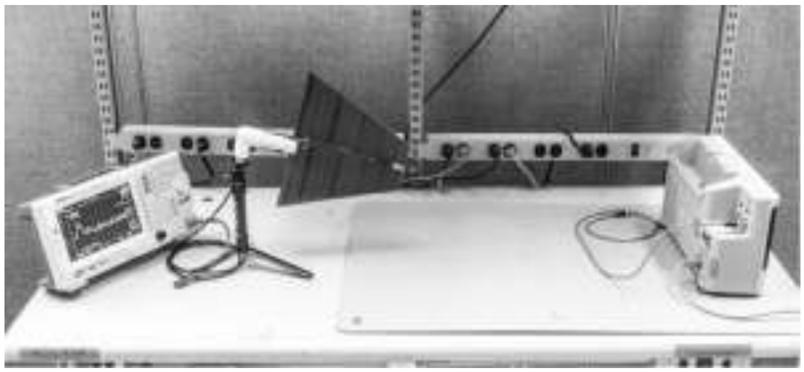
A 1.3m cable in "free space" (laying on a wooden table) resonates about 90 MHz. Because the propagation velocity in copper wire is about 0.8 compared to the speed of light, this ½-wave resonance is lower than the expected 115 MHz.

Quarter-wave resonance (with image reflected) of 46 MHz.



With the same 1.3m cable connected to an instrument, such that it's now resonating at ¼-wavelength with an image reflection in the shielded enclosure.

Setting up for a RE troubleshooting test



Ref: http://edn.com/electronics-blogs/the-emc-blog/4430335/Troubleshooting-EMI-on-your-bench-top

Radiated emission pre-compliance test

3m test range set up in an office.

Radiated emission pre-compliance test

3m test range set up in a conference room.

Troubleshooting radiated immunity

Discussion topics

Using unusual RF radiation sources to evaluate product susceptibilities

Use of RF signal generators with near field probes to generate a localized field

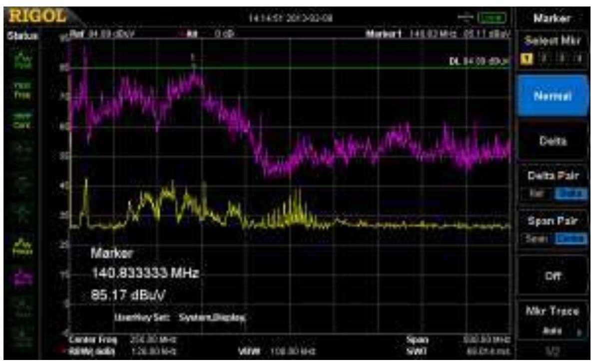
New low-cost RF synthesizers can replace bench top generators

3-volt motor

1 MHz to 1 GHz

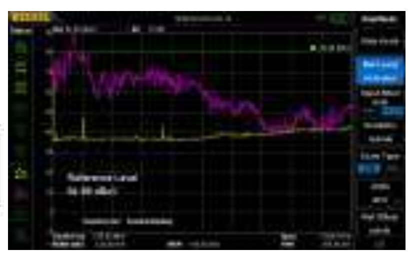
A small DC motor can generate a lot of broadband noise. Holding the power wiring close to product circuitry can reveal weaknesses in the design.

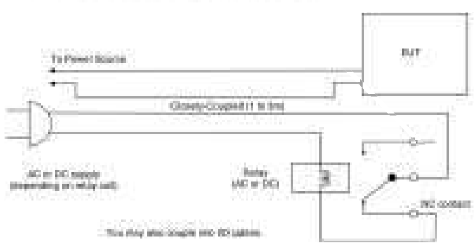
Dremel tool



A Dremel tool can generate a lot of broadband noise. Holding the power wiring close to product circuitry can reveal weaknesses in the design.

Chattering relay





A chattering relay made be constructed easily from a heavy-duty relay. By coupling the power cable to the product under test, a strong wideband field will be produced. Be sure to insulate the relay contacts if using line voltage.

License-free 2-way radios

By using an small FRS (Family Radio Service) transmitter at about 465 MHz, many radiated immunity issues may be discovered.

E-field versus power output

Calculating E-field from *Pout*

$$V/m = \frac{\sqrt{30 * Pout * Gain_{Numerical}}}{meters}$$

Pout (W)	V/m at 1m	V/m at 3m	V/m at 10m
1	5.5	1.8	0.6
5	12.3	4.1	1.2
10	17.4	5.8	1.7
25	27.5	9.2	2.8
50	38.9	13.0	3.9
100	55.0	18.3	5.5
1000	173.9	58.0	17.4

Chart of calculated E-fields in V/m (assuming antenna gain = 1)

License-free 2-way radios (V/m) - calculated

Device	Approx Freq	Max Power	Approx V/m at 1m
Citizens Band	27 MHz	5W	12
FRS	465 MHz	500 mW	4
GMRS	465 MHz	1 to 5W	5.5 to 12
3G Mobile Phone	830 MHz / 1.8 Ghz	400 mW	3.5

Chart of calculated E-fields in V/m

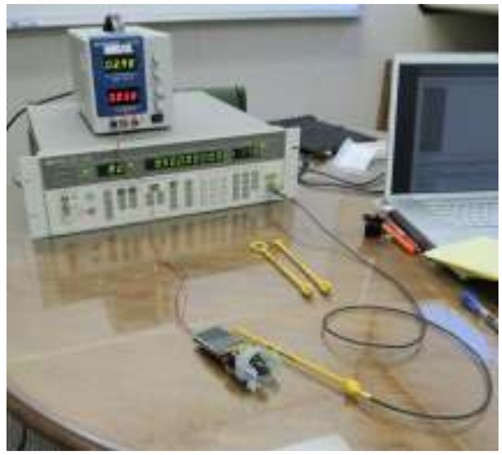
License-free 2-way radios (V/m) - measured

Device	Approx Freq	Max Power	Approx V/m at 1m
Citizens Band (HT)	27 MHz	4W	3
FRS	465 MHz	0.5W	2
915 MHz FHSS	915 MHz	0.5	3
3G Mobile CDMA Phone*	850 / 1900 MHz	300 mW, peak	Too small to measure

Chart of measured E-fields in V/m

* At two inches, the mobile phone registered 0.5 to 2 V/m

RF generators and near field probes



By connecting an RF generator to an E-field or H-field probe, you can generate very high localized fields.

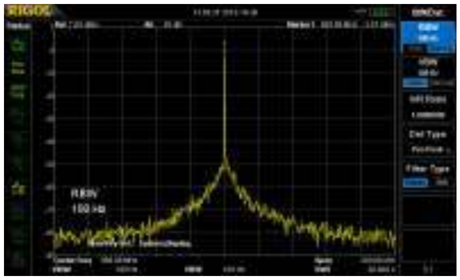
Low-cost RF synthesizer (TPI)

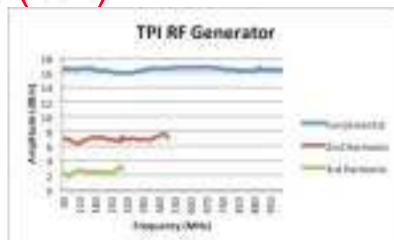
Recently, there have been low-cost PC-controlled RF synthesizers available. This one produces up to +17 dBm from 35 to 4400 MHz ($200). USB-powered (PC).

Available from: Trinity Power, Inc., www.rf-consultant.com. See the review article here:

http://www.edn.com/electronics-blogs/the-emc-blog/4423710/Review--inexpensive-RF-generator

Low-cost RF synthesizer (TPI)





Typical RF output spectrum.

Note that the harmonic distortion isn't the best, but the second-order harmonic is 10 dB down.

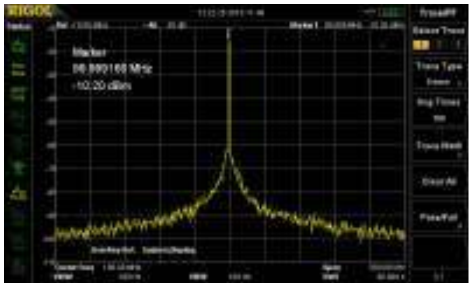
RF synthesizer with AM/pulse modulation

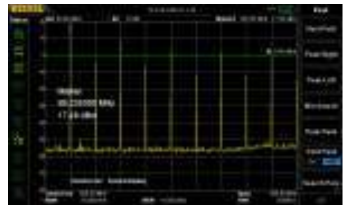
Here's another moderate-cost PC-controlled RF synthesizer. This one produces up to +19 dBm from 35 to 4400 MHz and also includes AM and pulse modulation, along with network analyzer and power meter features ($599). USB-powered (PC).

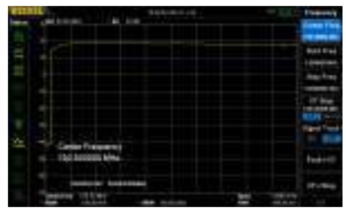
Available from: Windfreak Technology, www.windfreaktech.com. See the review article here:

http://www.edn.com/electronics-blogs/the-emc-blog/4424843/Review--Windfreak-Technologies-SynthNV-RF-generator--Part-1-

RF synthesizer with AM/pulse modulation







Typical RF output spectrum.

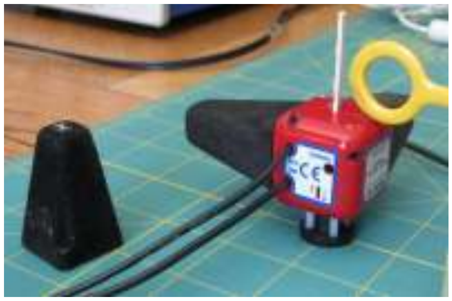
Because this synthesizer uses the same IC as the TPI design, the harmonic distortion is similar.

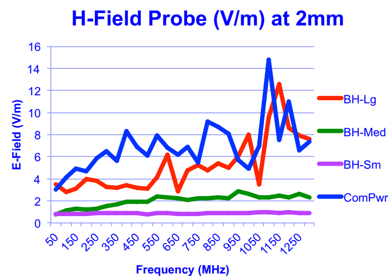
The RF amplitude is fairly flat with frequency.

RF synthesizer with AM/pulse modulation

Using the Windfreak Technologies "SynthNV" to test radiated immunity.

Measured field level from H-field probes

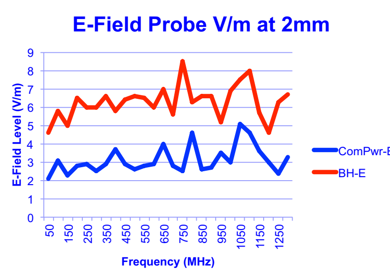




An ETS-Lindgren field sensor was used to measure the levels from several H-field probes*. The probes were driven by the TPI synthesizer at +17 dBm output with the probe about 2mm from the sensor antenna (to try and duplicate the field level when probing circuit traces.

*Beehive Electronics and Com-Power H-field probes were used.

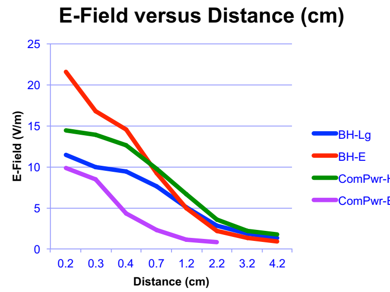
Measured field level from E-field probes



An ETS-Lindgren field sensor was used to measure the levels from several E-field probes*. The probes were driven by the Windfreak SynthNV synthesizer at +19 dBm output with the probe angled to match a realistic coupling and about 2mm from the sensor antenna (to try and duplicate the field level when probing circuit traces.

*Beehive Electronics and Com-Power E-field probes were used.

Field level versus distance (cm)



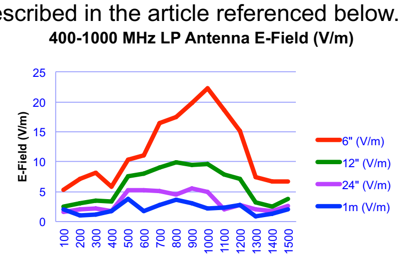
To investigate just how localized the field actually was, each probe* was measured at increasing distances from the field sensor. The closest the probe could get to the sensor antenna element was 2 mm.

*Beehive Electronics and Com-Power H-field probes were used.

Low-cost broadband antenna

This 400-1000 MHz, 6 dB gain, PC board log-periodic antenna may be used to apply a limited strength RF field over a wider area of your product.

The price is $28 and table top tripod is about $50. The antenna holder is described in the article referenced below.



Available from www.wa5vjb.com

NOTE: Be sure to perform this test in a shielded chamber to avoid interfering with other services!

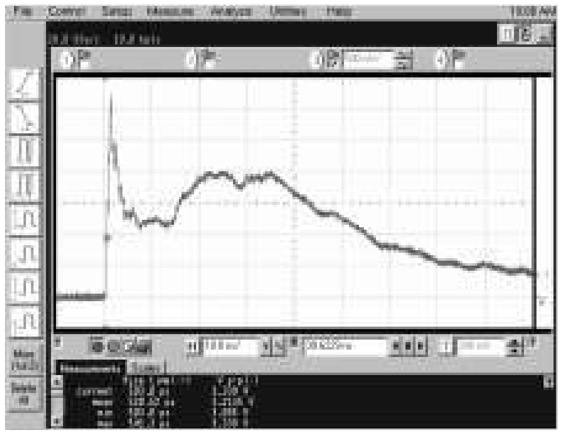
See review article: http://www.edn.com/electronics-blogs/the-emc-blog/4403451/PC-board-log-periodic-antennas

Summary…

- RF generators can drive near E-field or H-field probes to create strong localized E-fields for pre-compliance testing.
- Low-cost RF synthesizers may replace larger bench top instruments.
- Localized RF fields of 2 to 15 V/m may be generated to help diagnose radiated immunity issues with a product.
- *When using an antenna for pre-compliance testing, you should perform the testing inside a shielded chamber to avoid potential interference to other services.*

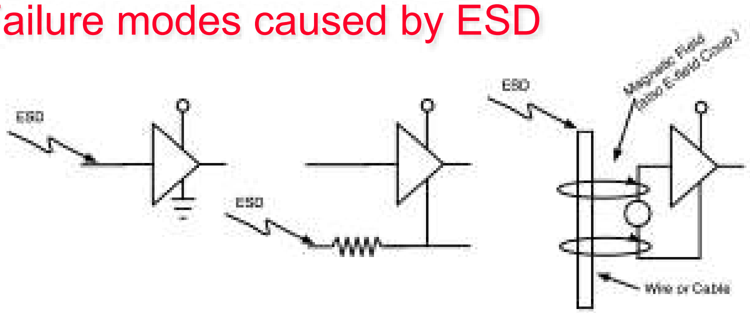
Troubleshooting ESD

Typical ESD waveform



Rise time is approximately 500 ps at over 30 amps, peak.

Failure modes caused by ESD



Direct discharge into circuit

Direct discharge into signal return

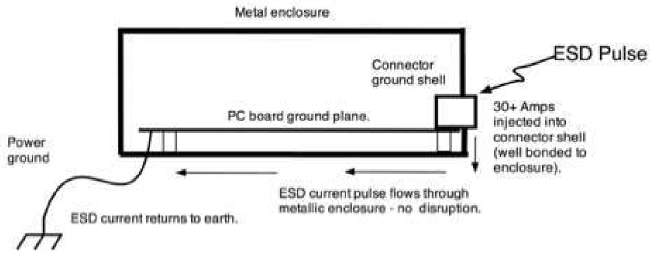
Indirect discharge (both H & E fields)

- 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

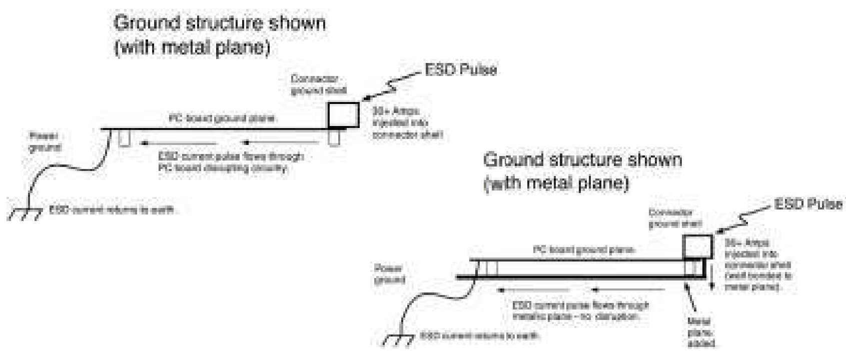
Electrostatic discharge

Ground structure shown
(with metal enclosure)



The very best protection from ESD discharges is to use a shielded enclosure and ensure all I/O connectors are well bonded to the enclosure.

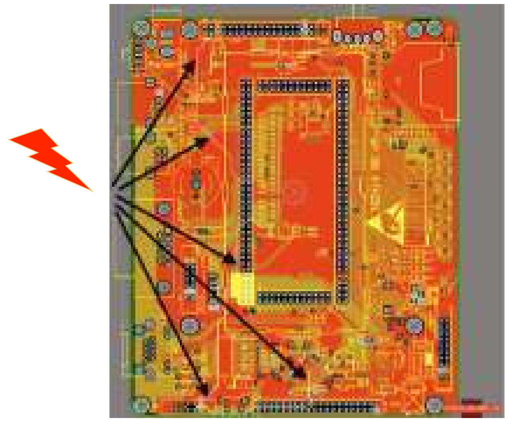
Electrostatic discharge



Identify the path of ESD current and then design an alternate (safer) path around your electronics.

Alternatives: common-mode filtering and transient protection.

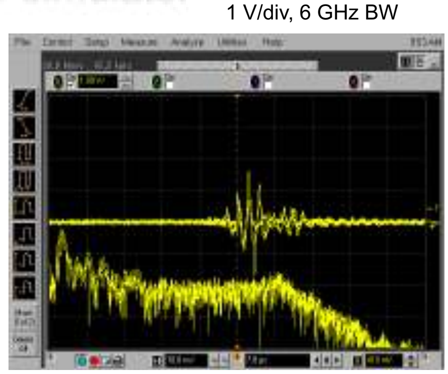
CPU reset line



ESD coupling to processor reset line. Reduce length and filter at CPU.

Inexpensive DIY ESD simulator

1 V/div, 6 GHz BW



BBQ Igniter - the piezoelectric action produces an intense ESD arc at the tip of the igniter (100 to 500 ps rise times). Attaching a coil of wire will radiate a strong H-field into the circuit or device under test.

Another inexpensive ESD generator

500 mV/div, 6 GHz BW, <30 ps!

Jiggling a few coins inside a ZipLok bag will produce rise times of 30 to 500 ps at several volts!

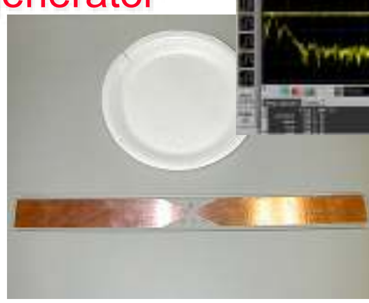
Idea courtesy, Doug Smith, http://www.emcesd.com

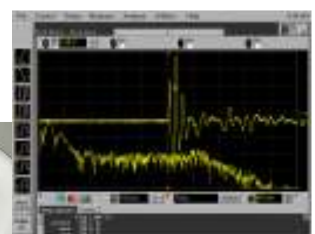
Spark gap ESD generator

"Doug Smith" spark gap ruler.
www.dsmith.org

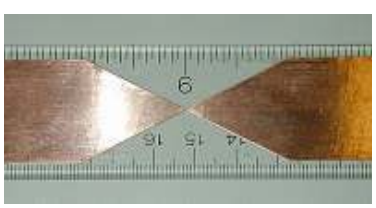
Use an Exacto knife to make the cuts. Try to keep the gap distance as short as possible.

Produces rise times of 350 ps at several volts!





1 V/div
6 GHz BW
350 ps



Charge up the Styrofoam plate (or packing "bubbles") by rubbing across the hair of your arm. Then slowly pass the plate back and forth across the spark gap.

Wrap in aluminum foil when traveling by air and orient it vertically inside your luggage!

Inexpensive ESD simulator

The Coleman lighter is unique that the butane has a separate control switch to allow the gas to flow. Cut the metal shroud back with a Dremel tool to expose the tip and connect a length of grounding wire. Pulling just the trigger produces about 4-6 kV.

ESD event detector

An inexpensive portable AM radio tuned off-station can detect ESD events (clicking) from a long distance away. This is useful for troubleshooting potential ESD issues.

Bonus: low cost spectrum analyzers

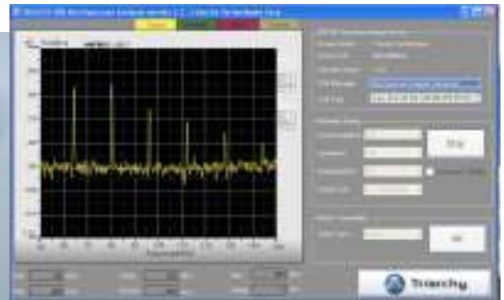
$269 spectrum analyzer

RF Explorer WSUB3G handheld spectrum analyzer, 15 to 2700 MHz at just $269

Available from Seeed Studio (http://www.seeedstudio.com)

See http://www.edn.com/design/test-and-measurement/4389545/Can-a-129-spectrum-analyzer-be-any-good- for a previous (similar) model.

USB spectrum analyzer



Triarchy Technologies TSA5G35 ($599), USB-powered (PC)

1 MHz to 5.35 GHz

http://www.triarchytech.com/product.html

Ref: http://www.edn.com/electronics-blogs/the-emc-blog/4410523/Review--Amazing-USB-5-35-GHz-spectrum-analyzer

Truly handheld spectrum analyzer

Thurlby Thandar PSA2702T

($1,695 at Newark Electronics)

1 – 2,700 MHz with all the "bells & whistles".

Note: they now have models up to 6 GHz.

http://www.tti-test.com

Ref: http://www.edn.com/electronics-blogs/the-emc-blog/4428816/Review--TTi-PSA2702T-handheld-spectrum-analyzer

Affordable bench top spectrum analyzer

Rigol DSA815TG, ($1,295 plus $200 tracking generator and $600 EMI options)

9 kHz to 1.5 GHz with all the “bells & whistles” – AND MORE.

They now have models that go up to 6 GHz.

http://www.rigol.com/prodserv/DSA800/

First Impressions: http://www.edn.com/electronics-blogs/the-emc-blog/4389791/First-Impressions--Rigol-DSA815TG-Spectrum-Analyzer

Product Review: http://edn.com/electronics-products/electronic-product-reviews/other/4398946/Product-review--Rigol-DSA815TG-spectrum-analyzer

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Summary

Most EMC problems can be traced to poor PC board design which causes common-mode currents, faster-than-necessary edge rates, poorly bonded cable shields, poorly routed cables leading to high frequency coupling, and/or poorly designed product enclosures.

- The spectrum analyzer is the instrument of choice when it comes to measuring or troubleshooting EMC issues. It is also invaluable for pre-compliance testing.
- An oscilloscope is also useful for measuring edge rates, ringing on waveforms and measuring noise voltages in ground planes and power busses. Some, such as the R&S RTE 1104 are sensitive enough (1mV/div) for low-level spectral analysis.
- Simple DIY or low-cost probes and equipment may be made or purchased, which are useful for troubleshooting the top three EMC issues – radiated emissions, ESD and radiated immunity.
- When troubleshooting EMC problems, identifying the path of current – *especially return currents* – is the key to solving many EMI issues.

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www.emc-seminars.com

The EMC Blog (on EDN.com)

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