EMC in Audio Systems

Jim Brown K9YC
Audio Systems Group, Inc.
Chicago
jim@audiosystemsgroup.com

Audio System Characteristics

- Very wide dynamic range
  - 100 dB typical
- Sources and Electronics widely separated
  - 100 m cable runs at mic level (-130 dBV noise floor) are common
  - Vulnerable to LF, MF, and HF EMI
- Analog distribution at mic level is the rule
  - No digital mics
  - Latency and operational issues generally preclude digital distribution in live systems

Audio System Architecture

- Source locations often widely separated
- Strong EMI sources in audio spectrum
  - Power and power harmonics
  - Switching transients
  - Clock signals
- Magnetic coupling to equipment and wiring
  - Common impedance coupling on shields of unbalanced wiring

Power System Issues

- Power system harmonics
  - "Triplen" harmonics do no cancel in the neutral of 3-phase systems, *nor in the net magnetic field surrounding 3-phase delta feeders!*
- Strong magnetic fields
  - Power transformers
  - Motors
  - Feeders not in conduit
- Variable speed drive motors
- PVC conduit provides no shielding

Audio System Architecture

- Many sources (mics) often combined to a single output
  - EMI often coherent and in phase, thus adds by 6 dB for each doubling of number of sources receiving interference at equal level
  - Signals not coherent, so 3 dB/doubling
  - Signal/noise degrades by 3 dB/doubling
  - A signal buried in the noise on a single channel can be 10 dB above the noise if present in many inputs of a multi-mic mix

Audio System Architecture

- In performance systems, each microphone often feeds three preamps in parallel, each at a different location
  - Audience sound mix
  - Performer (stage monitor) sound mix
  - Recording/broadcast sound mix
- Splitting methods usually passive
  - Three-winding transformer w/Faraday shields
  - Hard-wired Y (no transformer)

Audio System Architecture

- Why Not Preamplify and then split?
- Preamps can't accommodate wide dynamic range of live performance, so gains may need to change during the show
  - That requires an additional operator, just to "babysit" the preamps! Out of the question for most installations.
  - The preamp/DA is expensive too!

Audio System Architecture

- System interconnection issues dominate
- Must be robust with respect to
  - Magnetic fields
  - Common mode voltages and currents
  - MF and HF RF on long cable runs
  - Differences in earth potentials of interconnected equipment
- Must be practical (and economical) for widely distributed system elements

Audio System Architecture

- Star-connected isolated-ground power systems are the rule in North America
- Mesh grounding can work in video facilities
  - Far fewer mics in use
  - Hundreds of coax shields to carry ground current
- Balanced signal interconnections
- Transformer inputs with Faraday shields can be important when high common mode voltages are present

Audio System Architecture

- Digital distribution, including fiber, works for interconnections between buildings and rooms, but is impractical for most "live" systems
  - Latency
  - Cost (related to scale)
  - Distributed sources
- Analog audio at mic level drives the design

Audio System Architecture

- Steel conduit provides magnetic shielding
  - Thin wall (EMT) provides about 17 dB at power frequencies
  - Rigid steel provides about 32 dB
- Cable shields provide almost none

Audio System Architecture

- In some systems, wiring must be exposed (not in conduit)
  - Conduit not practical (or expensive to install)
  - Renovations
- Must be routed away from strong fields
- Both cable and equipment must have good RF rejection

Audio System Levels

- 0 dBu = 0.775V
- Constant voltage system, "bridging" inputs
- "Line level" typically +4 dBu – +8 dBu rms
  - Peaks typically 10-13 dB greater
  - Output impedance ~ 100 Ω
  - Input impedance ~ 10 kΩ
- "Mic level" typically -60 dBu – 0 dBu rms (varies widely with mic, placement, program)
  - Output impedance ~ 150-300 Ω
  - Input impedance ~ 1-4 kΩ

Audio System Levels

- Audio levels can be quite dynamic
  - Level at any mic can vary >60 dB during a performance
  - Sometimes the variations are good, while at other times the mix operator will smooth them out
- Compression of program dynamics is widely used
  - < 6 dB peak to average ratios in pop music broadcasting are common!
  - > 20 dB common for jazz and classical music

How Consumer Audio Systems Differ

- All equipment is unbalanced (shameful, especially with "high futility" gear!)
- Peak signal level is 1 volt sine wave (clip)
  - Output Z ~ 300Ω, input Z ~ 50kΩ
- Still attempt 100 dB dynamic range
  - Noise floor 10 µV
  - 100 µV clearly audible
- Still have noise on equipment grounds
- Shield current causes IR drops
- Magnetic fields not nearly so great

Loudspeaker Levels (Home and Pro)

- Nearly all are 4-8 ohms nominal
- Typically rated for 50 – 1,000 w peak power
- 70V distribution used for "commercial sound"
  - Background music, paging, airports, etc.
- Power amps typically < 0.05Ω output Z
- Typically have 20 dB too much gain
  - Enough to use with home or pro systems
  - Poorly designed input stages clip at pro levels!

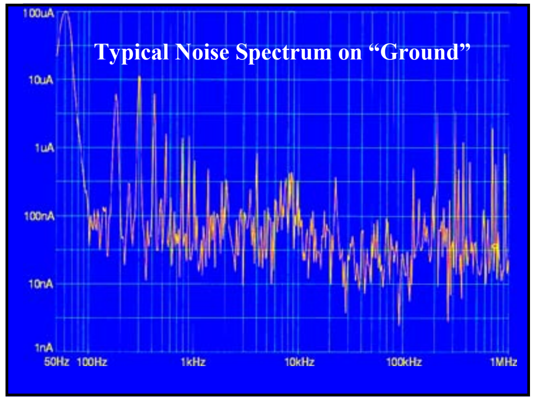
Primary Interference Mechanisms

- Pin 1 problems
  - Improper shield termination within equipment
- Shield-current-induced noise (SCIN)
  - Cable imbalance couples shield noise current to signal pair as a differential signal
  - Inadequate low-pass filtering lets it in the box
- Capacitance imbalance of cable degrades CMRR (4% - 6% typical of "good" cables)
  - No shield connection at receive end helps (Whitlock, JAES, June, 1995)

The Pin 1 Problem

- Pin 1 is the shield contact of XL connectors (AES14-1992)
- No connection should be made to the shell of <u>cable-mounted</u> connectors

Why isn't the shell the shield contact?

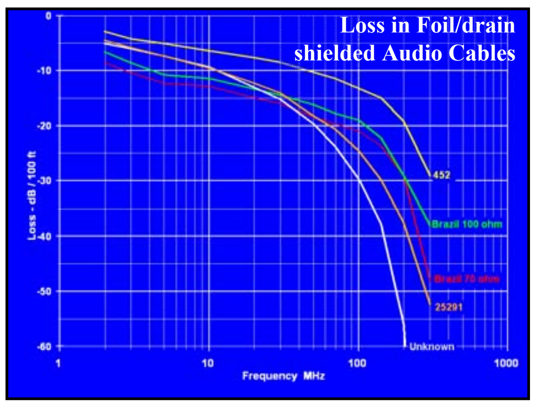


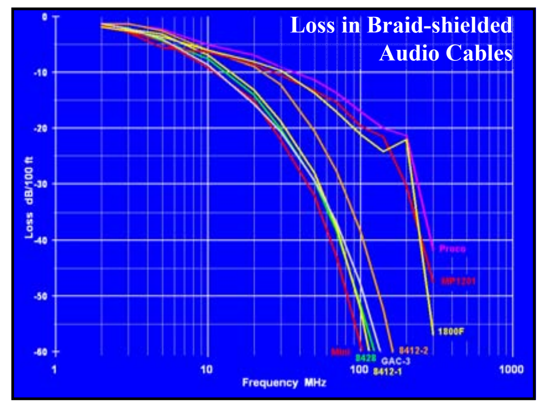
Why isn't the shell the shield contact?

- **To minimize noise current on the shield!**
  - Interconnect wiring often terminates to XL's on steel panels grounded to the conduit system
  - High noise voltages between widely separated "grounds"
- No need to <u>connect</u> the shield to wiring panels
  - No active electronics to detect RF
  - Audio cable is lossy at RF
- Shield is carried <u>through</u> panel

Why isn't the shell the shield contact? (After all, it's concentric!)

- **Audio cable is lossy at RF**
  - **VHF/UHF coupling to cable is important only very close to active electronics**
- **Minimizing noise current on the shield is far more important than slightly better UHF E-field shielding!**





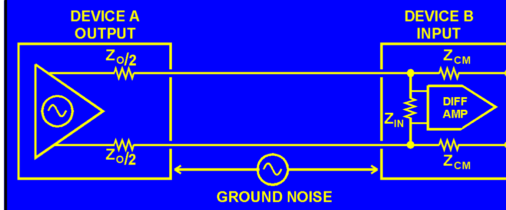
Sources of Noise on "Ground"

- Leakage currents to ground
  - Transformer stray capacitances
- Intentional currents to ground
  - Line filter capacitors
- Power wiring faults
- Shunt mode surge suppressors
- Magnetic coupling from mains power
  - Harmonic current in neutral
  - Motors, transformers

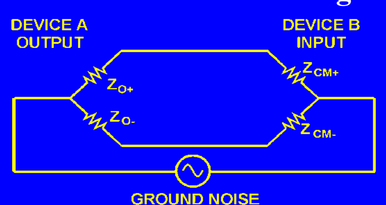
Other Sources of Shield Current

- AM Broadcast
- FM Broadcast
- Television Broadcast
- Cell Phones
- Ham Transmitters
- Digital Wireless Mics
- Radiated Noise from Lighting, etc.

The Balanced Interface

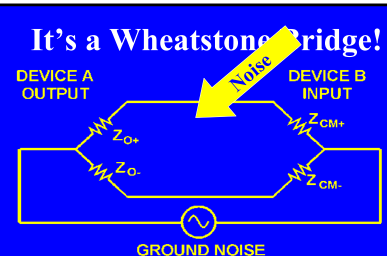


It's a Wheatstone Bridge!



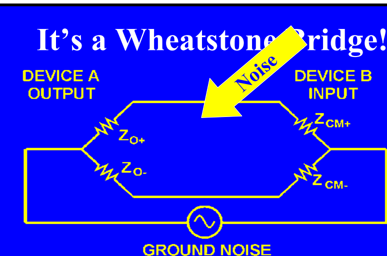
- Noise immunity depends **only** upon the balance of the bridge

It's a Wheatstone Bridge!



- Noise immunity depends **only** upon the balance of the bridge

It's a Wheatstone Bridge!



- Signal symmetry affects **only** crosstalk and headroom!

Balance ≒ Signal Symmetry

"A balanced circuit is a two-conductor circuit in which both conductors and all circuits connected to them have the same impedance with respect to ground and to all other conductors.

The purpose of balancing is to make the noise pickup equal in both conductors, in which case it will be a common-mode signal which can be made to cancel out in the load."

Henry Ott

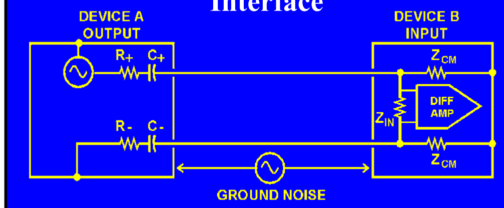
Balance ≒ Signal Symmetry

"Only the common-mode impedance balance of the driver, line, and receiver play a role in noise or interference rejection. This noise or interference rejection property is independent of the presence of a desired differential signal. Therefore, it can make no difference whether the desired signal exists entirely on one line, as a greater voltage on one line than the other, or as equal voltages on both of them.

"Symmetry of the desired signal has advantages, but they concern headroom and crosstalk, not noise or interference rejection."

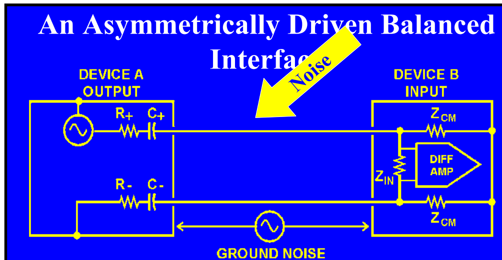
from IEC Standard 60268-3

An Asymmetrically Driven Balanced Interface



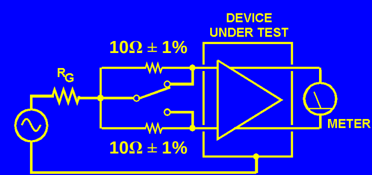
- Device A has a perfectly good balanced output if R+ = R- and C+ = C-

An Asymmetrically Driven Balanced Interface



- Device A has a perfectly good balanced output if R+ = R- and C+ = C-

Revised IEC 60268-3 CMRR Test

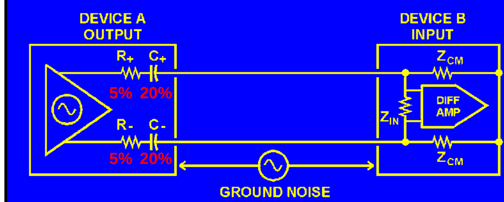


- The switch is toggled, and the highest meter reading is used to compute CMRR
  - 10 Ω typical of real world output stages
  - Shows the superiority of transformers and better input circuits

Optimizing Performance

- If bridge is unbalanced, a portion of the common mode noise will be converted to a differential noise
- Balance critically depends on ratio match of driver/receiver common-mode pairs
  - Most sensitive to component tolerances when all arms are the same impedance
  - Least sensitive when source and receiver arms have widely different impedances
  - Low Z driver and high Z receiver is standard

Real World Balanced Interface

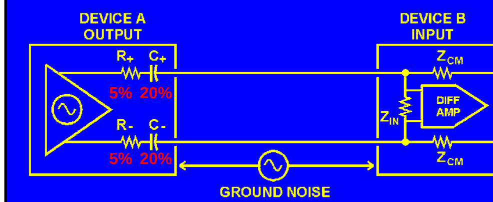


- **Z_O of <u>real</u> output stages set by 5% series resistors and 20% series capacitors**
- 5-10 ohms R and X unbalance typical

Real World CMRR

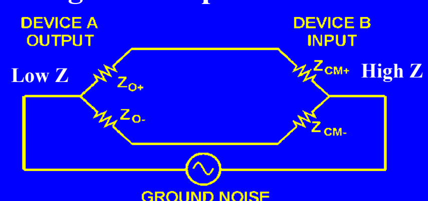
- **Z_O of <u>real</u> output stages set by 5% series resistors and 20% series capacitors**
- **Z_{cm} of real "active balanced" (diff-amp) inputs ranges from 10 kΩ to 50 kΩ**
  - **This low Z_{cm} makes CMRR extremely sensitive to normal driver Z_O imbalances**
  - **CMRR of popular SSM-1241 <u>degrades 25 dB</u> with only 1Ω imbalance in driver Z_O**
- **Z_{cm} of <u>real</u> input transformer receiver is about 50 MS at 60 Hz**
  - **Z_{cm} about 1000 times that of ordinary "active" diff-amp inputs**

Real World Balanced Interface



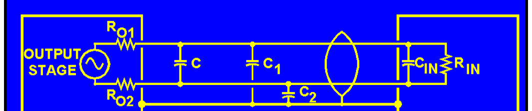
- **Z_O of <u>real</u> output stages set by 5% series resistors and 20% series capacitors**

High CM Input Z is Good



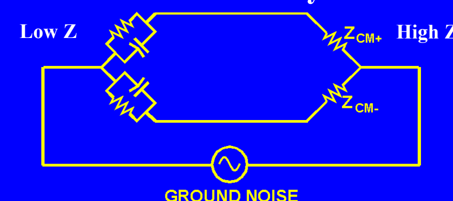
- **Minimizes CM current**
  - **Minimizes conversion**
  - **Important at RF too!**

And There's the Cable!



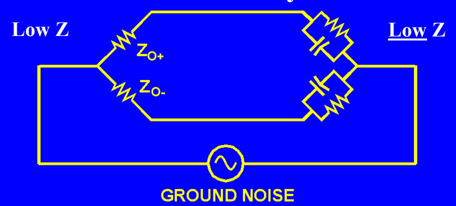
- **C_1 and C_2 typically differ by 4-10%**
- **Connect the shield at both ends?**
  - **If no, <u>which</u> end?**

Shield Connected Only at Source



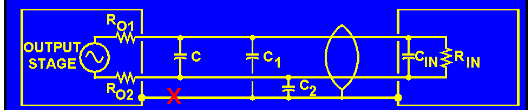
- **Cable capacitance is part of <u>output</u> circuit, and is shunted by low output Z (typically 50 Ω/leg)**

Shield Connected Only at Receiver



- Cable capacitances form unequal low pass filters and unbalance the bridge ($R_{in} >> X_C$)

Current Through C_1 and C_2 Must Return to its Source

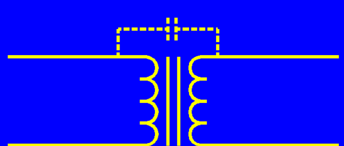


- If no shield connection at source, it will find its own path
  - –Crosstalk, distortion, oscillation
  - –Signal asymmetry makes it worse

Where/How to Connect the Shield?

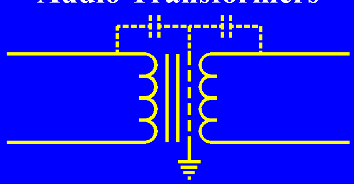
- Always provide a d.c. connection at the driver
- Never connect only at the receiver
- Connect at receiver if cable is > λ/10 at frequency of noise
- Connect through a capacitor at receiver to avoid low frequency shield current
- Always provide d.c. connection at receiver for mic level signals

Audio Transformers



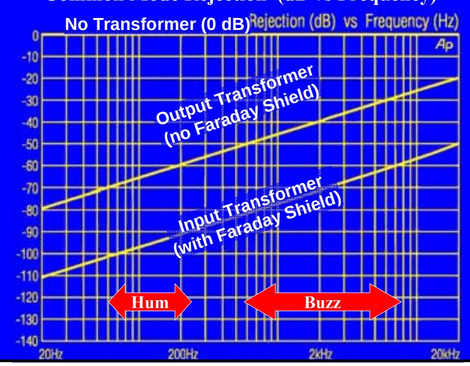
- Capacitance between windings couples common mode voltages through transformer

Audio Transformers

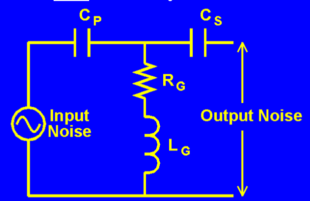


- A Faraday shield creates a two new capacitors. Grounding the shield (the common plate) shorts the common mode signal

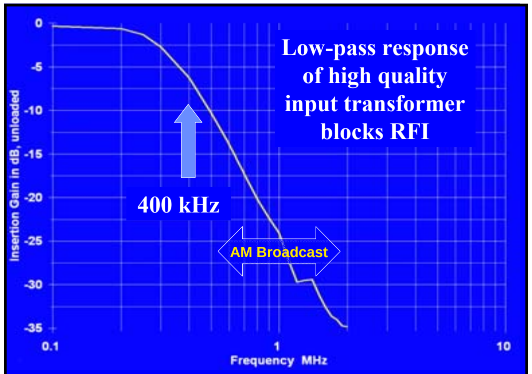
Common Mode Rejection (dB vs Frequency)



Common mode equivalent circuit – one Faraday shield



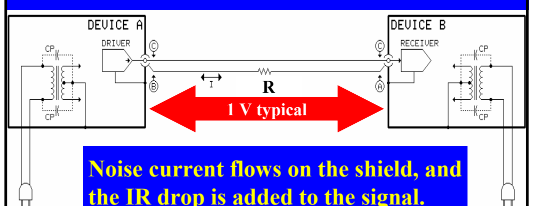
Above resonance of C_P, C_S, and L_G, Faraday shield fails



Consumer Audio Systems

- All equipment is unbalanced (shameful!)
- Peak signal level is 1 volt sine wave (clip)
- 100 dB dynamic range
  - Noise floor 10 µV
  - 100 µV clearly audible
- Noise on equipment grounds
- Shield current causes IR (and IZ) drops

The Problem with Unbalanced Interfaces



Noise current flows on the shield, and the IR drop is added to the signal.

- Use a "beefy" cable shield
  - Minimizes the drop
  - Lowers the shield cutoff frequency
  - Improves common-mode choke behavior of coax above the cutoff frequency

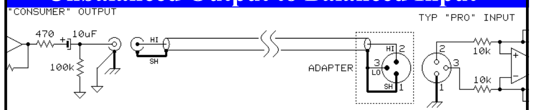
For Unbalanced interconnections, shield resistance can be important!

- Shield current (noise) creates IR drop that is added to the signal
- $E_{NOISE} = 20 \log (I_{SHIELD} * R_{SHIELD})$
- Coaxial cables differ widely
  - Heavy copper braid (8241F) 2.6 Ω /1000 ft
  - Double copper braid (8281) 1.1 Ω /1000 ft
  - Foil/drain shield #22 gauge 16 Ω /1000 ft
- Audio dynamic range 100 dB
  - For 1 volt signal, 10 µV noise floor

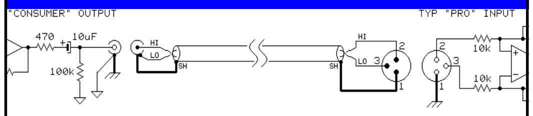
A Calculated Example

- 25-foot cable, foil shield and #26 AWG drain with resistance of 1 S
- Leakage current between ungrounded devices is 316 µA
- From Ohm's law, noise voltage = 316 µV
- Consumer reference level = 316 mV
- Signal to noise ratio = 316 mV ÷ 316 µV = 1000:1 = 60 dB = very poor!
- Belden #8241F cable, shield resistance of 0.065 S, would reduce noise ≈ 24 dB!

Unbalanced Output to Balanced Input

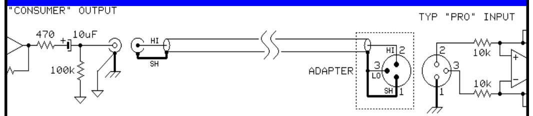


2-conductor cable and adapter gives no rejection of common impedance hum/buzz shield current



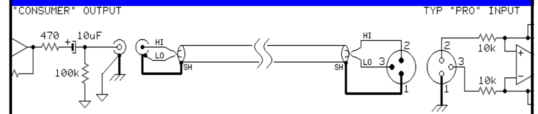
3-conductor cable gives about 30 dB rejection

A 2-Wire (Coaxial) Cable



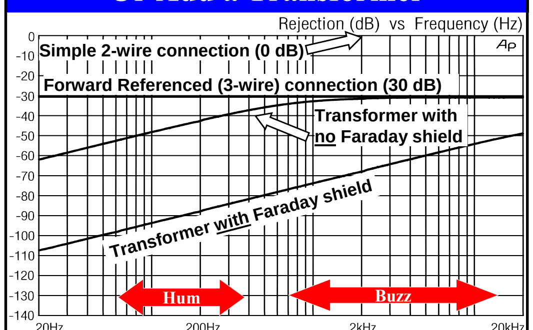
- 2-conductor cable and adapter fails to reject hum/buzz common impedance shield current
  - Shield is part of the signal path, so drop on the shield is added to the signal
  - No better than unbalanced interface

Balanced Shielded Pair Cable



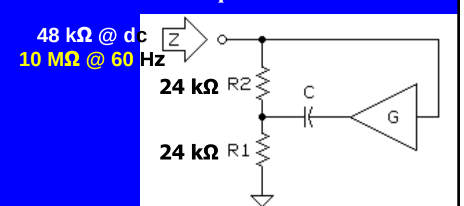
- 3-conductor cable gives about 30 dB rejection of hum/buzz current on the shield
  - Shield carries the "ground" noise current
  - Shield is not part of the signal path, so the input stage doesn't see the IR drop!
- Called "*forward referencing*"

Or Add a Transformer

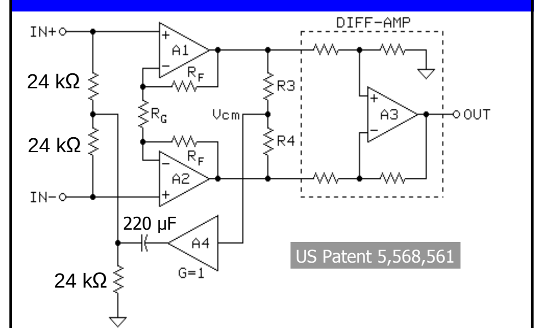


New Input Stage Approaches Transformer Performance

- Bootstrap circuit raises impedance of a resistor used in diff-amp



Applied to A Differential Amplifier

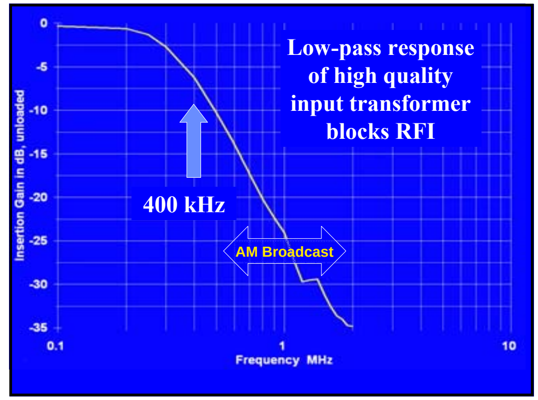


InGenius® Implementation

- R1, R2, and R5 necessary to supply amplifier bias currents (sources may have no dc path)
- CM voltage extracted by R3 and R4
- A4 buffers CM voltage and "bootstraps" R1 and R2 via external C, typically 220 µF
- Common-mode input impedance increased to 10 MΩ at 60 Hz and 3.2 MΩ at 20 kHz!
- R_F and R_G covered by patent for high gain applications like microphone preamps

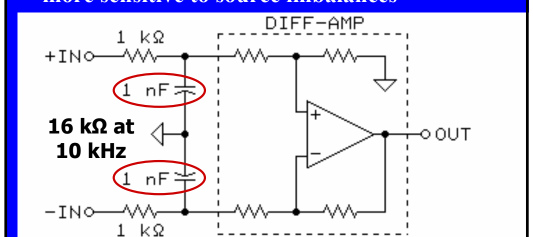
InGenius® Chip by THAT Corp

- 90 dB CMRR maintained with real-world sources
  - 90 dB @ 60 Hz, 85 dB @ 20 kHz with zero imbalance source
  - 90 dB @ 60 Hz, 85 dB @ 20 kHz with IEC ±10 Ω imbalances
  - 70 dB @ 60 Hz, 65 dB @ 20 kHz with 600 Ω unbalanced source!
- THD 0.0005% typical at 1 kHz and +10 dBu input
- Slew rate 12 V/µs typical with 2 kΩ + 300 pF load
- Small signal bandwidth 27 MHz typical
- Gain error ±0.05 dB maximum
- Maximum output +21.5 dBu typical with ±15 V rails
- Output short-circuit current ±25 mA typical



RFI Filter Capacitors

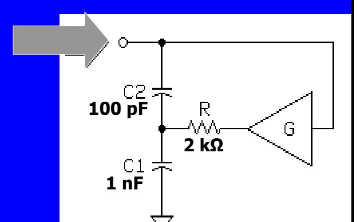
- Lower common-mode impedances significant at high audio frequencies, making interface more sensitive to source imbalances



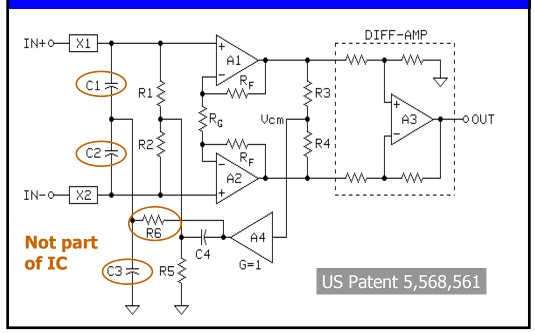
Bootstrap of RFI Filter Capacitors

- New circuit also increases impedance (i.e., decreases capacitance) of RF filter capacitors at audio frequencies

15pF @ 10 kHz,
91 pF at 100 kHz



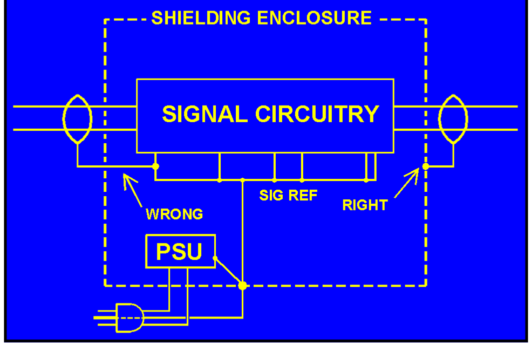
Bootstrap of RFI Filter Capacitors



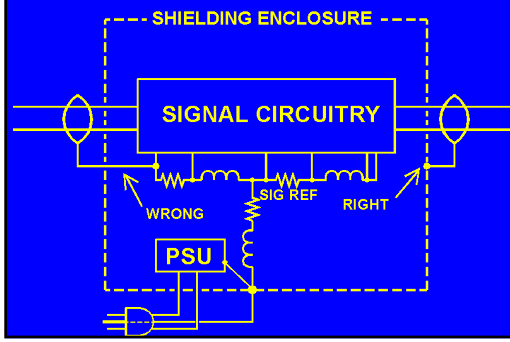
The Pin 1 Problem

- Pin 1 is the shield contact of XL connectors
- Cable shields must go to the shielding enclosure (and ONLY to the shielding enclosure)
- If shields go inside the box first (to the circuit board, for example), common impedances couple shield current at random points along the circuit board!
- Noise is added to the signal

Pin 1 in Balanced Interfaces



Pin 1 in Balanced Interfaces

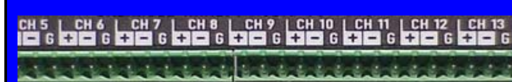


How Does It Happen?

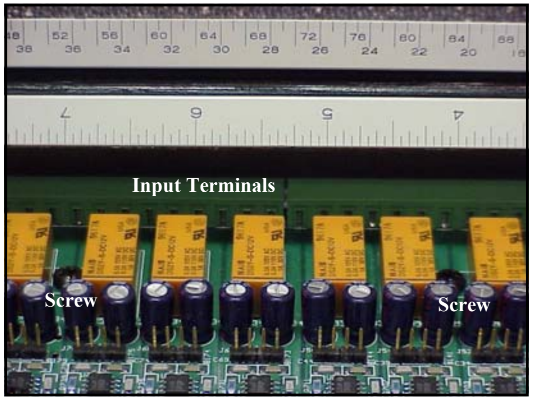
How Does It Happen?

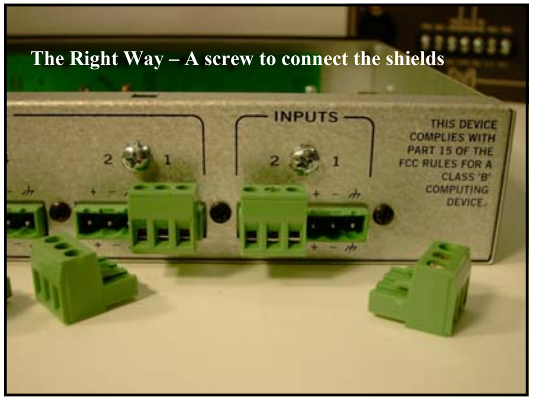
- Pin 1 of XL's go to chassis via circuit board and ¼" connectors (it's cheaper)
- XLR shell not connected to anything!
- RCA connectors not connected to chassis

The G terminal goes to the enclosure, right?



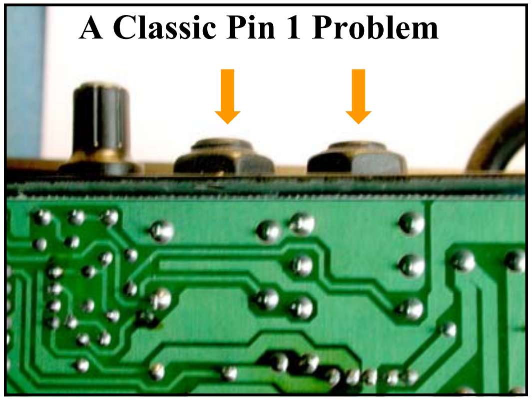
Well, sort of, but it's a long and torturous journey!


Input Terminals
Screw
Screw


The Right Way – A screw to connect the shields
INPUTS
THIS DEVICE COMPLIES WITH PART 15 OF THE FCC RULES FOR A CLASS 'B' COMPUTING DEVICE.

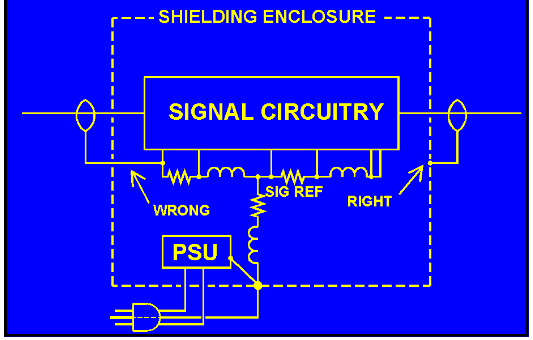

A Pin 1 Problem in Obsolete Equipment, and a Really Long Path to Chassis Ground
Let's look behind the panel.
OUTPUT
GE30
RANE


Chassis ground connection's LONG trace length *"lets the lion into the hen house - and closes the door behind him!"*
- Neil Muncy


A Classic Pin 1 Problem


An Effective (but Ugly) Fix

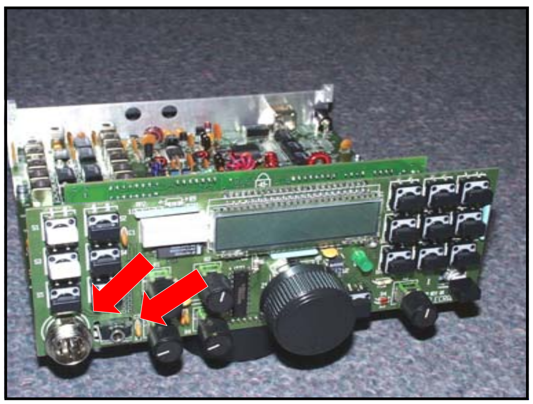
Pin 1 in Unbalanced Interfaces

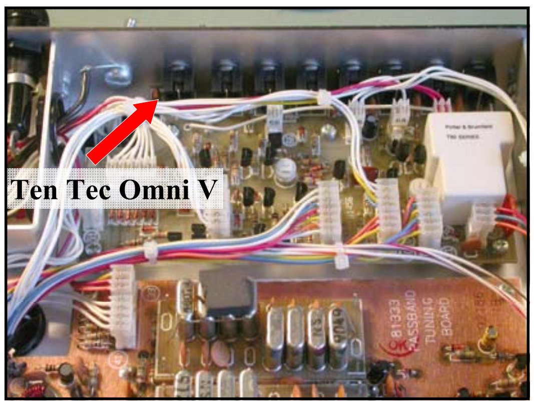


RF in the Shack is a Pin 1 Problem

- Nearly all ham gear has pin 1 problems
  - Mic inputs
  - Keying inputs
  - Control inputs and outputs
- Nearly all computers have pin 1 problems
  - Sound cards
  - Serial ports

Great Radio, Has Pin 1 Problems





Where are the Chassis Connections for this laptop's sound card?

- Hint: It isn't an audio connector shell!
  - That metal is a shield, but not connected to connectors!
  - And the cover is plastic too!

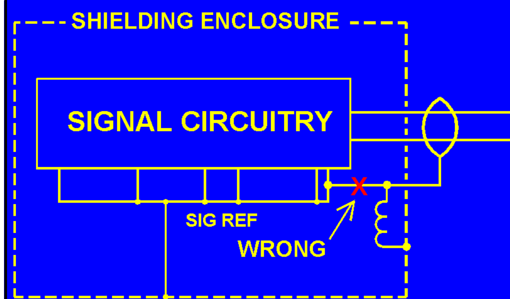
Where are the Chassis Connections for this laptop's sound card?

Yes, it's the DB9 and DB25 shells!

A classic pin 1 problem at RF

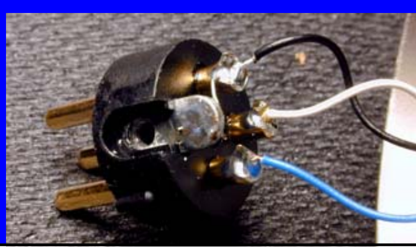
- Black wire goes to enclosure (good)
- Far too LONG - Inductance makes it high impedance
  - 7.5 Ω @ 100 MHz, 60 Ω at 850 MHz
- Orange wire is circuit board common
- Common impedance couples RF to circuit board

The Pin 1 Problem in a Mic



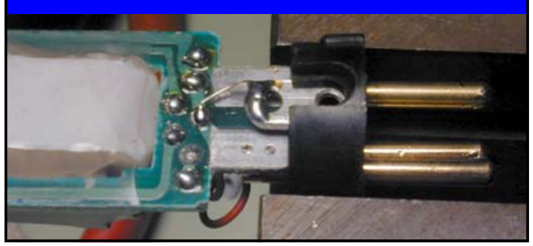
A pin 1 problem at RF

- Shield goes through connector retaining screw
  - 4 Ω @ 100 MHz, 30 Ω at 850 MHz
- Black wire is circuit board common
- Common impedance couples RF to circuit board
- This mic has RF problems



Another pin 1 problem at RF

- The screw gets loose
- Inductance of the wire, screw tab
- Common impedance to circuit board (wire + screw)
  - 4 Ω @ 100 MHz, 30 Ω at 850 MHz



Another pin 1 problem at RF

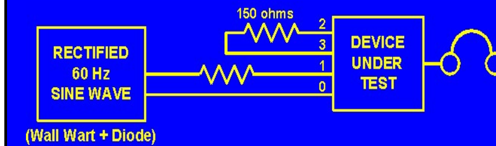
- The spring is a poor connection
- Inductance of the loop
- Common impedance to circuit board

A better connection for pin 1

- Broad, short copper, pressure fit to enclosure
- Less inductance
- Still some common impedance to circuit board
- 100 pf capacitors, common mode choke
- Much better RF performance, still not perfect

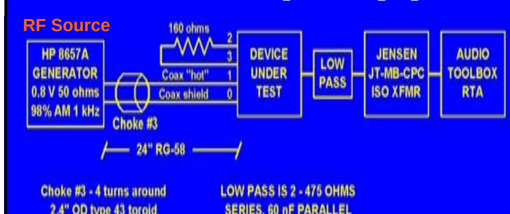
Testing for Pin 1 Problems

John Wendt's "Hummer" Test for Pin 1 Problems

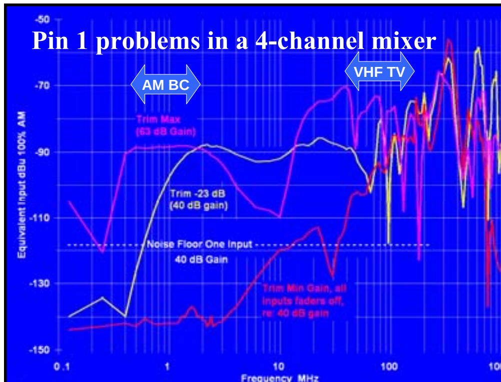


- Drive pin 1
- Listen to the output
- If you hear it, you have a problem

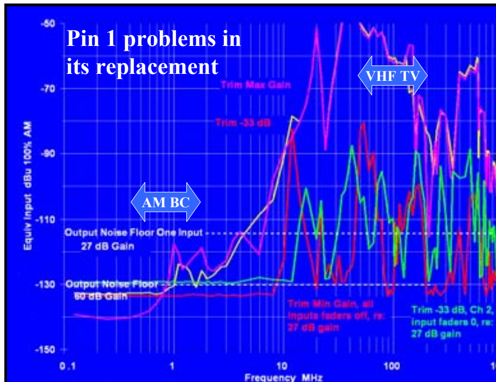
RF Pin 1 Test Setup for Equipment

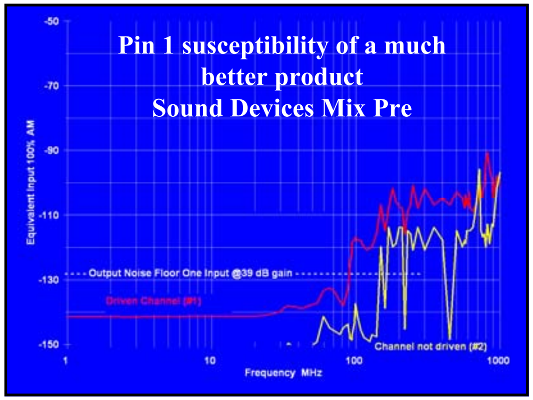


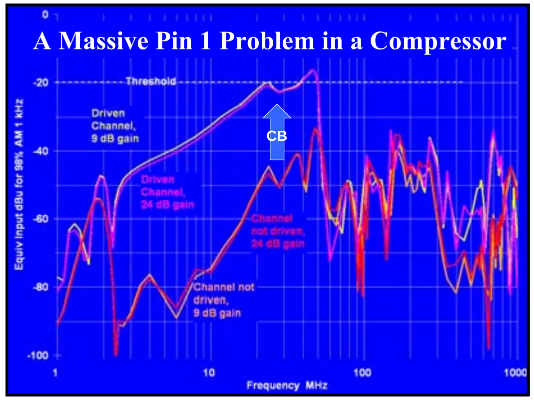
Pin 1 problems in a 4-channel mixer



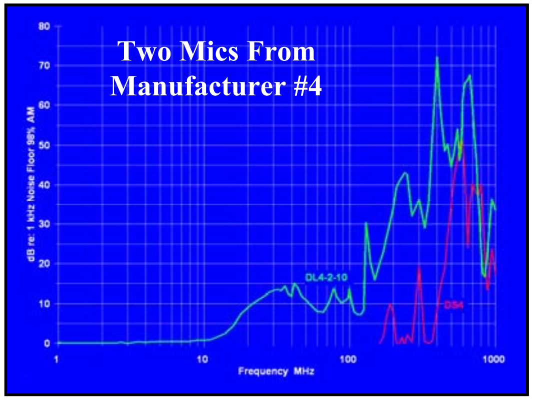
Pin 1 problems in its replacement



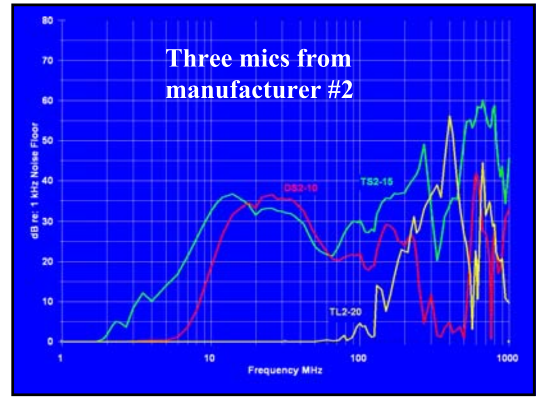

Pin 1 susceptibility of a much better product
Sound Devices Mix Pre
Equivalent Input 100% AM
Output Noise Floor One Input @39 dB gain
Driven Channel (#1)
Channel not driven (#2)
Frequency MHz

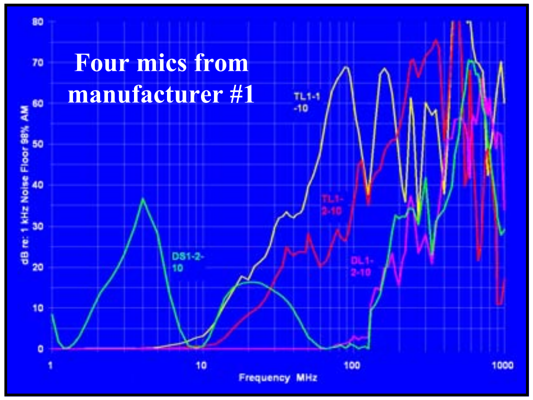

A Massive Pin 1 Problem in a Compressor
Threshold
Driven Channel, 9 dB gain
Driven Channel, 24 dB gain
CB
Channel not driven, 24 dB gain
Channel not driven, 9 dB gain
Equiv Input dBu for 98% AM 1 kHz
Frequency MHz

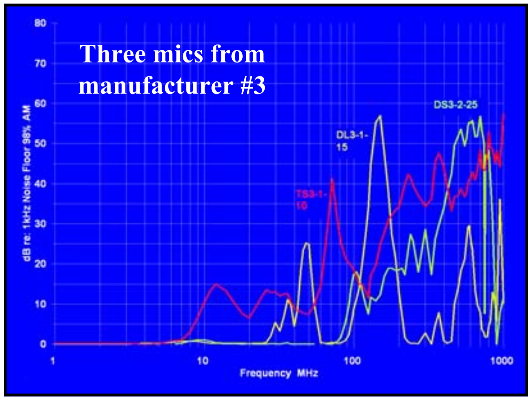

Plastic body connectors not connected to chassis
– Massive Pin 1 problem!
– Pin 1 test hits threshold of compression 20-50 MHz!
• The CE sticker assures EMC? Not here!
CH 2
INPUT
OPERATING LEVEL
-10 +4
OUTPUT

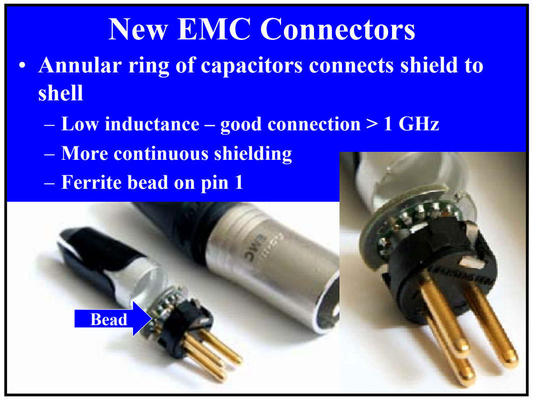

Two Mics From Manufacturer #4
dB re: 1 kHz Noise Floor 98% AM
DL4-2-10
DS4
Frequency MHz


Mics from three manufacturers with fairly good performance
dB re: 1 kHz Noise Floor 98% AM
TMO5
DS9
TMO7
Frequency MHz

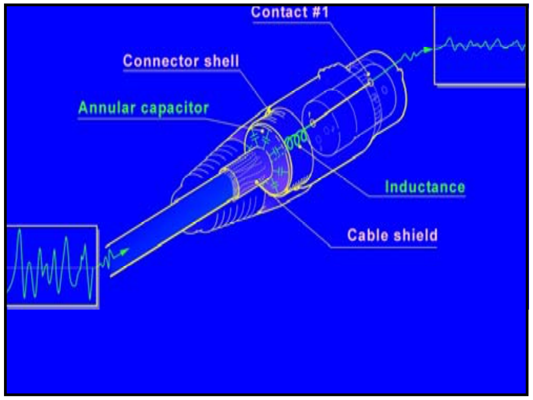

Three mics from manufacturer #2
dB re: 1 kHz Noise Floor
DS2-10
TS2-15
TL2-20
Frequency MHz

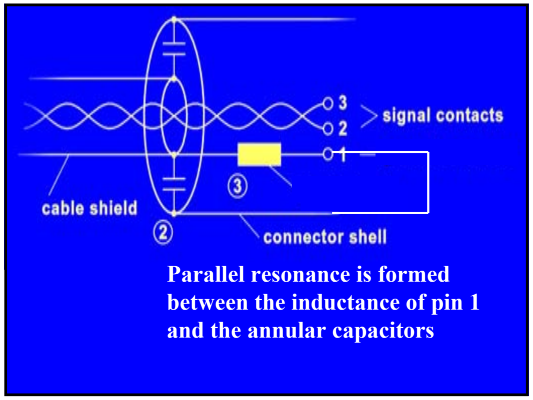

Four mics from
manufacturer #1
TL1-1
-10
TL1-
2-10
DS1-2-
10
DL1-
2-10
dB re: 1 kHz Noise Floor 98% AM
Frequency MHz
1
10
100
1000
0
10
20
30
40
50
60
70
80

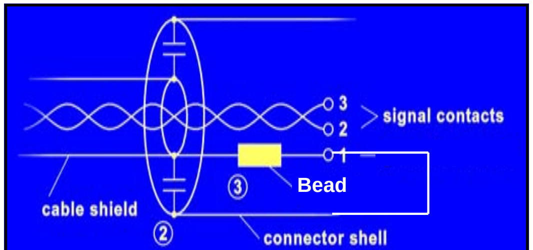

Three mics from
manufacturer #3
DS3-2-25
DL3-1-
15
TS3-1-
10
dB re: 1kHz Noise Floor 98% AM
Frequency MHz
1
10
100
1000
0
10
20
30
40
50
60
70
80


New EMC Connectors
• Annular ring of capacitors connects shield to shell
– Low inductance – good connection > 1 GHz
– More continuous shielding
– Ferrite bead on pin 1
Bead


New EMC Connectors
• Female has same internal construction
– Additional spring improves shell contact with mating connector


Contact #1
Connector shell
Annular capacitor
Inductance
Cable shield


3
2
signal contacts
1
cable shield
③
②
connector shell
Parallel resonance is formed between the inductance of pin 1 and the annular capacitors



Bead lowers frequency and Q of the resonance

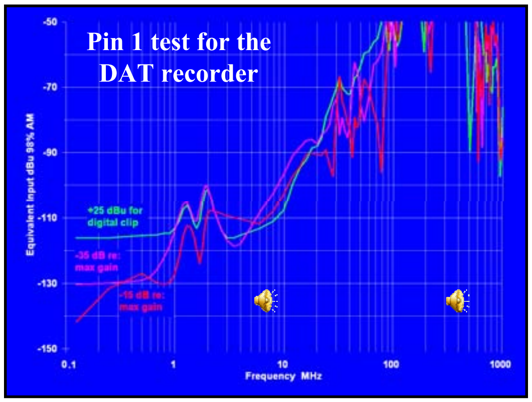
An Unexpected Side Benefit – A "band-aid for pin 1 problems!

- **A low inductance capacitive bond from shield to shell makes the right connection**
- **The ferrite bead disconnects the shield from the wrong connection**
- **But – the shells must make good contact on the equipment, and the shell must be bonded to the chassis.**

Benefits of the EMC Connector

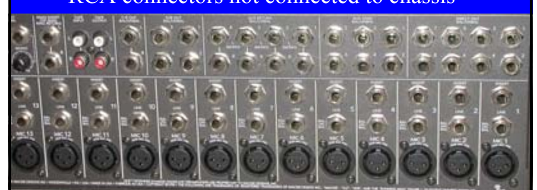
- Better VHF/UHF Shield connection to enclosure
  - Reduces common mode voltage on pins 2 and 3
- "Fixes" VHF/UHF pin 1 problems
  - Removes shield connection from Pin 1 at VHF/UHF
  - Connects the shield to enclosure
- **No Benefit if XL Shells Not Connected to Enclosure inside Equipment**

So the EMC connector can't help!



Remember This One?

- Pin 1 of XL's go to chassis via circuit board and ¼" connectors (it's cheaper)
- **XLR shell not connected to anything!**
- RCA connectors not connected to chassis



Cable **shield** construction can be part of the problem!

Foil/Drain Shield

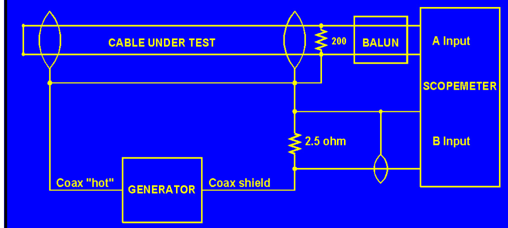
Braid/Drain Shield

Braid/Foil Shield

The drain wire is coupled more closely to the white conductor

So shield current induces more voltage on white than violet

SCIN Measurement Setup



Test Equipment

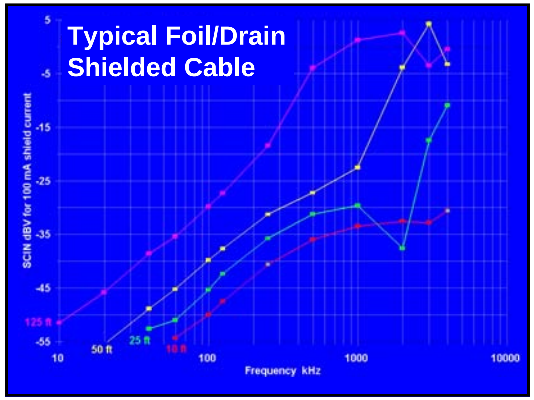
- Hewlett Packard 8657A RF Generator
  - 100 kHz - 1 GHz
- Hewlett Packard 200 CD Oscillator
  - 10 Hz - 600 kHz
- Fluke 199 200 MHz Scopemeter

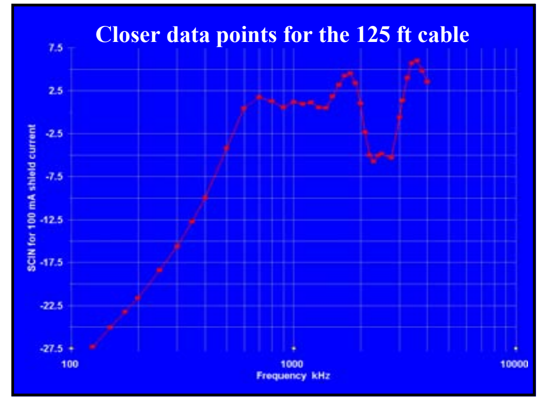
SCIN Measurements

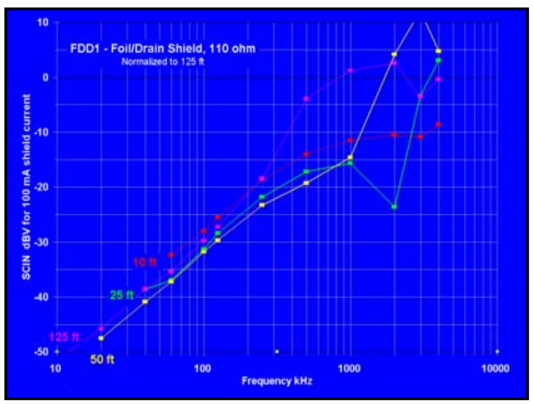
- Spot frequency measurements (not swept)
- Measure in increments of 1 octave
  - 10 kHz - 4 MHz
- Not a fixed current
  - Need to maximize current at low frequencies
  - Measure it with the scopemeter
- Normalize data to 100 mA

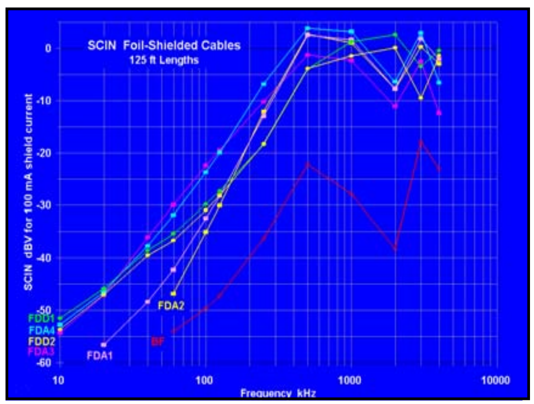
Addressing Wavelength Issues

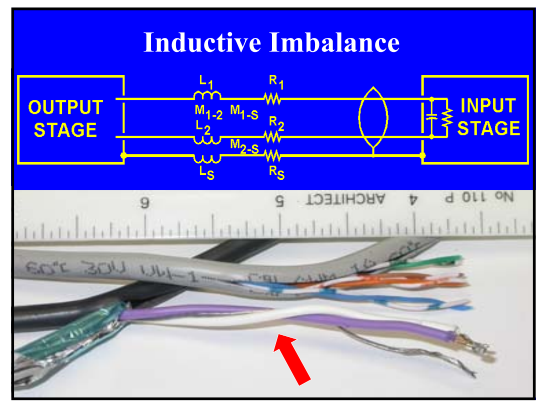
- Measure 4 cable lengths
- 125 ft (38 m)
  - Greatest sensitivity at lower frequencies
  - Resonances and wavelength effects > 250 kHz
- Must measure short cables for good HF data
  - 50 ft (15.24 m) good to at least 500 kHz
  - 25 ft (7.6 m) good to at least 1 MHz
  - 10 ft (3 m) good to at least 2 MHz



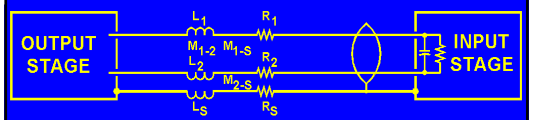






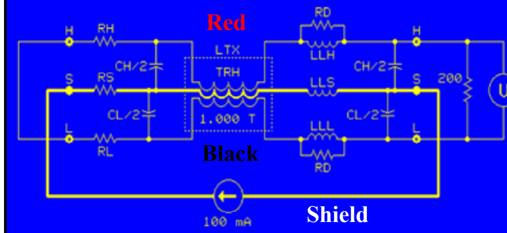


Inductive Imbalance

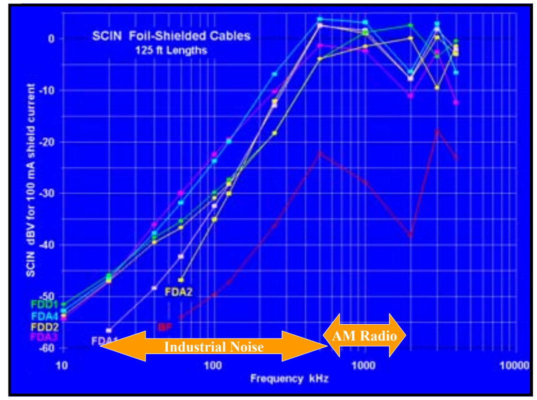


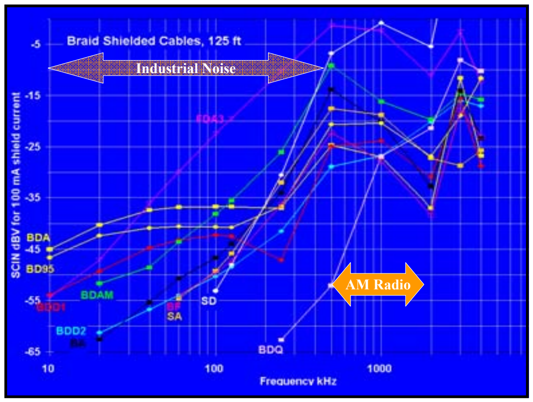
- Below about 2 MHz, most shield current in a foil/drain shield flows in the drain wire
- As a result of cable construction, the drain wire couples more closely to one signal conductor than the other
- That is, M_{1-S} is not equal to M_{2-S}

It's a 3-Winding Transformer



- The turns ratio is approximately, but may not be exactly, 1:1:1



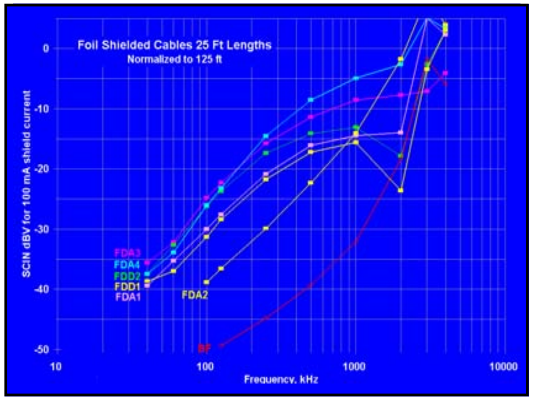


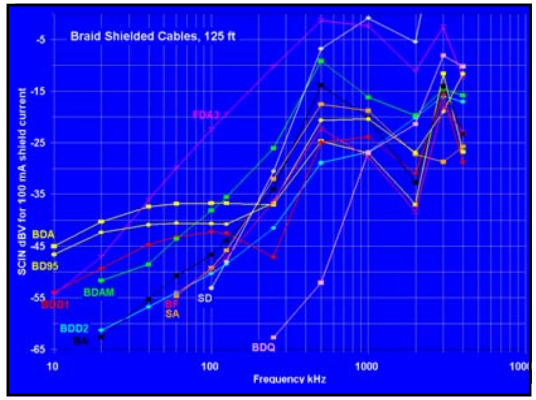
SCIN and Shield Construction

- Shield current divides between a drain wire and other shield conductors (braid or foil) according to Ohm's Law, with skin effect
- The drain wire has much lower R than foil, so nearly all current flows in the drain
- Braid has much lower R than drain, so most of the current flows in the braid
- Drain wires are the major cause of SCIN
- Cable manufacturing tolerances cause the rest (20-30 dB less)

SCIN and Shield Construction

- Foil/Drain shields are bad below 2 MHz
- Drain wire degrades braid performance below 500 kHz
- Foil/drain shields are good at HF, VHF
- Foil/braid shields are best at all frequencies





Cable and Noise Rejection

Cable and Noise Rejection

- A cable shield primarily shields the E-field
- A pair of wires works as a ***common mode choke*** by virtue of their mutual inductance
  - A coaxial cable is simply a special case of a pair of conductors that results in a coupling coefficient of 1
  - coefficient typically 0.7 for tightly twisted pairs
  - A coaxial cable shield does not provide magnetic shielding, it functions as a common mode choke!
- Twisting provides a spatial average of induction from both E and M fields

Baseband Interfering Fields

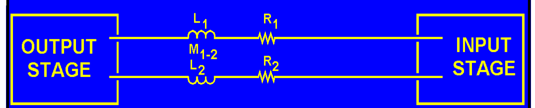
- Virtually all fields produced by power systems and equipment are magnetic fields
  - Exception – neon signs
- By virtue of their wavelength, all of our wiring and equipment is in their ***very*** near field

Rejecting LF Magnetic Fields

- Distance is your friend!
  - 18 dB/doubling for point sources ($1/r^3$)
  - 6 dB/doubling for line sources ($1/r$)
- Reduce loop area of both source and victim circuits (6 dB/doubling)
- Use tightly twisted pairs
- Only steel provides significant shielding
  - EMT (thinwall) ~ 16dB @ 60 Hz
  - Rigid steel ~ 32 dB @ 60 Hz

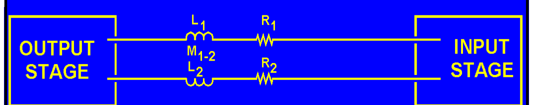
How Cables Reject Magnetic Fields

Coupled conductors as a common mode choke



- If the wires are tightly coupled, M_{1-2} will act to minimize the common mode current
- But M and L are zero at dc and small for small f, so all IR drop is across R_1 and R_2
- As f increases, M and L come into play, and the common mode choke starts to work

Cable Cutoff Frequency f_S



At the Cable Cutoff Frequency, $R = 2\pi f L_S$

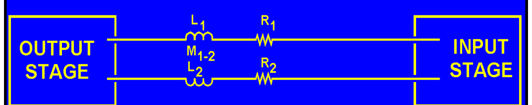
so $f_C = R / 2\pi L$ Hz

$$f_C = 0.265 R \text{ kHz}$$

where R is in Ω/1,000 ft

or $f_C \approx R/4$ kHz

Loop Inductance of Cable



Mutual coupling reduces the loop inductance (that is, the inductance the output stage sees)

For any cable,

$$L_{LOOP} = L_1 + L_2 - M_{1-2} - M_{2-1}$$

$$L_1 \approx L_2 \quad \text{and} \quad M_{1-2} \approx M_{2-1}$$

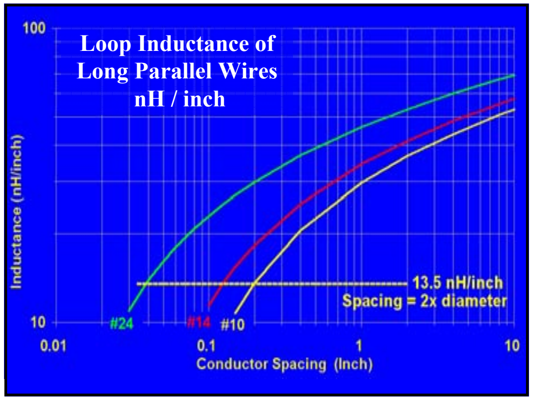
$$\text{so} \quad L_{LOOP} \approx L - M$$

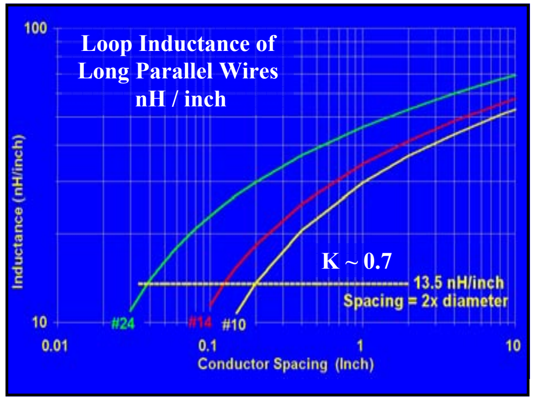
Loop Inductance of Parallel Wires

The loop inductance of two parallel wires carrying current in opposite directions is:

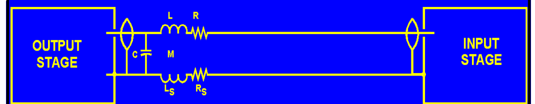
$L = 0.01 \ln(2D/d)$ µH / inch (Ott)

where D is the center-to-center spacing
d is the conductor diameter





Loop Inductance of Coax



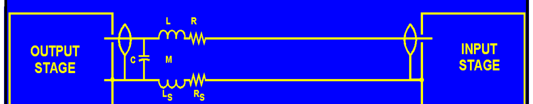
Coax is a special case, because it can be shown that for an ideal shield, $L_S = L = M$

So for coax,

so $L_{LOOP} \approx 0$ above $5f_S$

Where f_S is the *shield cutoff frequency*

Shield Cutoff Frequency f_S



At the Shield Cutoff Frequency, $R = 2\pi f L_S$

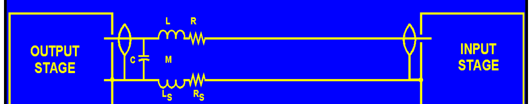
so $f_S = R_S / 2\pi L_S$ Hz

$f_S = 0.265\, R_S$ kHz

where R_S is in Ω/1,000 ft

or $f_S \approx R_S/4$ kHz

Shield Cutoff Frequency f_S

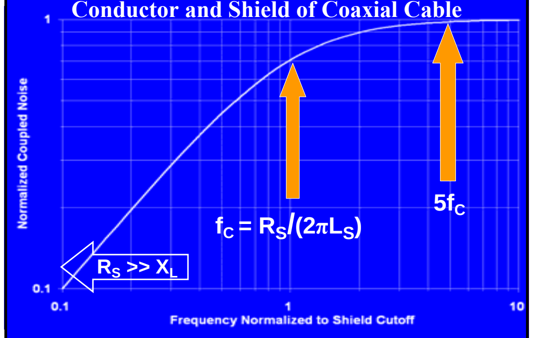


It's exactly the same mechanism, the difference is the magnitude of the coupling coefficient

Some Measured Shield Cutoff Frequencies

Type	F_S kHz)	5x F_S	
RG-6A	0.6	3	Double shield
RG-213	0.7	3.5	
RG-214	0.7	3.5	Double shield
RG-62A	1.5	7.5	
RG-59C	1.6	8	
RG-58C	2	10	
Twisted pair	2.2	11	Braid shield
	7	35	Foil/drain (8775)

Mutual Coupling Between Center Conductor and Shield of Coaxial Cable



Balanced Paired Cable As an Imperfect Common Mode Choke

- In very good twisted pair, $M \approx 0.7\ L_1$, the inductance of either conductor
- the voltage across L_1 = the voltage across L_2 and they cancel in the receiver
- The common mode voltage is the drop across R_G + 30% of the drop across L_1
- In an unbalanced circuit twisted pair cable provides modest common mode choking action above $5f_S$, but not as much as coax

Shielded Twisted Pair

The good:
- A shield provides E-field shielding
  - Connection should by < $\lambda/20$
  - Can be important for crosstalk
- Connecting the shield minimizes common mode voltage at the point of connection

The bad:
- The shield can cause SCIN and degrade noise rejection
- Unequal capacitances between conductors and the shield can degrade noise rejection

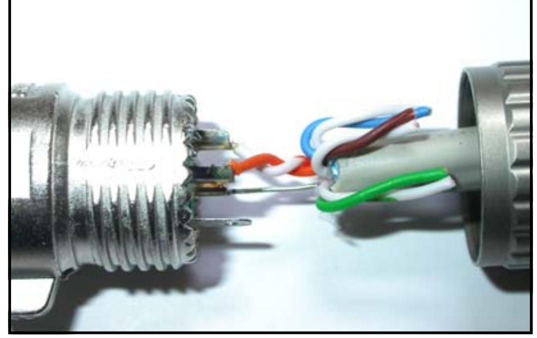
Twisting

- Twisting with good symmetry causes induced voltages and currents to be more closely balanced (equal) in the two conductors
- Most pronounced with near field sources
- A tighter twist ratio reduces coupling
  - Improves the balance in the presence of fields that vary along the cable
  - Improves the balance at higher frequencies

Twisting and Noise Coupling

- Cancellation of induced voltages occurs in the receiver, not in the cable!
- For magnetic fields and electromagnetic fields, helps in balanced or unbalanced circuits
- For low frequency electric fields, helps only in balanced circuits
- Loudspeaker cables should be twisted pairs to reject RF

Maintain Twisting Right Up to the Pins



An Experiment

Cable #1 – Belden 1800F –AES3, braid/drain

- Conventional wiring, shield to pin 1

Cable #2 – Belden 1752A – Unshielded CAT6

- One pair connects pins 2 and 3 at each end
- One pair tied together to pin 1 at each end

Test: Cable connects dynamic mic to mic preamp, gain set to very high level. Tape demagnetizer, Nextel phone, 5w VHF/UHF talkie are moved along cable to inject interference.

An Experiment

Results:

- Neither cable coupled audible interference from demagnetizer – except at connector mating to an extension cable
- Neither cable coupled audible interference from the radios

Repeat w/ condenser mic with RFI problems

- RF interference with unshielded CAT6 cable was noticeably less audible than with shielded twisted pair! ~ 6-10 dB

An Experiment

Conclusions:

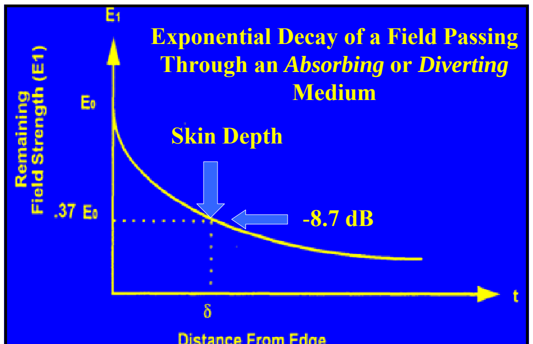
While the experiment is neither rigorous or conclusive, it reinforces assertions that:

- Twisting is far more important than shielding
- A cable shield can degrade immunity

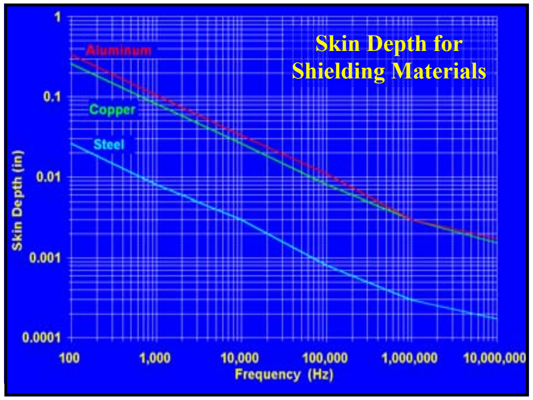
Shielding

Baseband Magnetic Field Shielding

- Low Frequency Magnetic Field Shielding is difficult
- Reflection loss doesn't help because Z_W is so small (fractional ohms)
- *Absorption* or *diversion* does the work
- Field decays exponentially passing through the shield
  - 8.7 dB per "skin depth"
  - Skin depth = thickness for 1/e attenuation

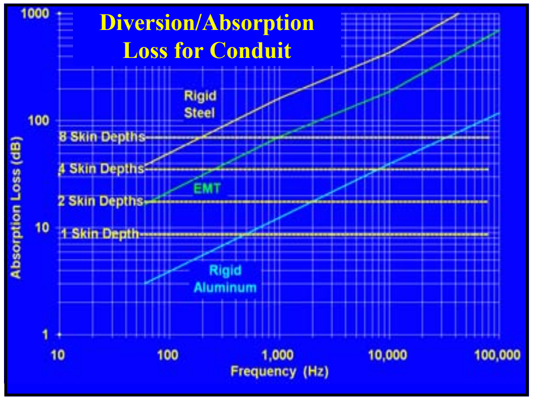


Courtesy Henry Ott, hottconsultants.com



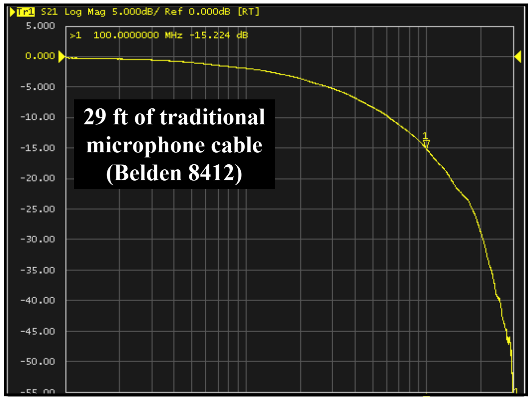
Conduit in North America

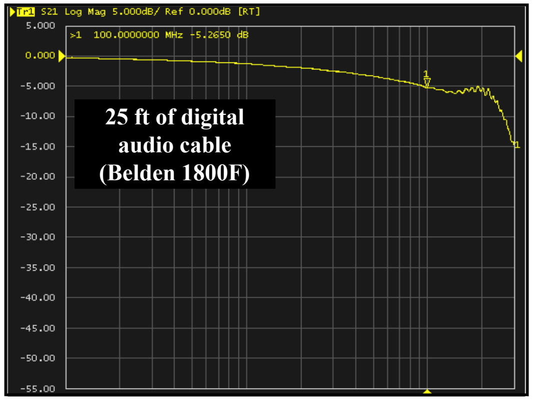
	Wall thickness (inch)	
Trade Size	EMT	Rigid steel
½ inch	.045	.11
¾ inch	.05	.115
1 inch	.055	.135
1¼ inch	.065	.14
1½ inch	.065	.145
2 inch	.065	.15

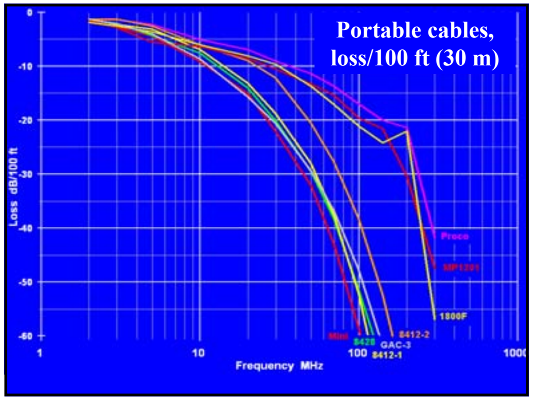


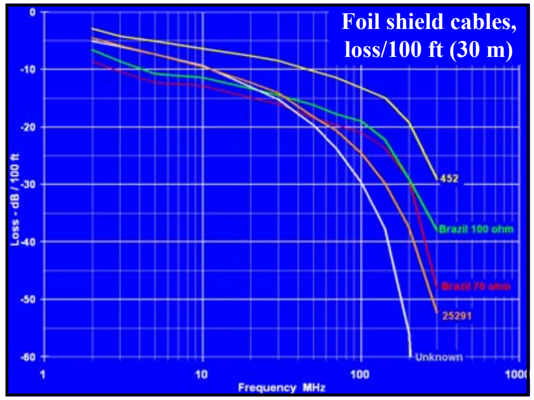
Audio Cable is Lossy at RF

- Data measured by Brown and Steve Kusiceil
- Agilent network analyzer
- North Hills baluns good to 300 MHz









Cable Handling Noise

- Capacitance between conductors changes
  - Caused by stress on the cable, or by motion
  - If phantom power is present, the motion will cause the voltage to change
- Triboelectric noise
  - Static charge is generated on insulation materials within the cable due to motion, and discharged as breakdown voltages are reached
  - Minimized by careful selection of materials, shield construction, the use of fillers, and other measures that reduce the static

CAT5 Works for RS232

- Use one pair for each circuit
- Wire connectors to avoid pin 1 problems
- Use returns for each circuit
- Use any extra conductors to reduce return R

CAT5 Works for RS232

- Use one pair for each circuit
- Wire returns to DB9 shell to avoid pin 1 problems (if there is a shell)
- Use returns for each circuit
- Use any extra conductors to reduce shield R

Why CAT5 Works for RS232

- Very low capacitance (RS232 runs un-terminated, so capacitance causes HF rolloff)
- Tight twisting with very good balance
- Pairs minimize coupling of noise
- Different twist ratios minimize crosstalk between pairs
- Combining of returns reduces IR drop of noise current (ground loops)
- Twisted pairs minimize magnetic coupling of noise

AES Papers on EMC (www.aes.org)

- ***Radio Frequency Susceptibility of Capacitor Microphones,*** Brown/Josephson (AES Preprint 5720)
- ***Common Mode to Differential Mode Conversion in Shielded Twisted Pair Cables (Shield Current Induced Noise)***, Brown/Whitlock (AES Preprint 5747)
- ***Testing for Radio Frequency Common Impedance Coupling in Microphones and Other Audio Equipment***, Brown (AES Preprint 5897)
- ***A Novel Method of Testing for Susceptibility of Audio Equipment to Interference from Medium and High Frequency Broadcast Transmitters***, Brown (AES Preprint 5898)

AES Papers on EMC (www.aes.org)

- ***New Balanced-Input Integrated Circuit Achieves Very High Dynamic Range in Real-World Systems,*** Whitlock/Floru (AES Preprint 6261)
- ***A Better Approach to Passive Mic Splitting,*** Brown/Whitlock (AES Preprint 6338)
- ***New Understandings of the Use of Ferrites in the Prevention and Suppression of RF Interference to Audio Systems***, Brown (AES Paper to be presented in New York, October 2005)
- ***Noise Susceptibility in Analog and Digital Signal Processing Systems***, Muncy, JAES, June 1995
- ***Balanced Lines in Audio Systems: Fact, Fiction, and Transformers,*** Whitlock, JAES, June 1995

Acknowledgements

- Bill Whitlock
- Ron Steinberg
- Markus Natter
- Bruce Olson
- John Schmidt (ABC)
- Neil Muncy
- David Josephson
- Werner Bachmann
- John Woodgate
- Fair Rite Products

EMC in Audio Systems

Jim Brown K9YC
Audio Systems Group, Inc.
http://audiosystemsgroup.com