

# **RFI In Audio Systems Pin 1 Problems, Poor Shielding, and Poor Input/Output Filtering**

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**Audio Systems Group, Inc.**

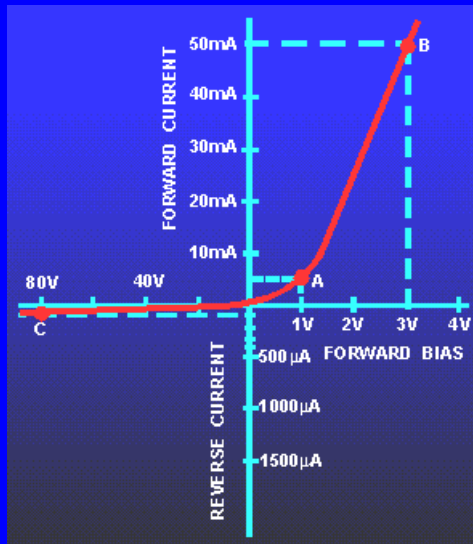
**<http://audiosystemsgroup.com>**

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## **The Heart of the Problem**

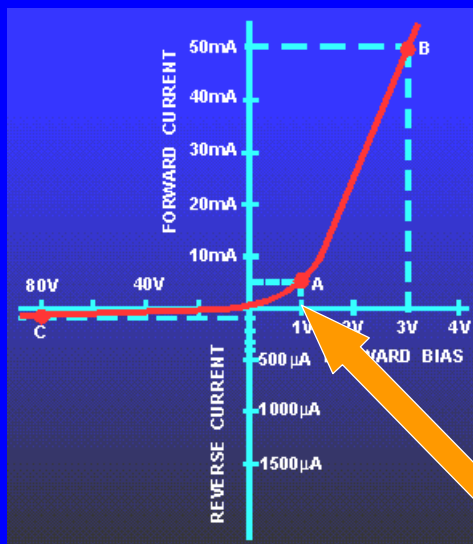
- **Audio equipment can work as a radio receiver if we allow it to do so**
- **The wires inside our equipment, and cables that interconnect our equipment, are antennas, and can bring radio signals into our gear**
- **Some of our equipment is poorly designed**

## Square Law Detection



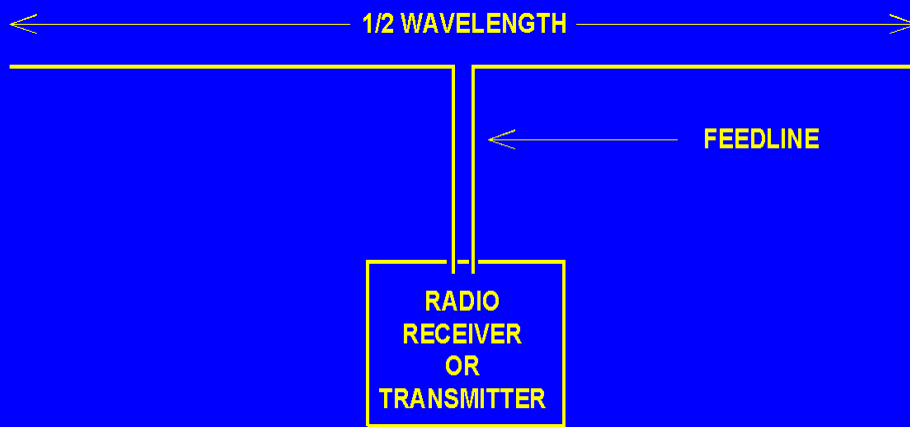
- Diodes
- Transistors
- IC's

## Square Law Detection

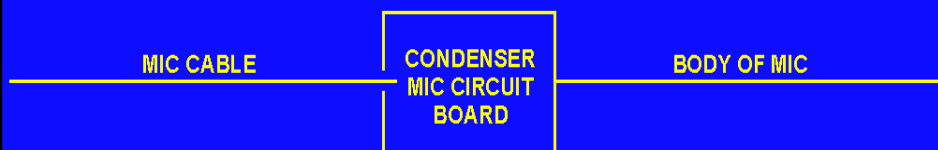


- Diodes
- Transistors
- IC's

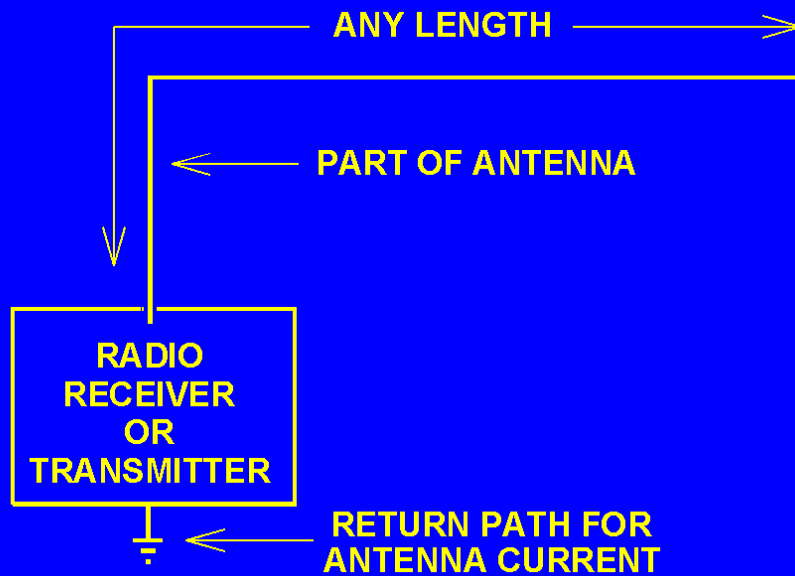
## A “Textbook” 1 / 2 Dipole



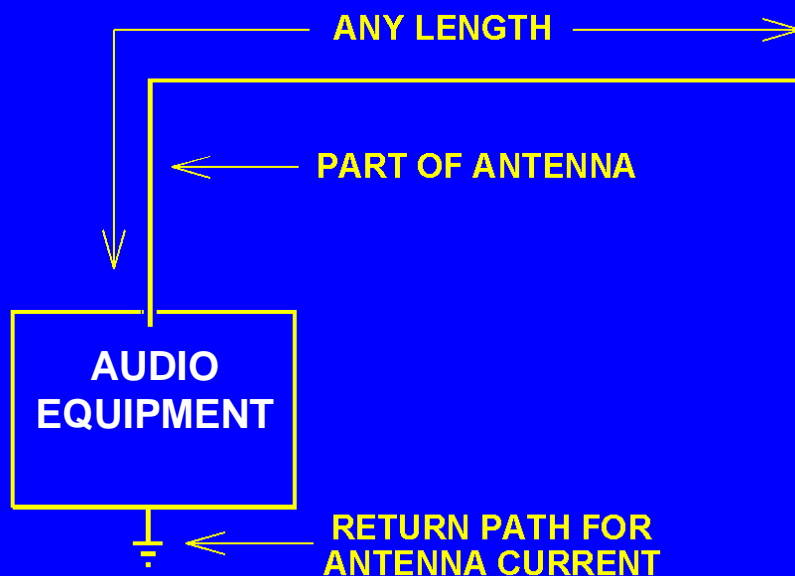
## A Microphone and its Cable can form a Dipole



## Basic Random Long Wire

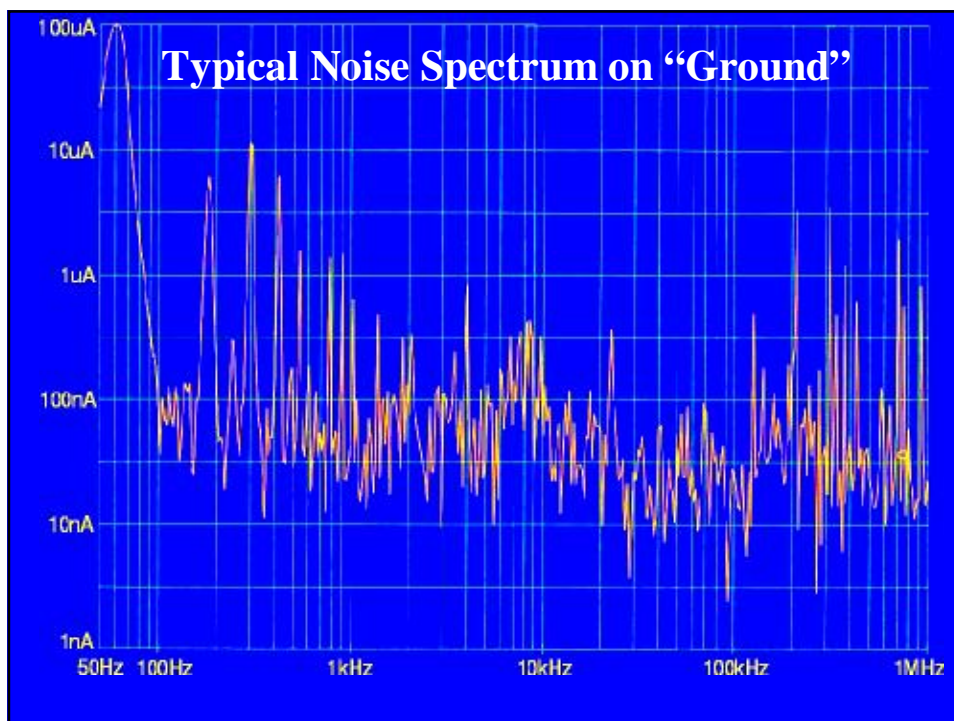


## Basic Random Long Wire

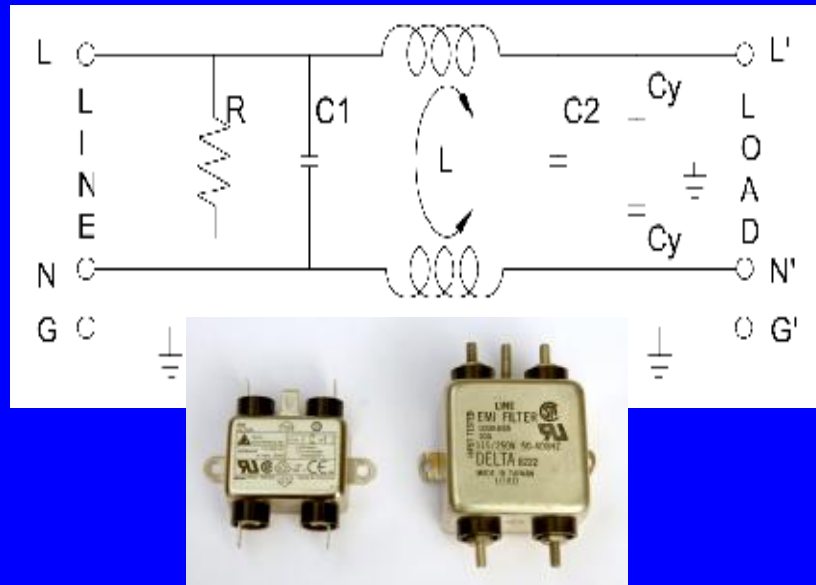


## Radio Interference Sources

- AM Broadcast Transmitters
- FM Broadcast Transmitters
- Television Broadcast Transmitters
- Ham Transmitters
- Digital Wireless Mics
- Radiated Noise from Lighting, etc.
- Variable Speed Motors
- Cell Phones, Wireless PDA's



## Line Filters Can Add Noise to Ground



## Other Noise on “Ground”

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

## Primary Coupling Mechanisms

- Pin 1 problems
  - Improper shield termination within equipment
- Differential noise on signal pair
  - Inductive imbalance between shield and signal conductors -- Shield-current-induced noise (SCIN)
  - Capacitance imbalance of cable
  - Inadequate low-pass filtering lets it in the box
- Common mode noise
- Inadequate shielding of internal wiring

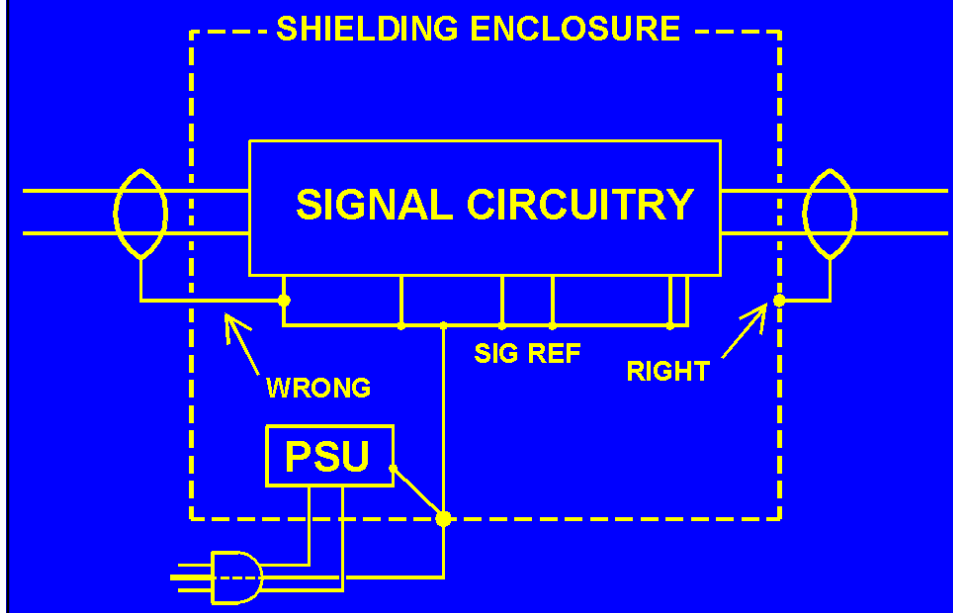
## Pin 1 in Cable-Mounted Connectors

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

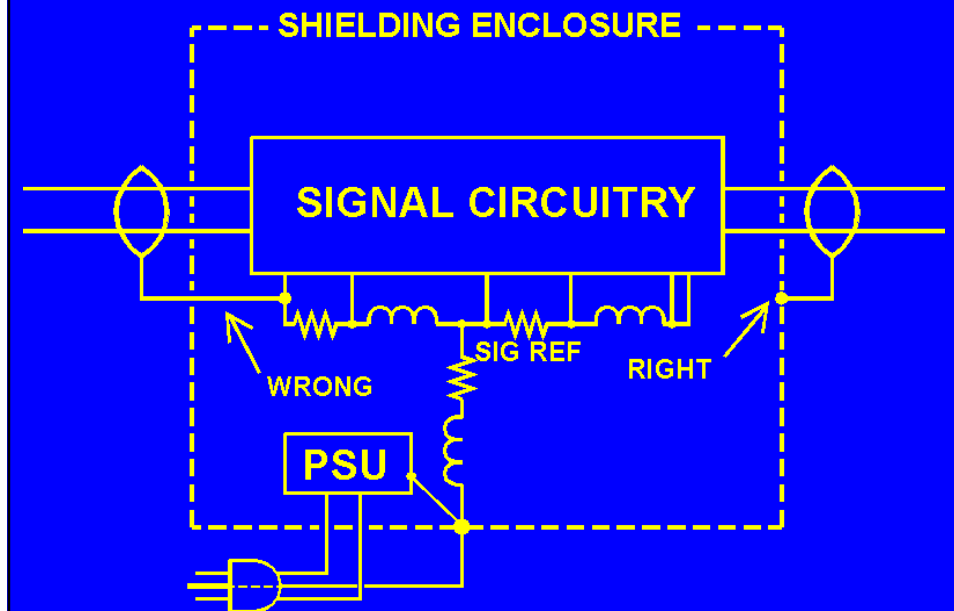
## Pin 1 Within Equipment

- Pin 1 is the shield contact of XL connectors
- Cable shields must go to the shielding enclosure (and ONLY to the shielding enclosure) (AES48)
- 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?

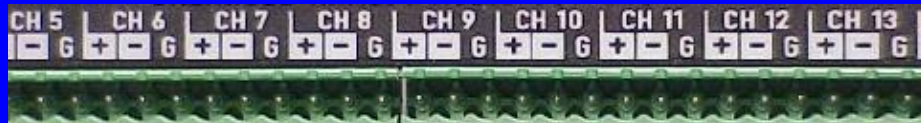


## How Does It Happen?

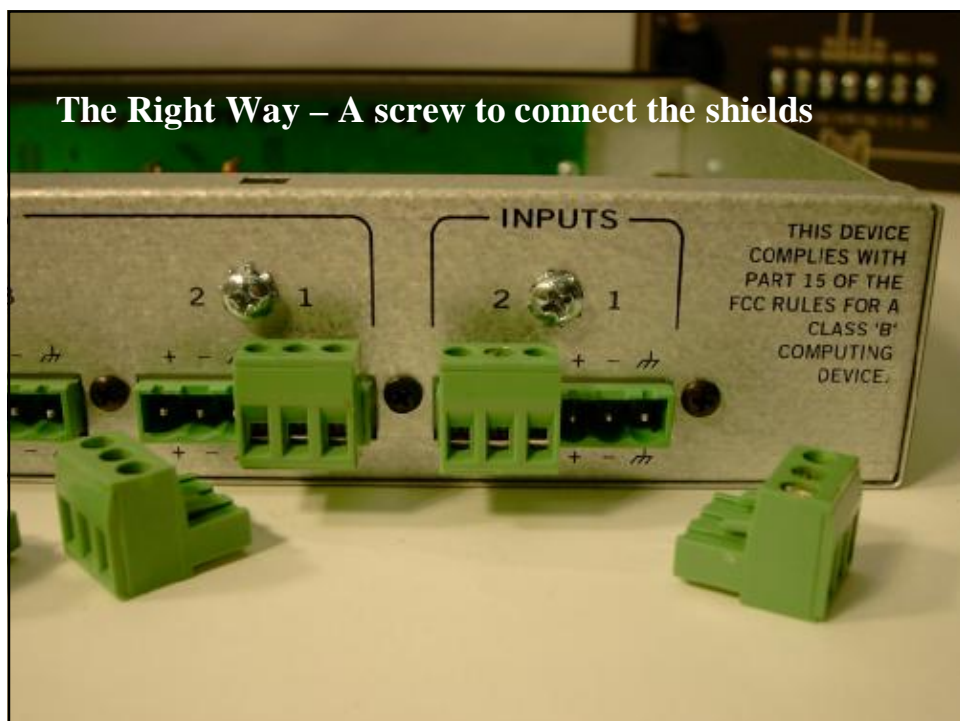
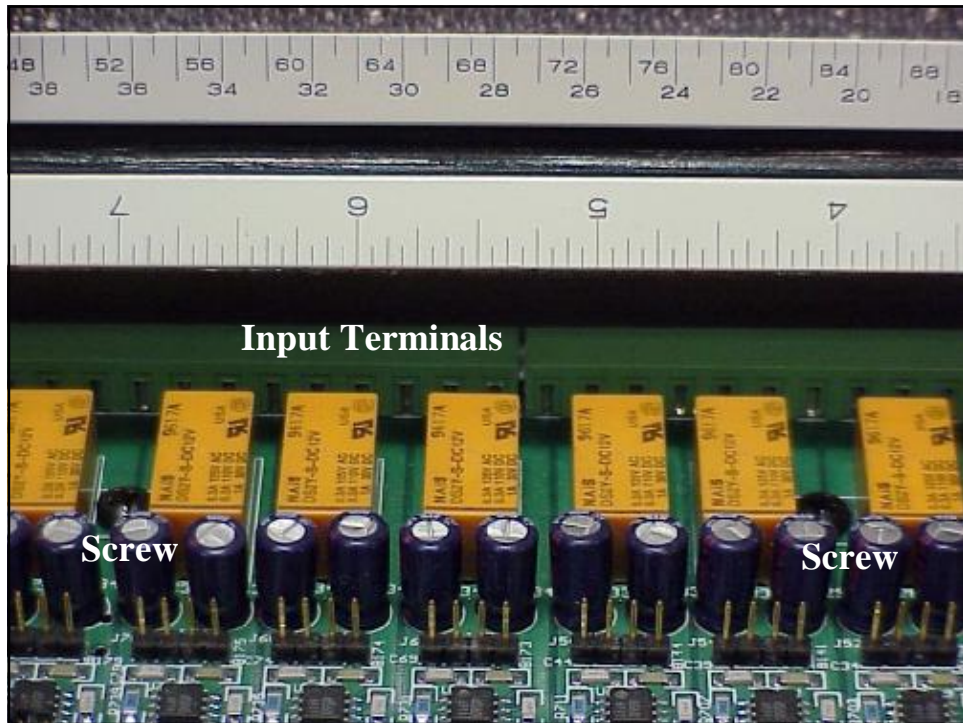
- Pin 1 of XL's go to chassis via circuit board and 1/4" connectors (it's cheaper)
- XLR shell not connected to anything!
- RCA connectors not connected to chassis



The G terminal goes to the enclosure, right?

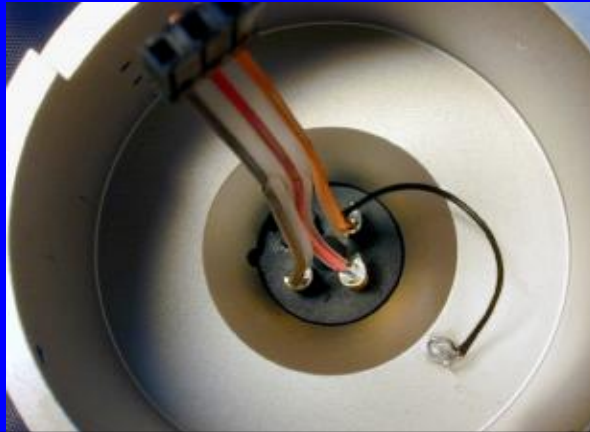


Well, sort of, but it's a long and torturous journey!

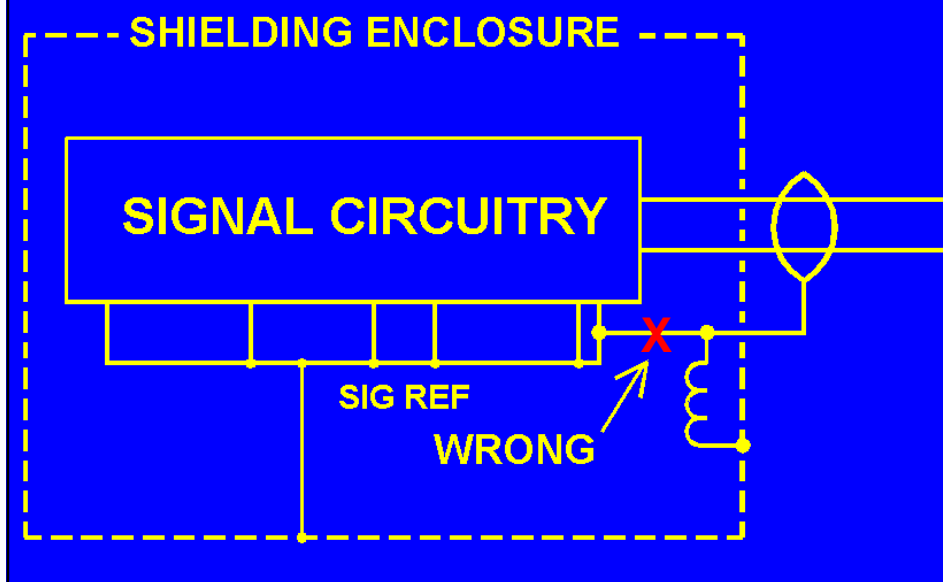


## A classic RF pin 1 problem in a microphone

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



## The Pin 1 Problem in Microphones



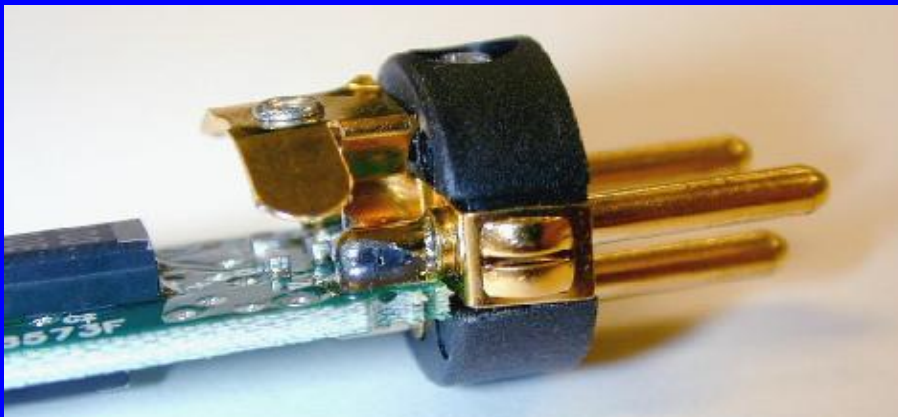
### **A pin 1 problem at RF**

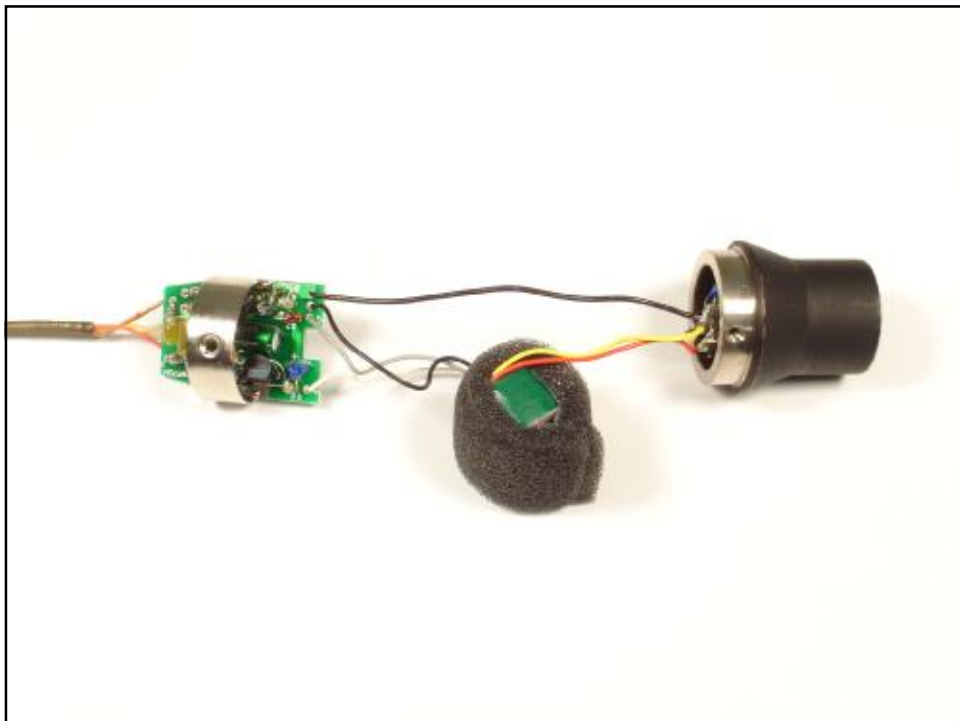
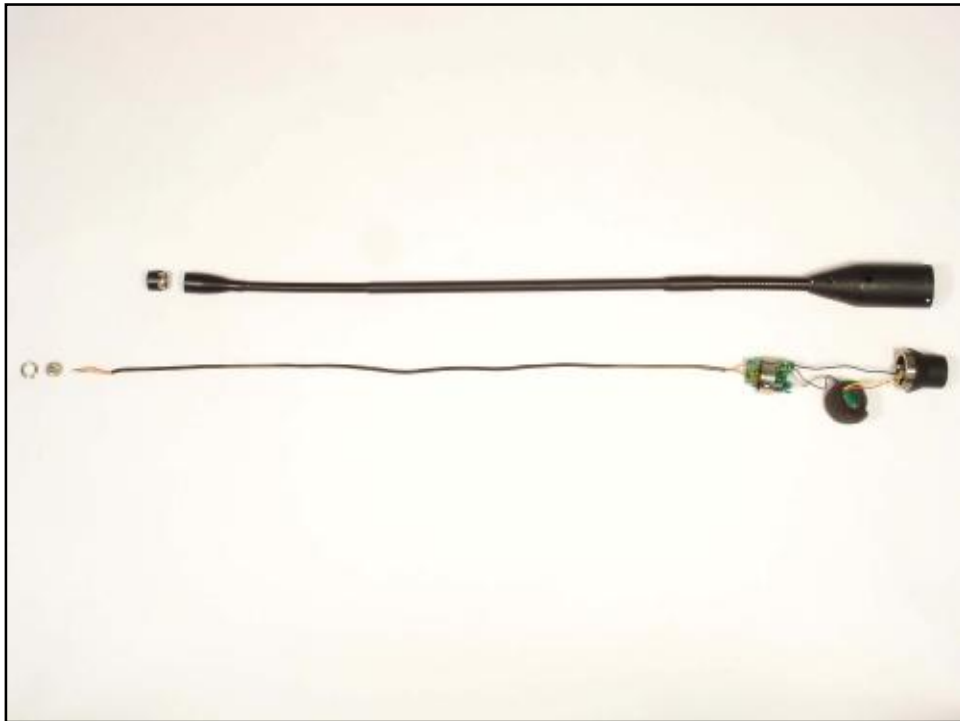
- Shield goes through connector retaining screw
  - $4\ \Omega$  @ 100 MHz,  $30\ \Omega$  at 850 MHz
- Black wire is circuit board common
- Common impedance couples RF to circuit board
- This mic has RF problems

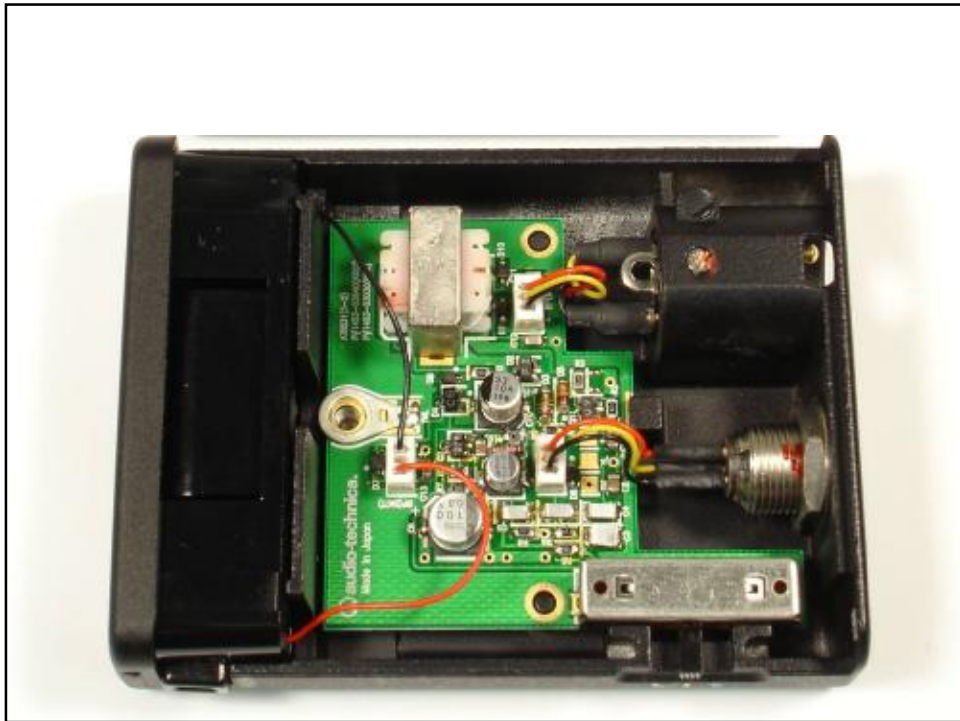


### **A better connection for pin 1**

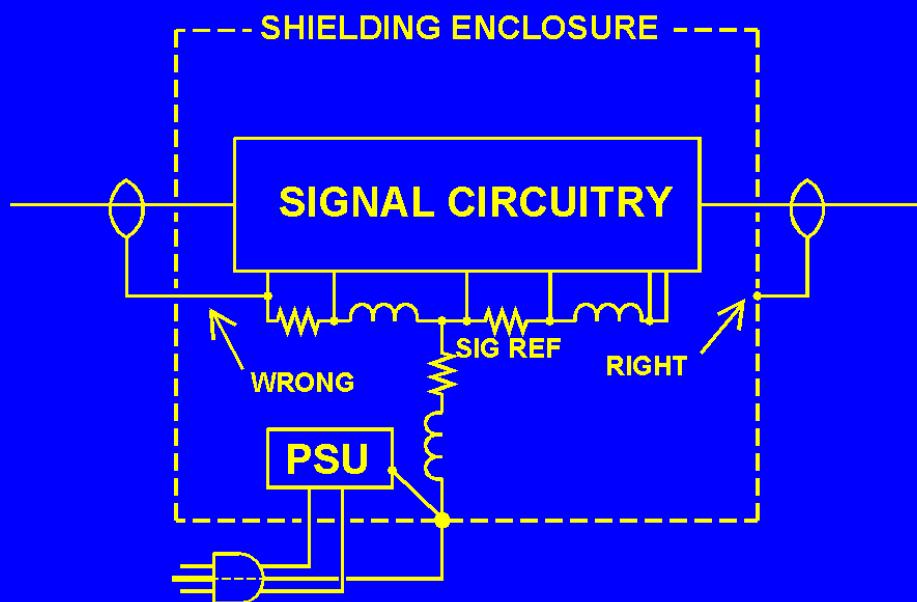
- Broad, short copper, pressure fit to enclosure
- Less inductance
- Still some common impedance to circuit board
- 100 pf capacitors, common mode choke
- Much better RF performance, still not perfect







## Pin 1 in Unbalanced Interfaces



## 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



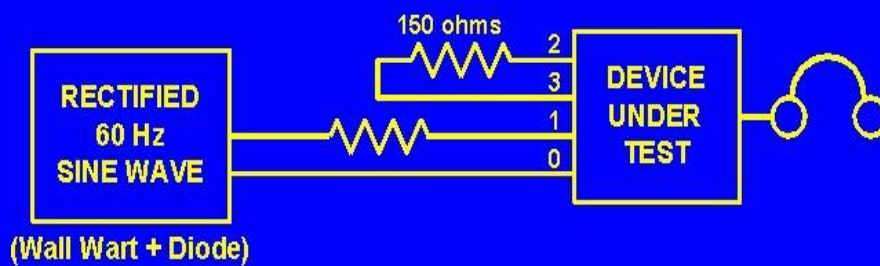
## Where are the Chassis Connections for this laptop's sound card?

**Yes, it's the DB9 and DB25 shells!**



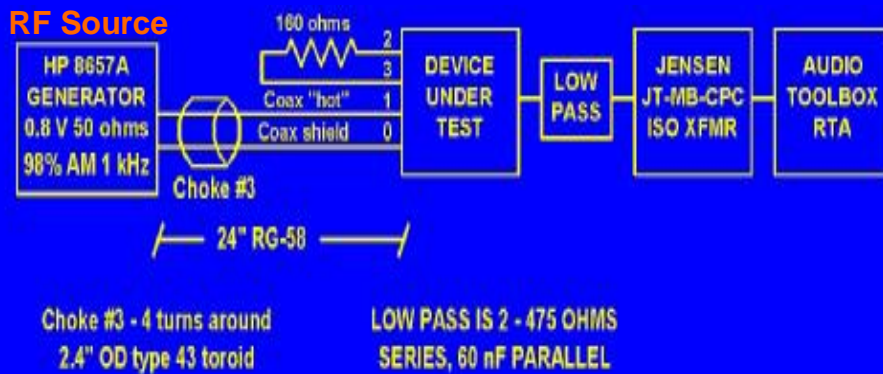
## Testing for Pin 1 Problems

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



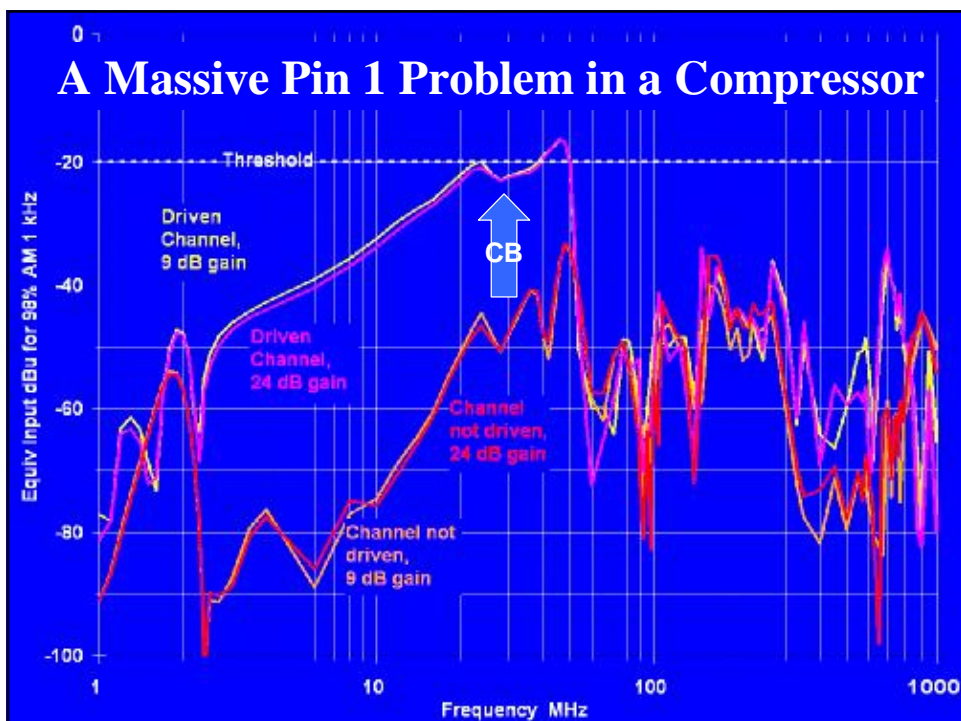
- Drive pin 1
- Listen to the output
- If you hear it, you have a problem

## RF Pin 1 Test Setup for Equipment



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

## A Massive Pin 1 Problem in a Compressor

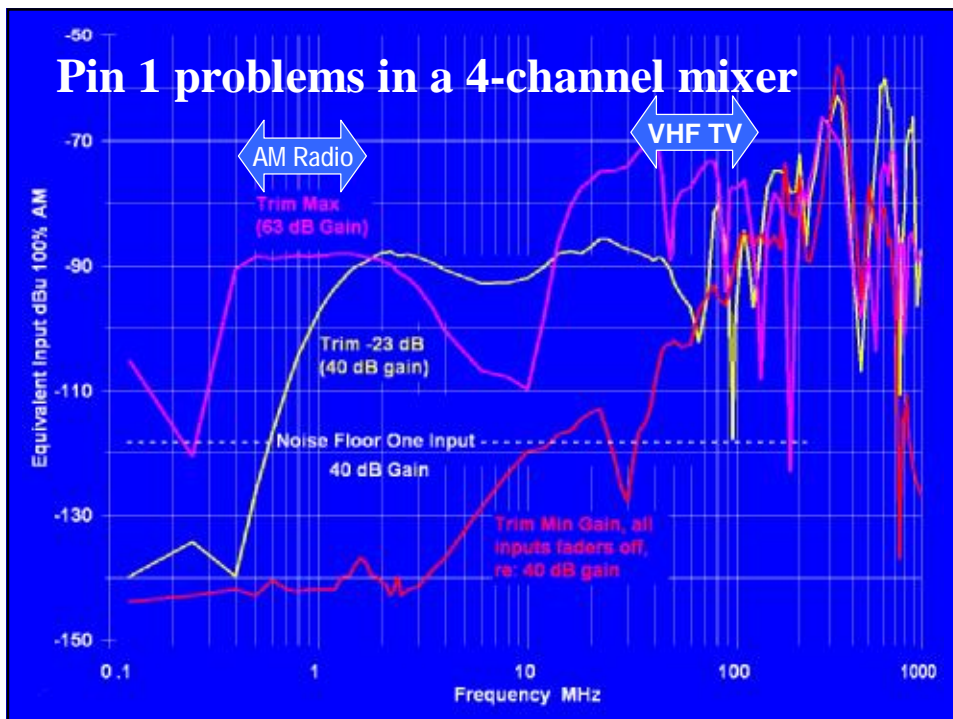


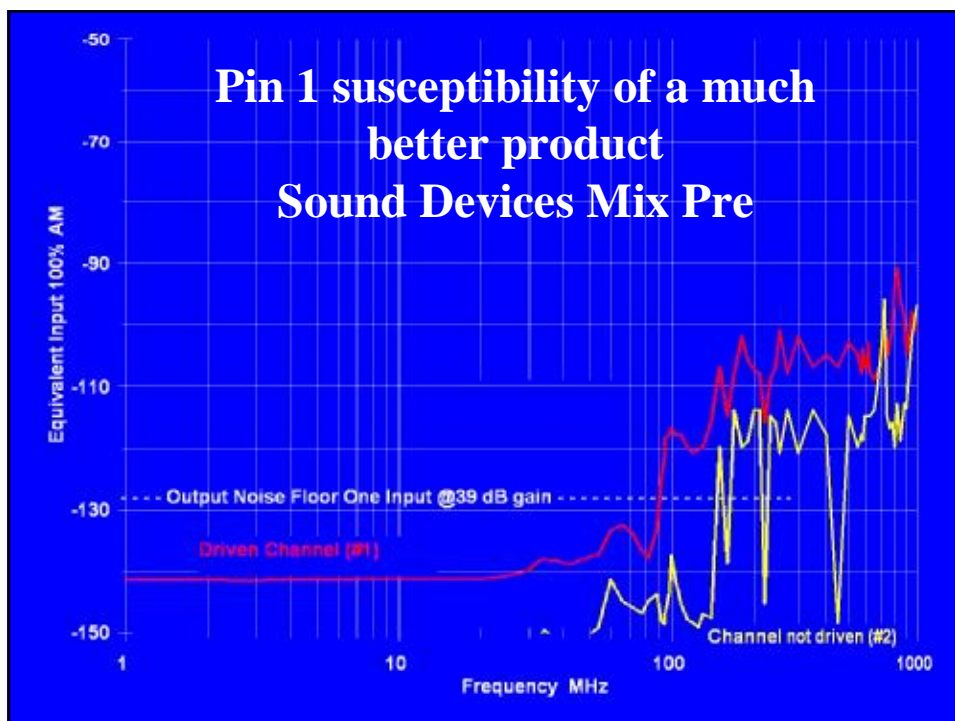
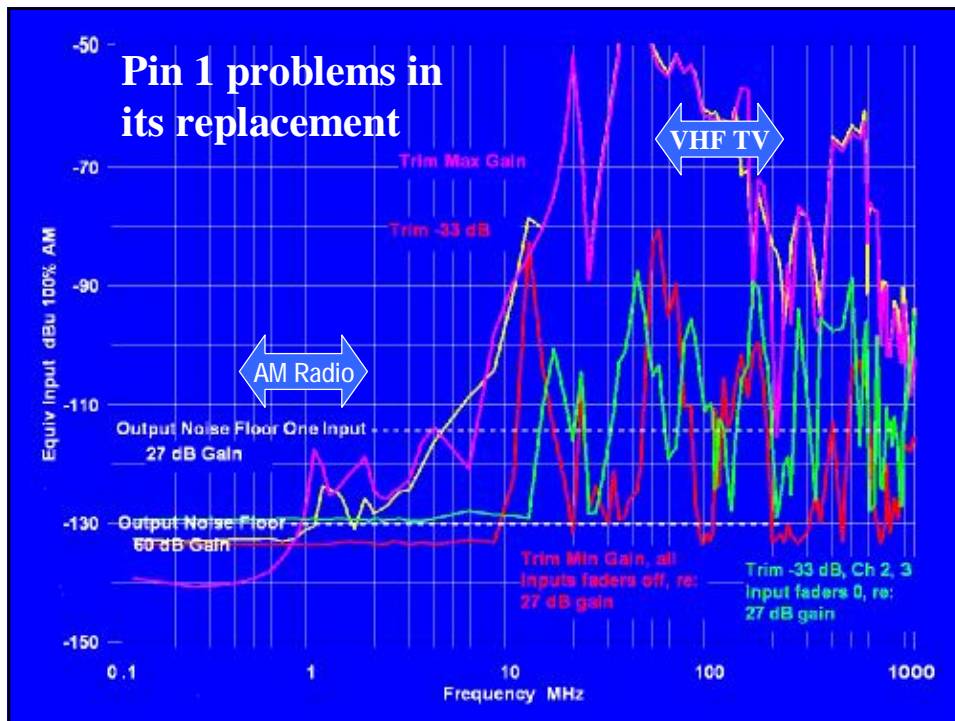
## Plastic body connectors not connected to chassis

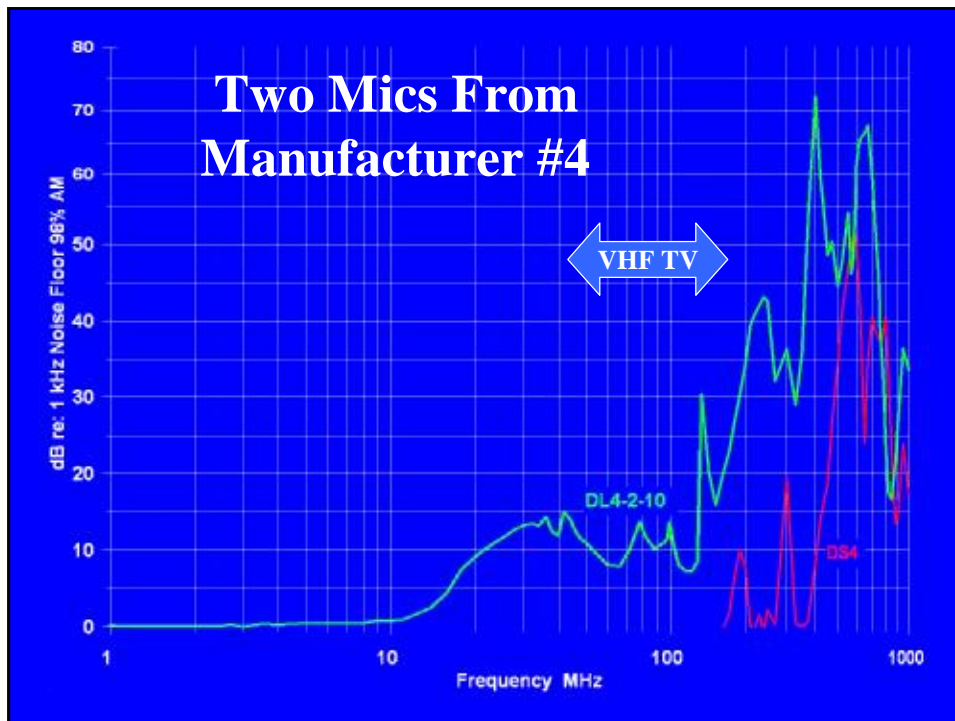
- Massive Pin 1 problem!
- Pin 1 test hits threshold of compression 20-50 MHz!
- The CE sticker assures EMC? Not here!

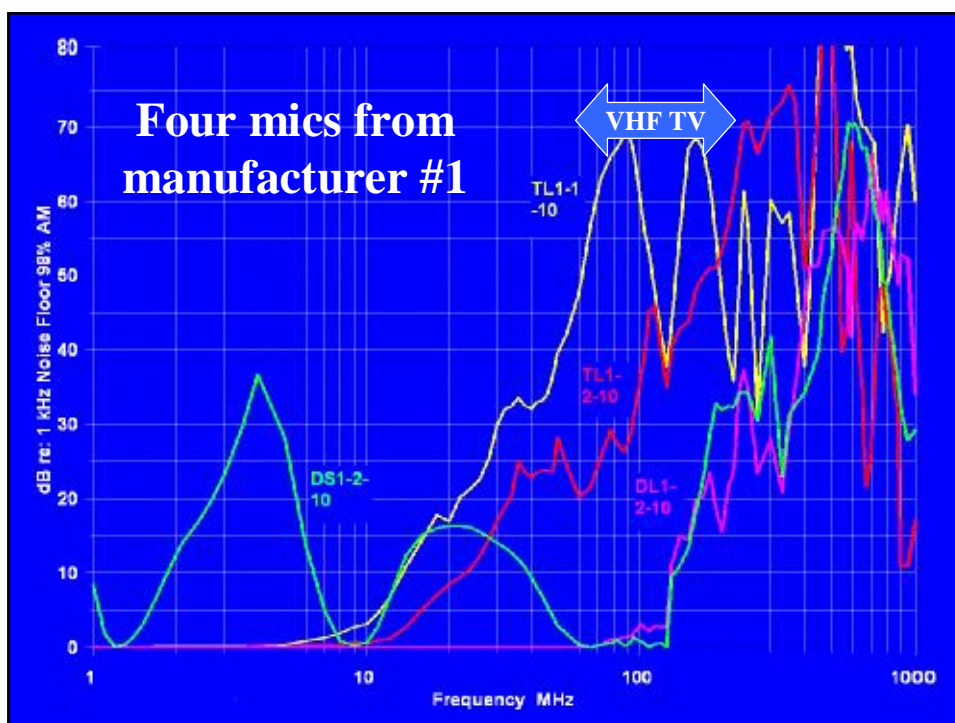


## Pin 1 problems in a 4-channel mixer



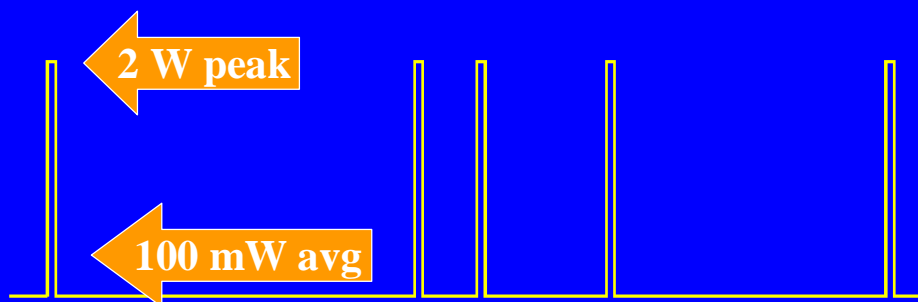






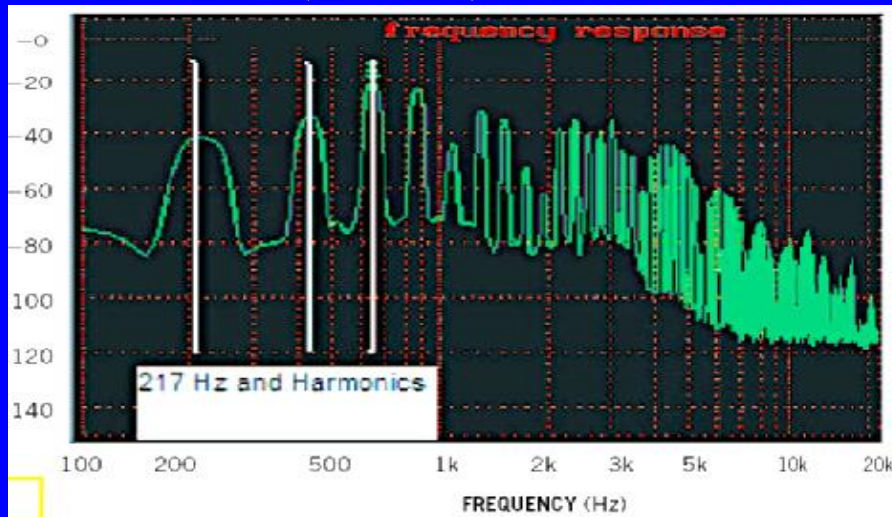
## Why are Cell Phones Difficult?

- Very close to our equipment
- Ultra high frequency = very short wavelength
- Short wavelengths are difficult to filter
- Short wavelengths are difficult to shield
  - Small openings let RF in
- 100% AM, short square pulses



**Low Duty Cycle Waveform of  
typical GSM and IDEN Cell Phone.  
Generically, it is Time Division  
Multiplex (TDMA)**

## Spectrum of detected GSM or IDEN (Nextel) Cell Phone



## Why are Cell Phones Difficult?

- Very close to our equipment
- Short wavelengths are difficult to filter
- Short wavelengths are difficult to shield
- 100% AM, short square 217 Hz pulses
- 2 W peak power, 100 mW average
- Detected spectrum is midrange audio
- Equipment designers have ignored them

## **Cable construction is part of the problem!**

- **No cable is perfect**
  - Inductive imbalance (SCIN)
  - Capacitive imbalance
  - Imperfect shielding (tiny openings in braid)
- **Even small imperfections become more important at higher frequencies**
  - No effect on audio
  - BIG effect on RFI



**Foil/Drain Shield**



**Braid/Drain Shield**



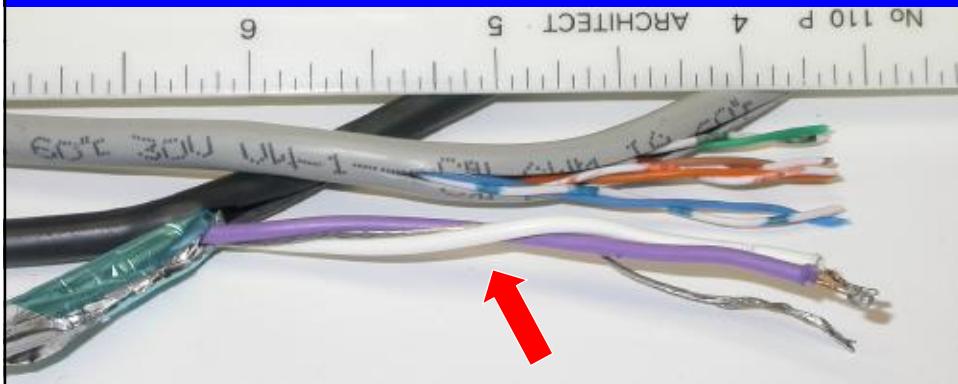
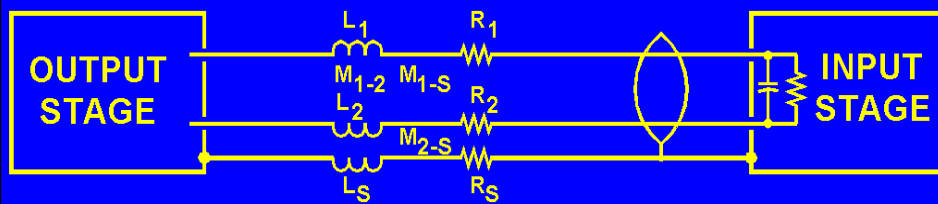
**Braid/Foil Shield**

**The drain wire is coupled more closely to the white conductor**

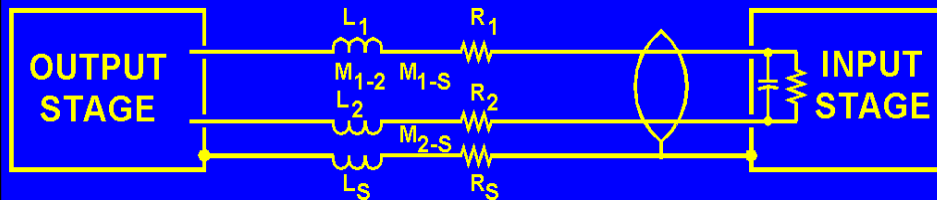


**So shield current induces more voltage on white than violet**

### **Inductive Imbalance**

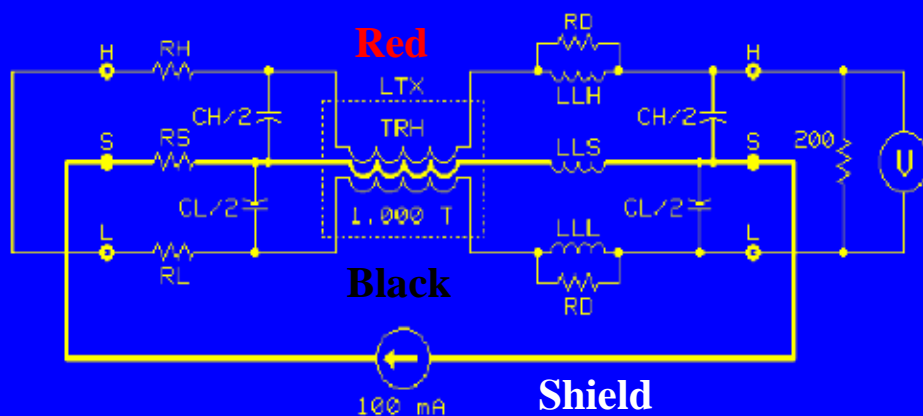


## Inductive Imbalance



- Below about 5 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

## **So Equipment Needs RF Filtering!**

- **Antenna action induces common mode RF to equipment**
  - Need common mode filtering
- **Cable imbalances convert common mode to differential mode**
  - Need differential mode filtering

## **Current Flows in Loops**

- **Where does the return current flow?**
  - Large loop area = strong magnetic coupling
  - Long wires = better antennas

## **Antennas Work Without a Loop**

- **Most efficient if  $\lambda/4$  or odd multiple of  $\lambda/4$**
- **Start “kicking in” at  $\lambda/20$**
- **Generally need something to be “the other half of the antenna”**
- **Current and voltage peak  $\lambda/4$  apart, repeat at intervals of  $\lambda/2$**

## **Antennas Inside Equipment**

- **Wires and circuit traces are antennas too**
- **Shield the equipment**
- **Add a ground plane on a second layer**
  - **Each circuit trace becomes a transmission line**
  - **Return current flows on the ground plane under the trace**
  - **Minimizes the loop area**
  - **Minimizes antenna action**
  - **Microstrip (one ground plane)**
  - **Stripline (two ground planes sandwich the trace)**

## **Enemies of Good Shielding**

- **Plastic cases**
- **Openings in shielded cases**
  - Slots
  - Paint

## **Is a Cable Shield Important for Balanced Audio Cables?**

## Shielded Twisted Pair

### The bad:

- The shield provides no magnetic shielding
- The shield can cause SCIN, degrading noise rejection
- Unequal capacitances between conductors and the shield can degrade noise rejection
- Provides a current path to excite pin 1 problems

## Shielded Twisted Pair

### The good:

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

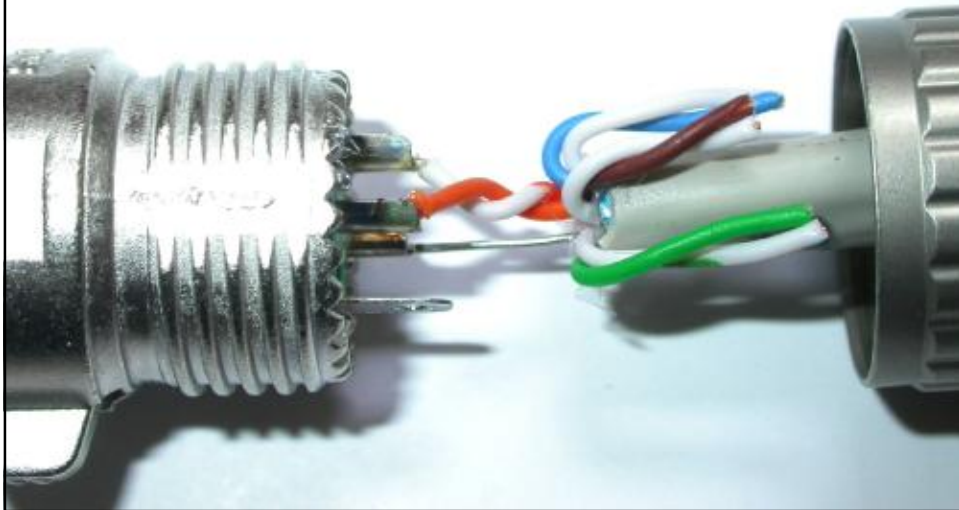
## **Twisting**

- **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**

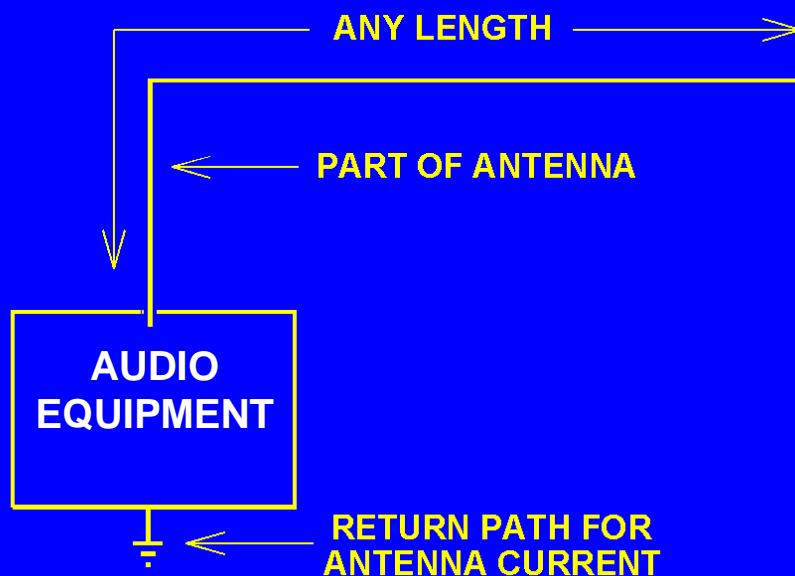
### **Conclusions:**

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

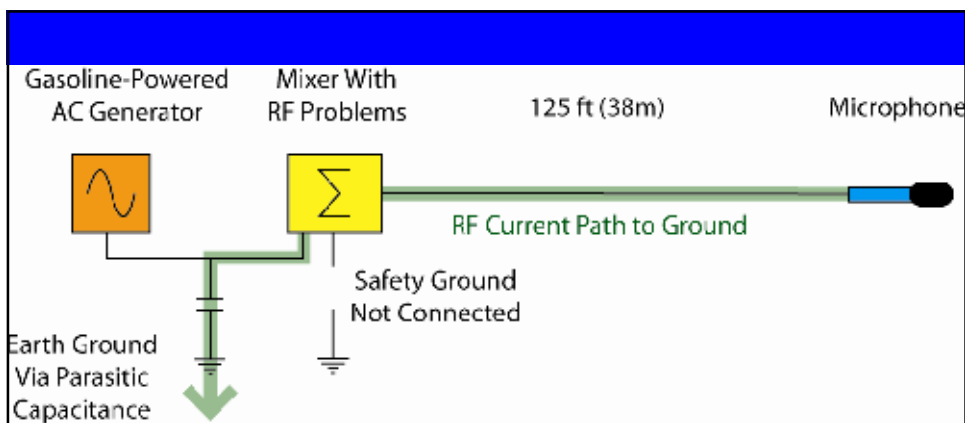
- **Twisting is far more important than shielding**
- **A cable shield can degrade immunity**

## Using Ferrites to Tame the Antennas

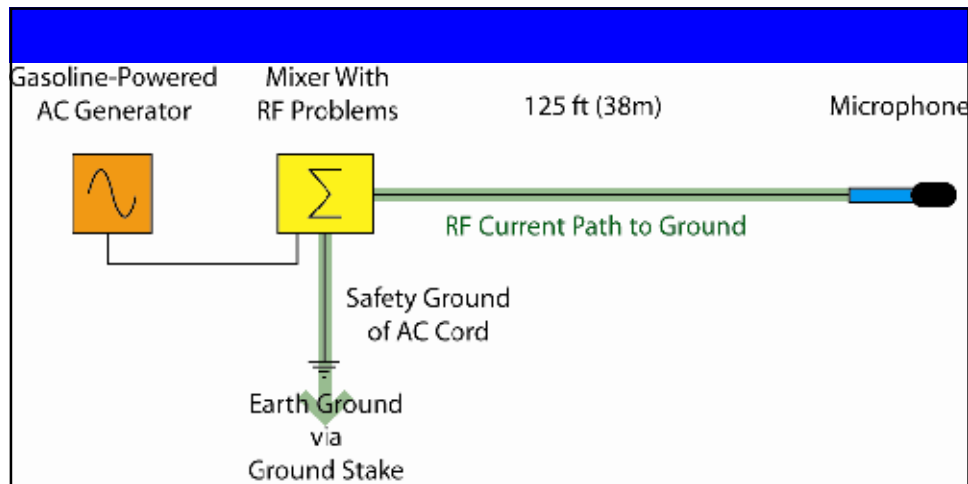
### Basic Random Long Wire



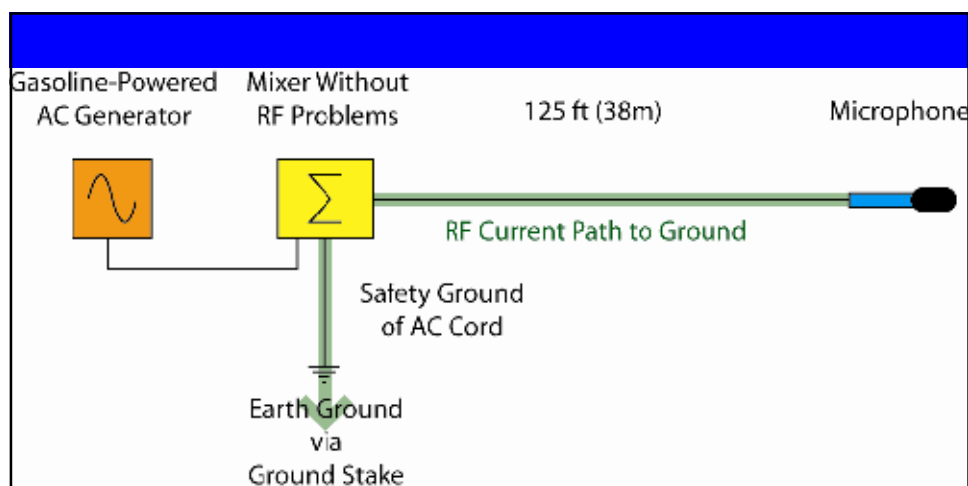
## Testing mics and input gear for RFI AM Radio – 50kW on 720 kHz



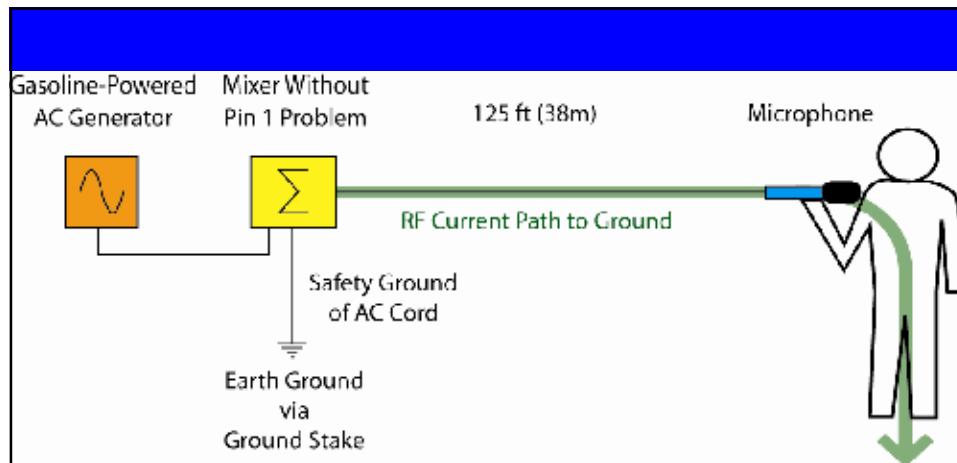
**A poor RF ground (only the capacitance), so not much interference**



**A better RF ground (the ground stake), so much more interference**



**No RF ground for the mic, so no interference**

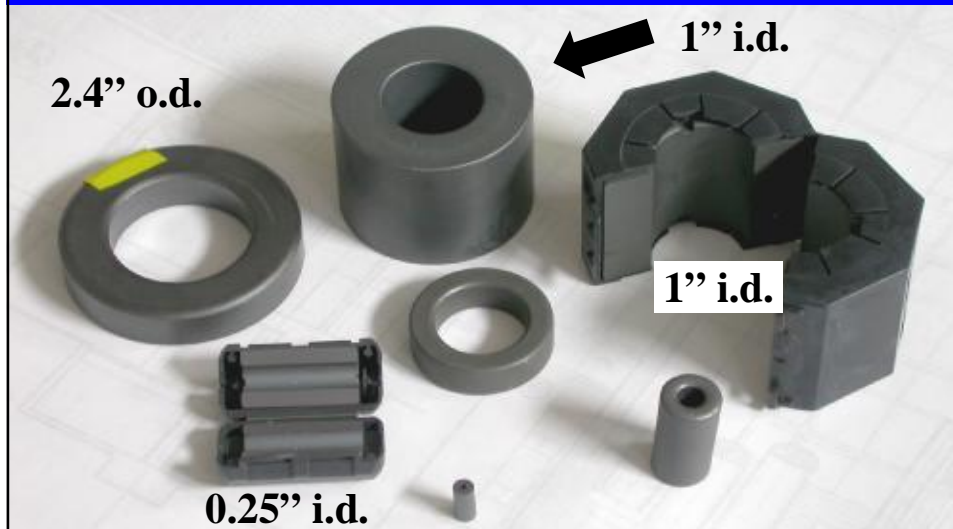


**But when my assistant held the mic in his hand, some mics had RFI**

**Ferrites can block the current!**



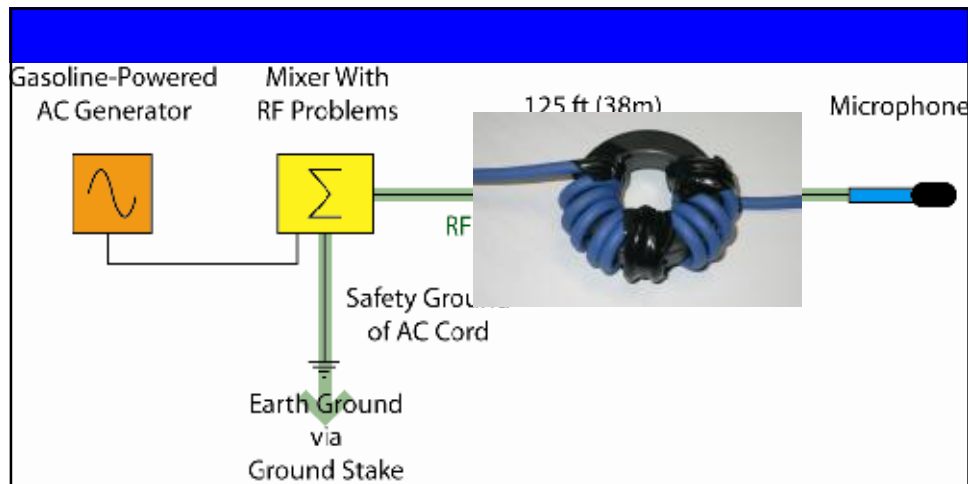
## Different sizes and shapes



## An AM Broadcast Choke



**14 turns of mic cable around this ferrite can kill AM broadcast RFI**



**This choke reduced the current,  
and thus the RFI**

**This “Clamp-On” forms a choke that  
can kill interference from FM and TV**



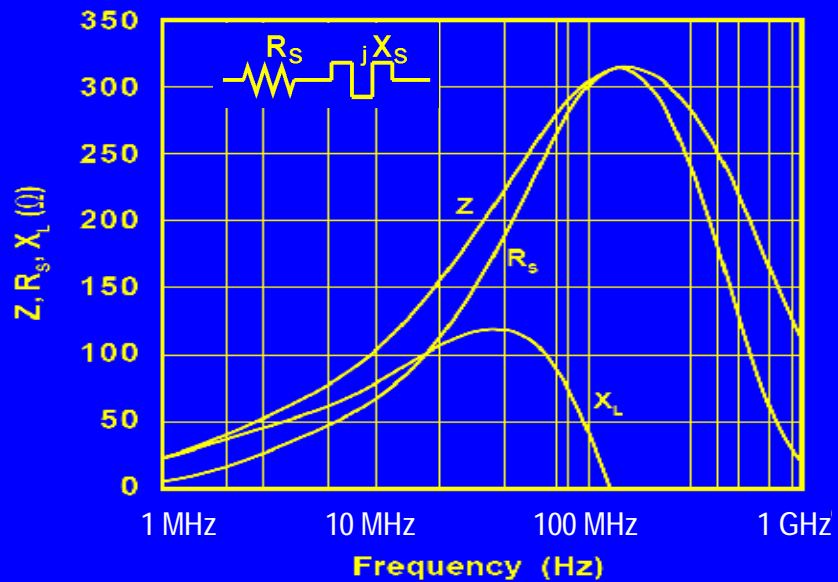
## What's a Ferrite?

- A ceramic consisting of an iron oxide
  - manganese-zinc – 1-30 MHz (AM broadcast, hams)
  - nickel-zinc – 30 MHz-1 GHz (FM, TV, cell phones)
- Has permeability ( $\mu$ ) much greater than air
  - Better path for magnetic flux than air
  - Multiplies inductance of a wire passed through it
- Is very lossy at radio frequencies
- Does not affect audio

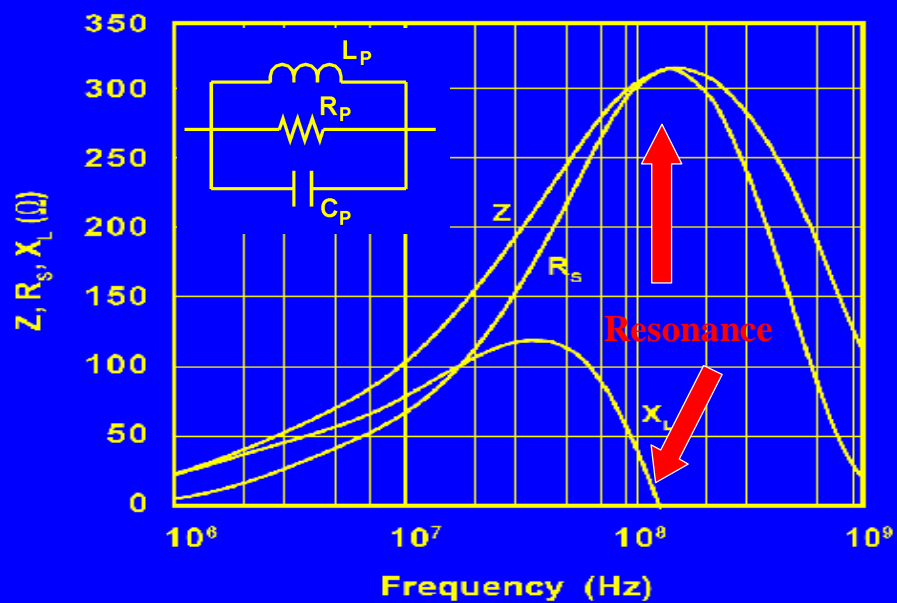
## A (too) simple equivalent circuit of a wire passing through a ferrite



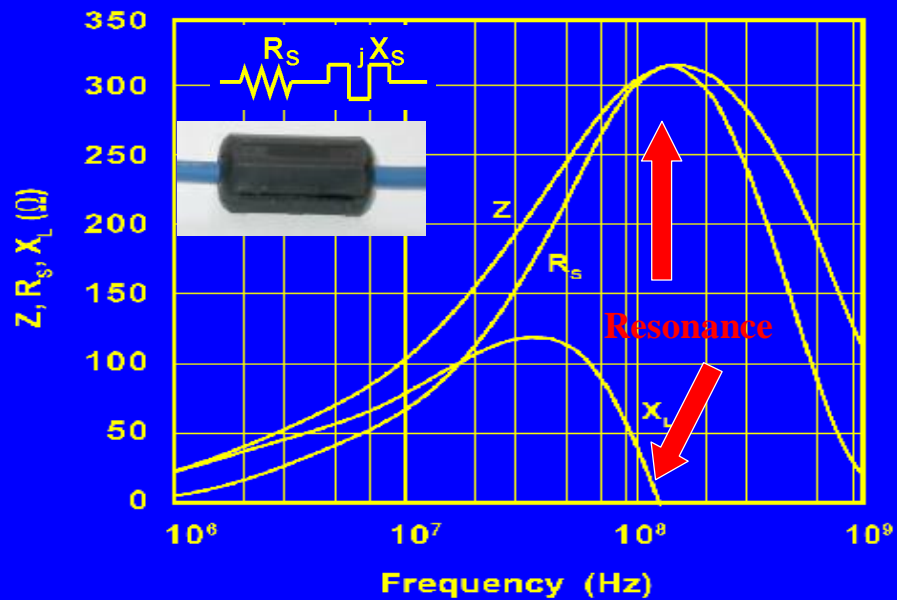
## Impedance of Wire Through Ferrite



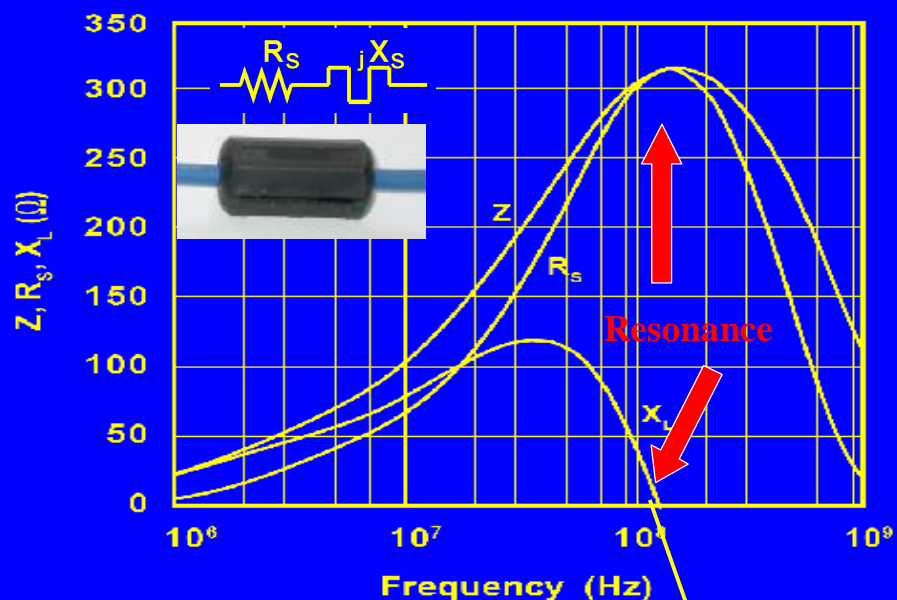
## It's Really a Parallel Resonance



## Data Sheets Show the Resonance



## Data Sheets Show the Resonance



**Where's the Capacitance here?**

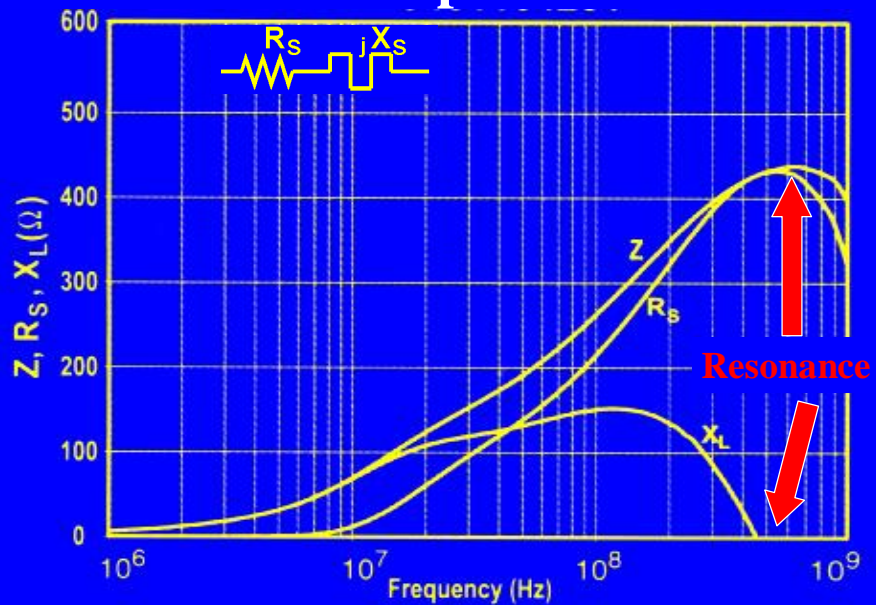


**Where's the Capacitance here?**

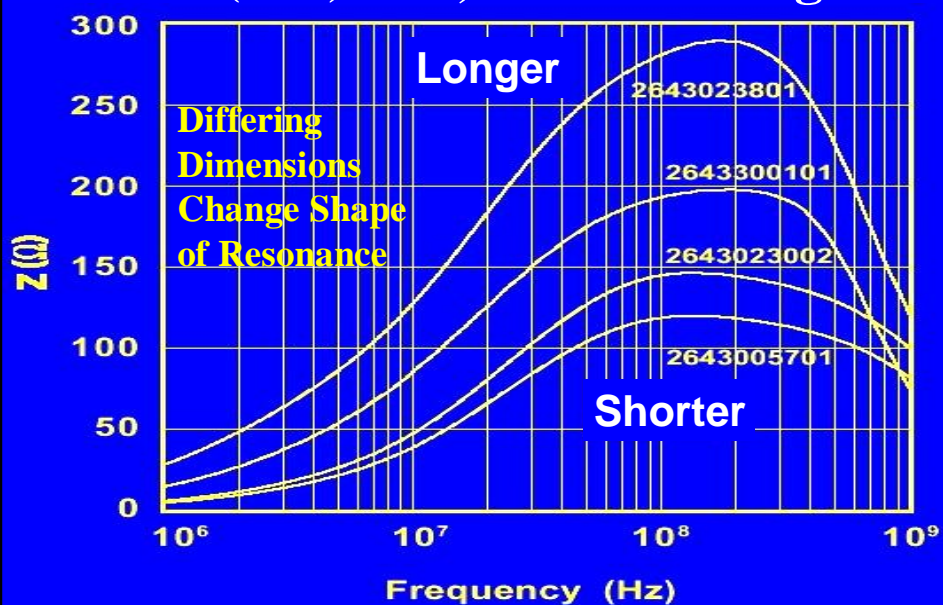


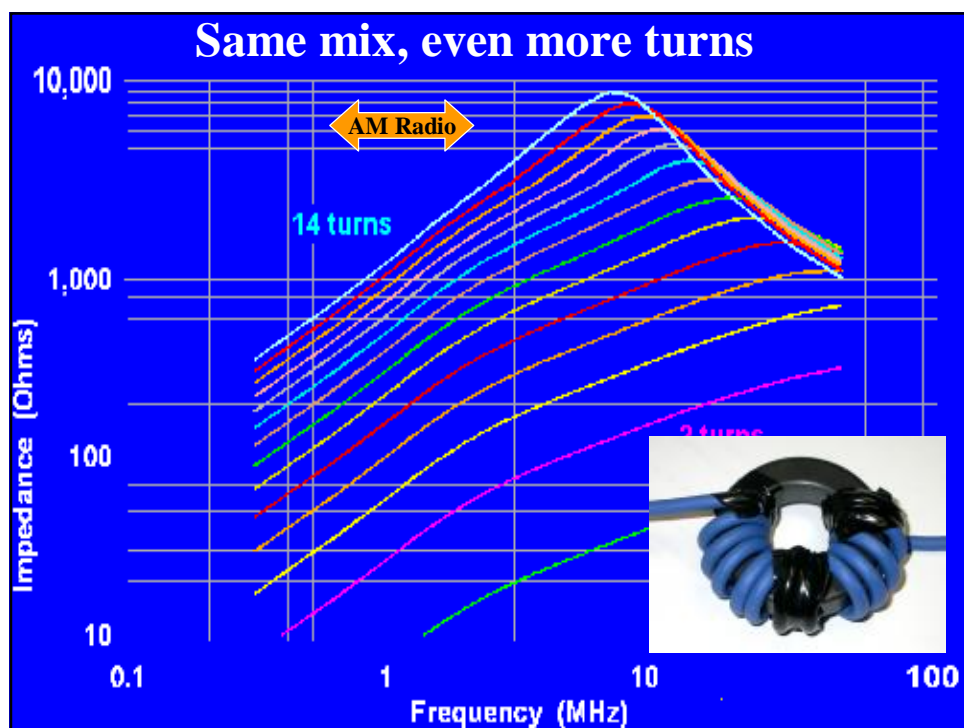
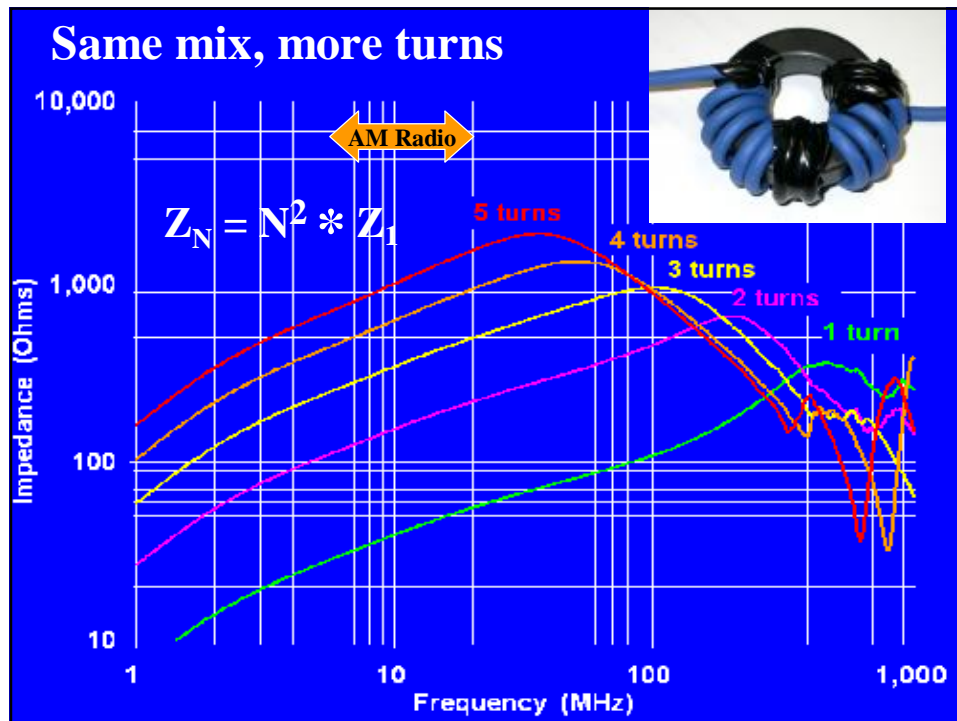
**From the wire at one end of the choke to the wire at the other end, through the permittivity of the ferrite (it is a dielectric!)**

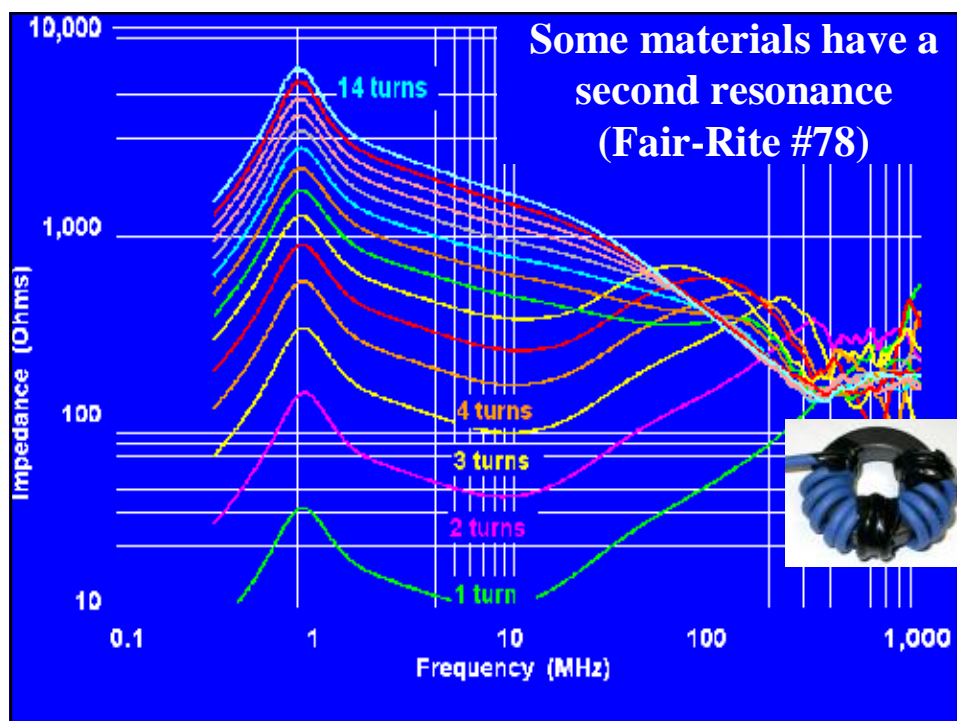
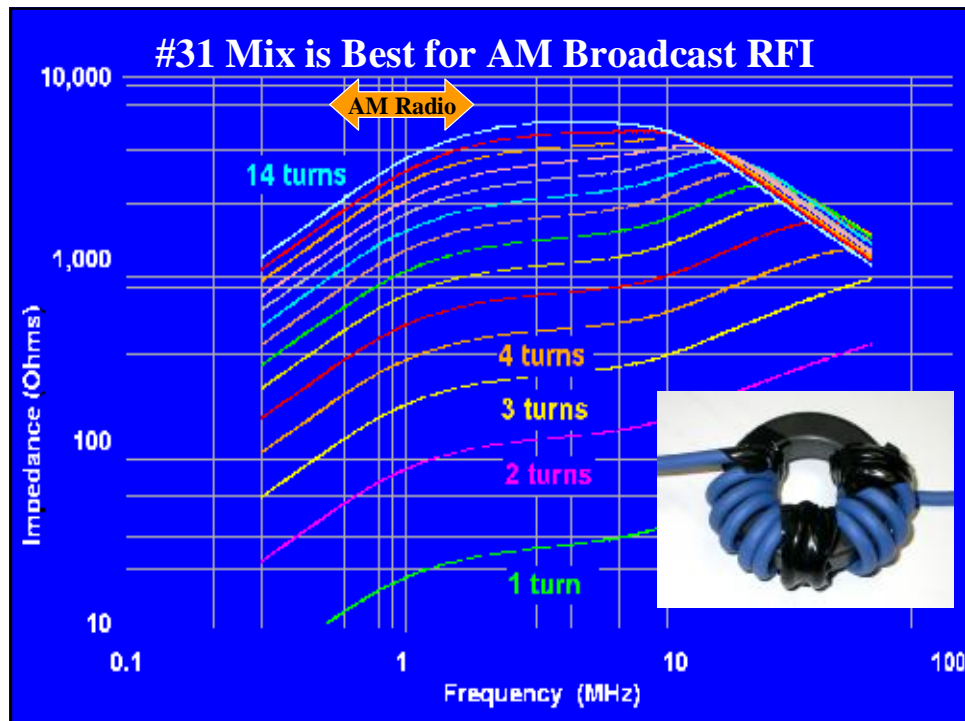
## A Ferrite Mix Optimized for UHF

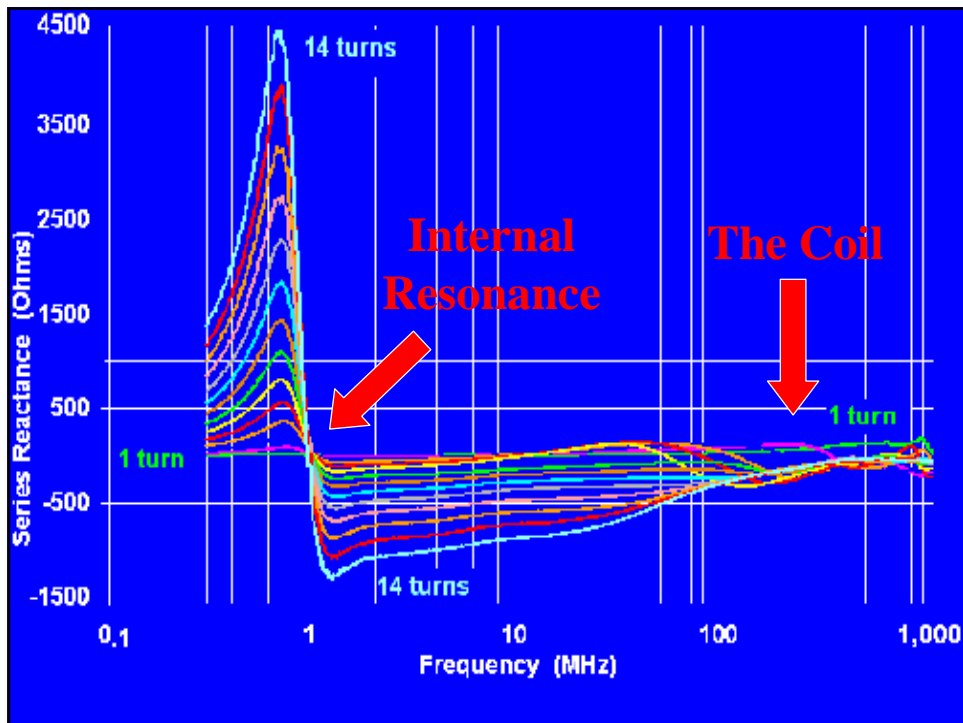


## VHF (#43) mix, different lengths!

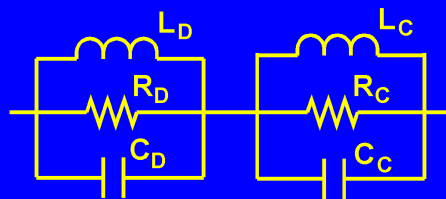








## A Better Equivalent Circuit



**Coil**

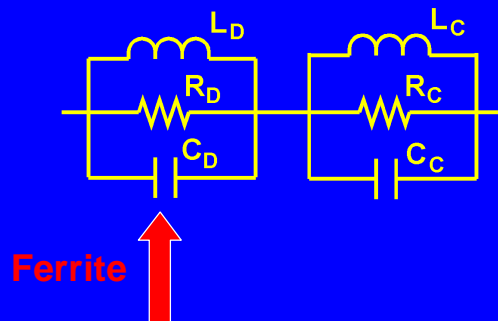
$L_C$  is the inductance of the coil

$C_C$  is the stray capacitance of the coil

$R_C$  is the resistance of the wire.

$L_C$  and  $C_C$  form the resonance that moves!

## A Better Equivalent Circuit



$L_D$  and  $C_D$  represent the *dimensional* resonance of the ferrite itself

$R_D$  is the loss within the ferrite

## What Causes this Resonance?

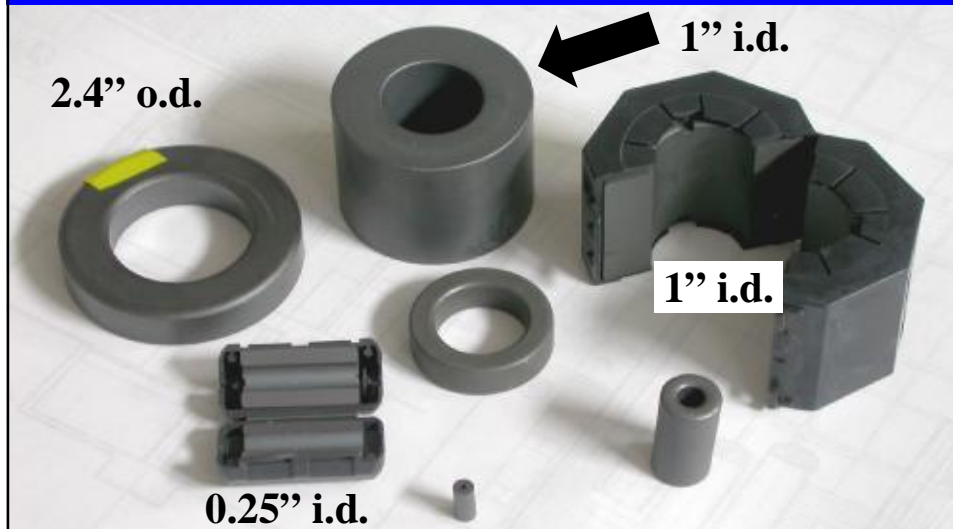
The ferrite material (called the “*mix*”), and  
The physical dimensions of the ferrite core.

- The velocity of propagation within the ferrite establishes standing waves within the core

$$V_P = \mu e \text{ (that is, permeability * permittivity)}$$

- *Dimensional resonance* occurs when the cross-section is a half-wavelength
- Frequency of the resonance depends on:
  - Velocity of propagation (depends on the “*mix*”)
  - Dimensions of the cross-section of the flux path

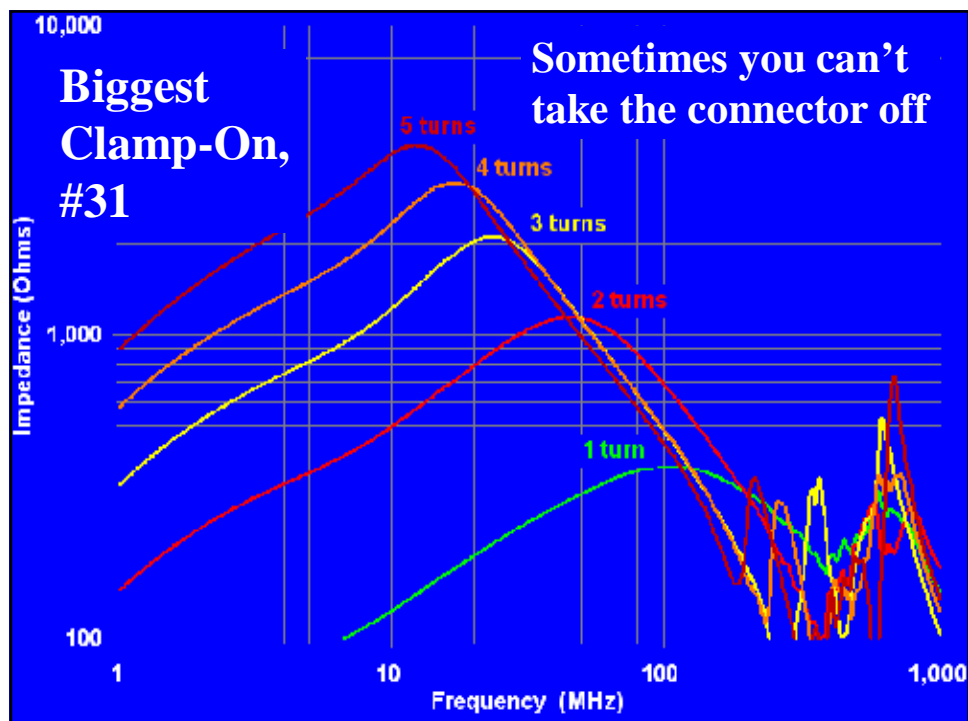
## How About Mic Snakes?



## If You Can't Remove the Connector



**If you can't easily remove the connector**

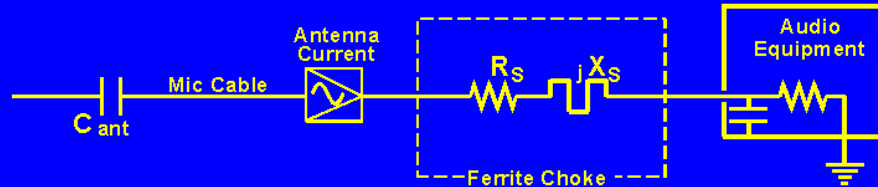


## **Techniques for Suppression**

### **You May Not Need an Elephant Gun**

- **Most detection is square law, so:**
  - **A 10 dB reduction in RF level reduces audible interference by 20 dB**
- **But we must add enough impedance to overcome the threshold effect**

## Threshold Effect



### Example:

Our antenna is short, so looks capacitive

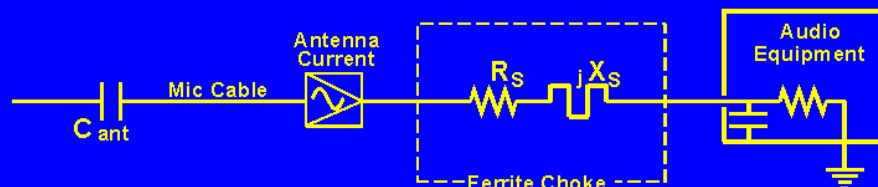
Without the choke, the total antenna circuit is  $300 \angle -60^\circ \Omega$ ,

and we add a choke that is  $300 \angle 60^\circ \Omega$ ,

$$Z_T = (150 - j260) + (150 + j260) = 300 \Omega$$

Our choke has not helped!

## Threshold Effect



But if we make the choke larger (more turns or more cores in series), additional  $R_s$  will begin to reduce the current.

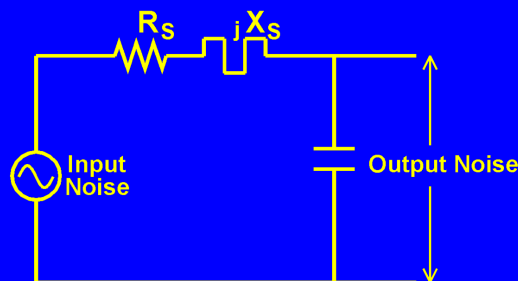
Increasing  $R_T$  to  $425 \Omega$  (3 dB) reduces detected RF by 6 dB, and increasing  $R_T$  to  $600 \Omega$  (6 dB) reduces detected RF by 12 dB (assuming no change in  $X_s$ ).

## Threshold Effect

- For “brute force” suppression, the ferrite choke should add enough series  $R$  that the resulting  $Z$  is 2x the series  $Z$  of the “antenna” circuit without the choke. This reduces RF current by 6 dB, and detected RF by 12 dB.
- Very little suppression occurs until the added  $R$  is at least half of the starting  $Z$ .

## Capacitance Can Help a Lot

- Outside the box, we’re stuck with what the designer provided, so a big ferrite is needed
- Inside the box, we can use a much smaller ferrite part if we provide the capacitor



## Criteria for Good Suppression

- Choke should be predominantly resistive
- With voltage divider (capacitor across input)
  - A few hundred ohms can be very effective
- No voltage divider (brute force)
  - 500–1,000 ohms typically needed to hit threshold
  - More is better
- 1,000 ohms  $R_S$  is a minimum design goal
- More is better

## Golden Rules to Avoid RFI

- Loudspeaker Cables
  - Always use TWISTED PAIR
  - Shielding is not important
  - Exotic cable is a waste of money

**This expensive loudspeaker cable  
makes equipment vulnerable to RFI**



**Parallel wire (zip cord) has very  
poor RFI rejection**

**Twisted pair cables help  
equipment reject RFI**



**#12 POC \* is great loudspeaker cable!**



**POC – Plain Ordinary Copper**



## **Golden Rules to Avoid RFI**

### **Mic and Line level Cables**

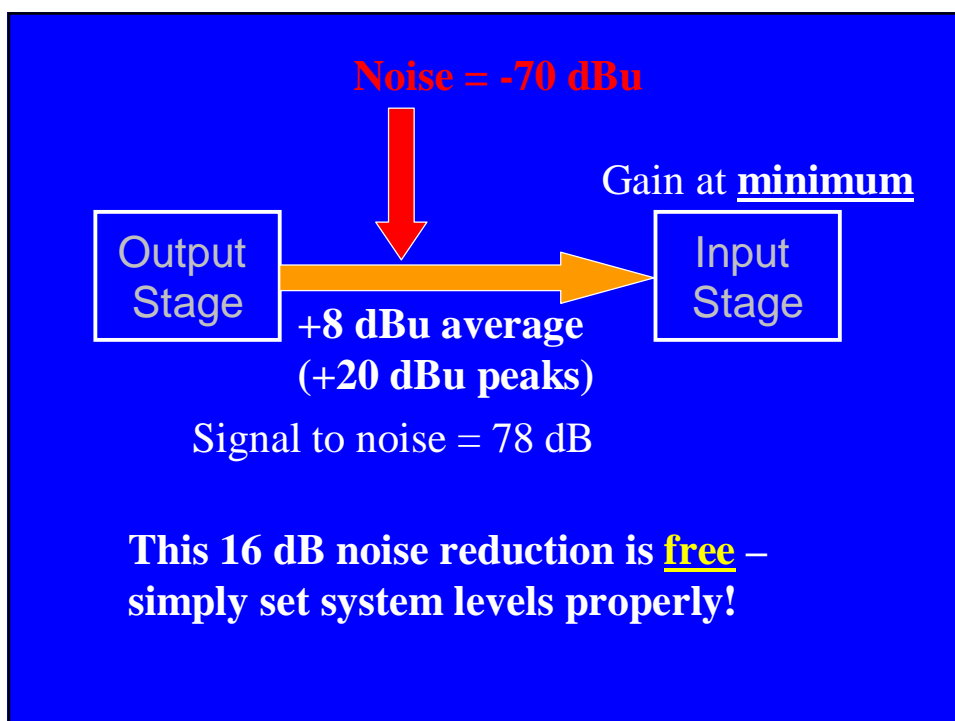
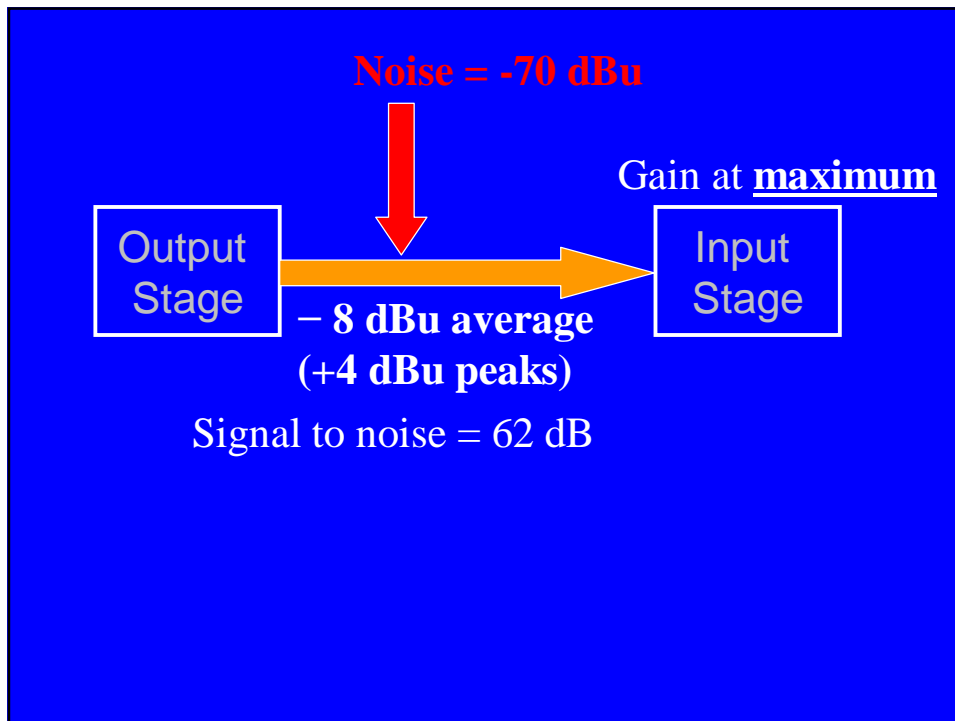
- Avoid drain wires in shields
- Use braid shielded cable
- Use twisted pair (tighter twist helps too)

## Golden Rules to Avoid RFI

- Maximize audio levels on cables
  - Run line level outputs near their maximum levels
  - Set inputs near their minimum gain
- 15-20 dB of noise rejection for free!

## Critical Product Specifications

- Maximum input level
  - How much signal does it take to clip the input stage?
- Maximum output level
  - How much can the box produce cleanly?

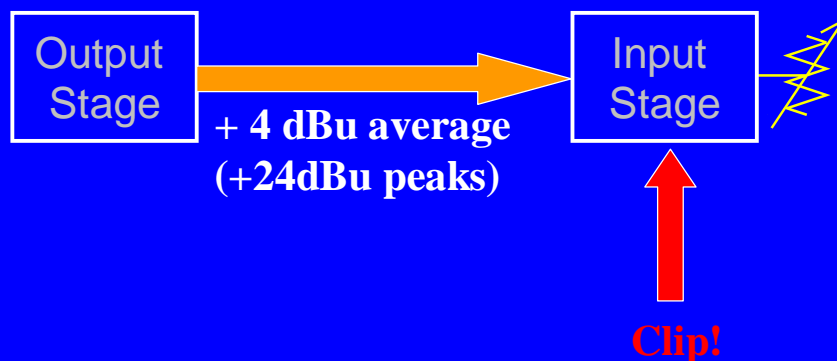


## What is Professional Level?

- Average level of Program: +4 dBu
- RMS value of Program Peaks: +24 dBu

**A product that does not support these levels is not a professional product!**

## A Poorly Designed Input Stage

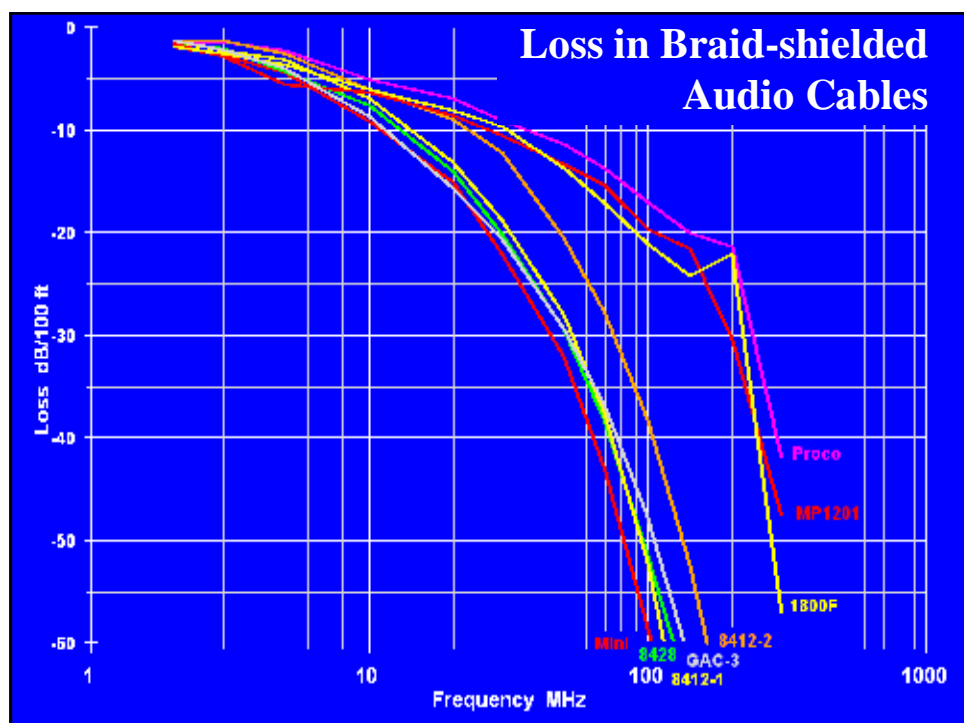
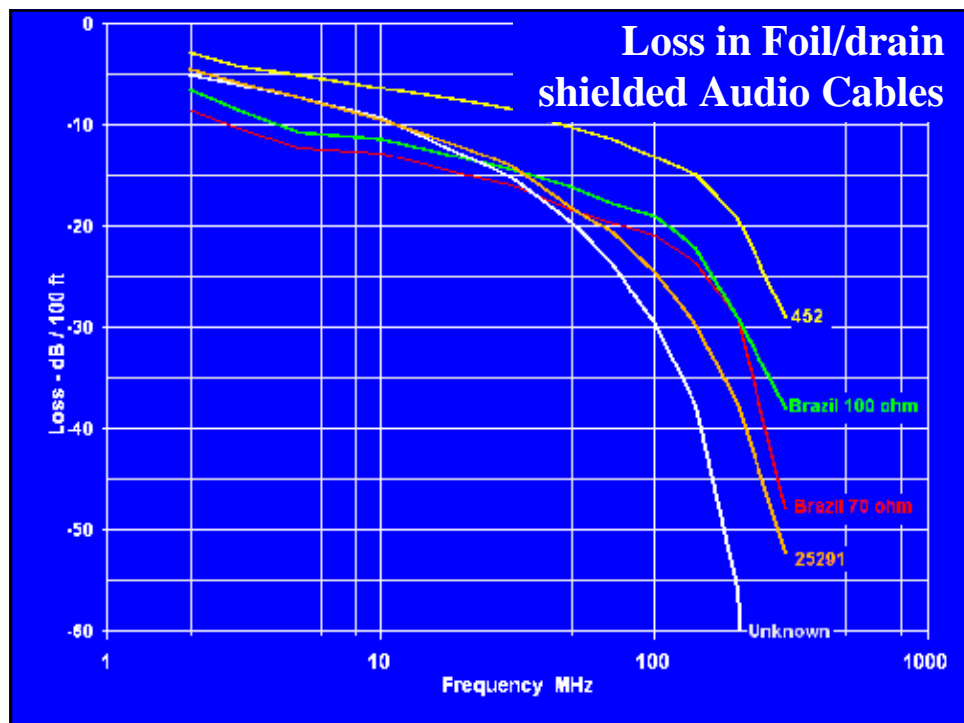


## **Golden Rules to Avoid RFI**

- **Don't overlook output stages**
  - Feedback networks
  - Pin 1 problems
- **Power amplifiers**
- **Headphone amplifiers**
  - Twisted pair

## **Golden Rules to Avoid RFI**

- **RFI often enters equipment (and systems) by more than one path.**
- **Always assume that there are other paths!**
- **Take a methodical approach. Don't give up when one "right" technique doesn't fix it – keep on doing other "right" things. The "right" techniques really are right!**



## Digital Equipment

- Any equipment with digital circuitry, a clock, or a switching power supply can cause RFI as well as receiving it
  - Unlikely to interfere with audio
  - Is likely to interfere with wireless mics

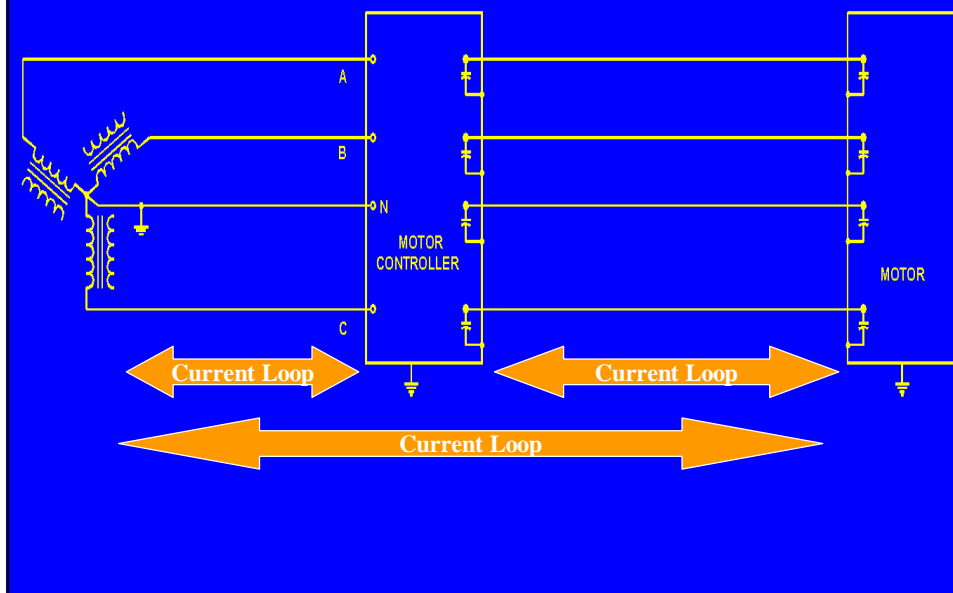
## Reciprocity

- In general, shielding and filtering that reduces emissions will also reduce susceptibility
- Passive networks, shielding, and antennas work in both directions  
BUT:
- If impedances on either side are different, they may not work equally in both directions

## Common Bear Traps

- Watch out for coherent addition
  - RF at multiple inputs will have random phase at each input
  - Detected audio is precisely in phase at multiple inputs (maybe out of polarity)
- RFI can build by 3 dB per doubling
  - 6 dB for four inputs
  - 12 dB for 16 inputs
  - 15 dB for 32 inputs

## Variable-Speed Drive Motors



## **Variable Speed Drive Motors**

- **Operates by chopping sine wave with a variable pulse width**
  - 10-20 kHz typical switching frequencies
  - Harmonics extend to hundreds of kHz
- **Stray capacitance (and filter capacitors) between motor and earth causes very large currents to flow on earthed structure**
  - Establishes a very large current loop
- **Controllers often widely separated from motors to make installation easier**

## **Variable Speed Drive Motor Solutions**

- **Minimize the size of the current loops**
  - Locate transformer, controller, and motor in closest possible proximity to each other
  - Transformer should have delta primary, wye secondary, bonded very close to motor
    - Prevents feeders to transformer from being part of the current loop
  - Twist neutral and phase conductors

## New EMC Connectors

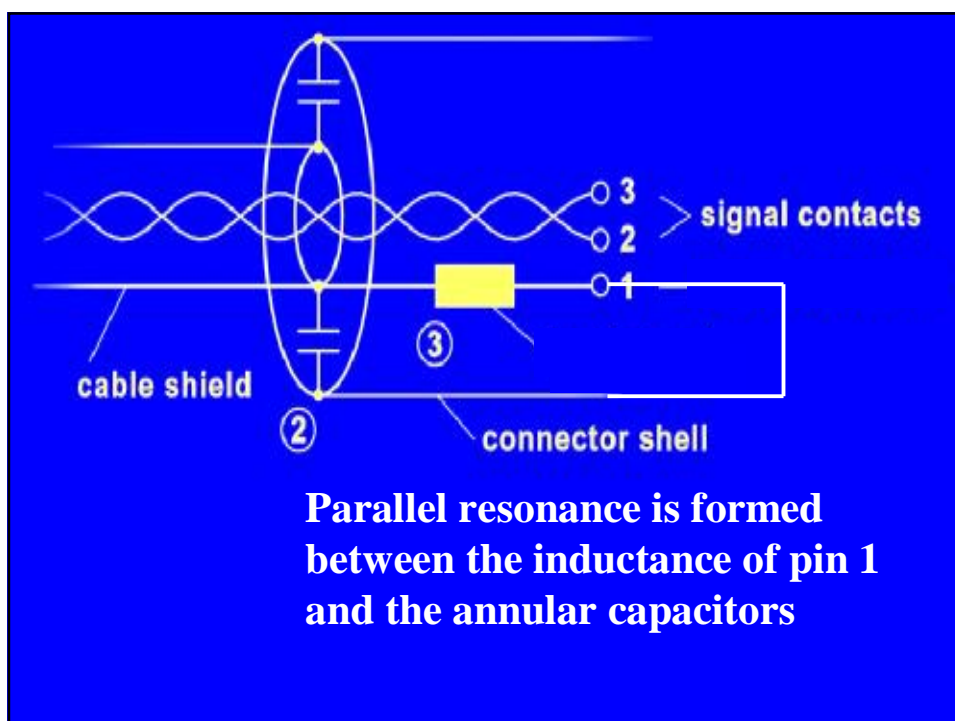
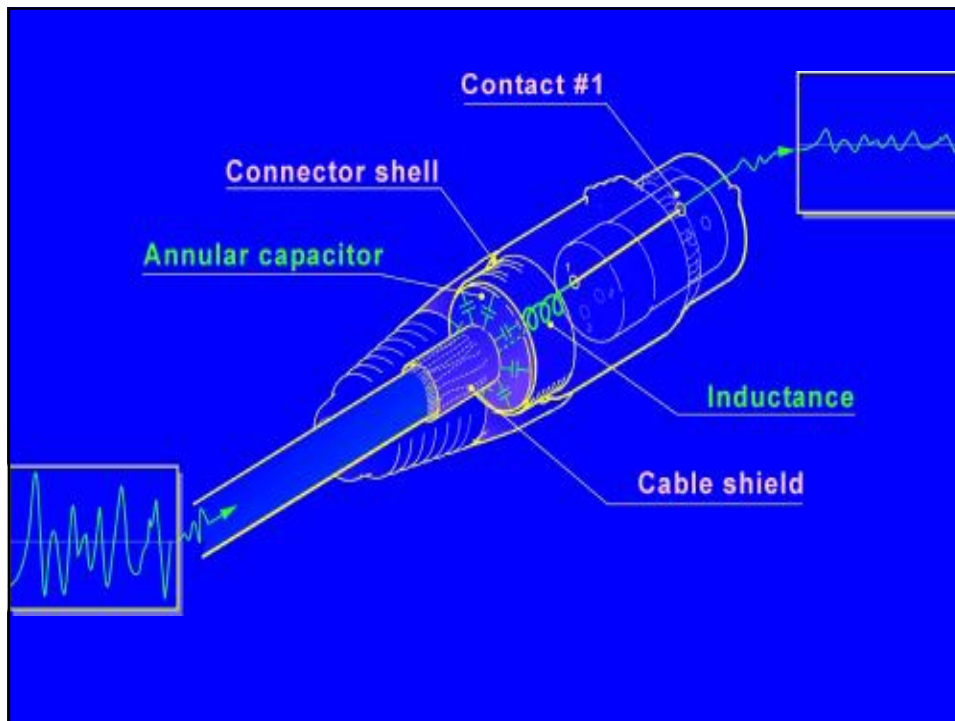
- Annular ring of capacitors connects shield to shell
  - Low inductance – good connection  $> 1$  GHz
  - More continuous shielding
  - Ferrite bead on pin 1

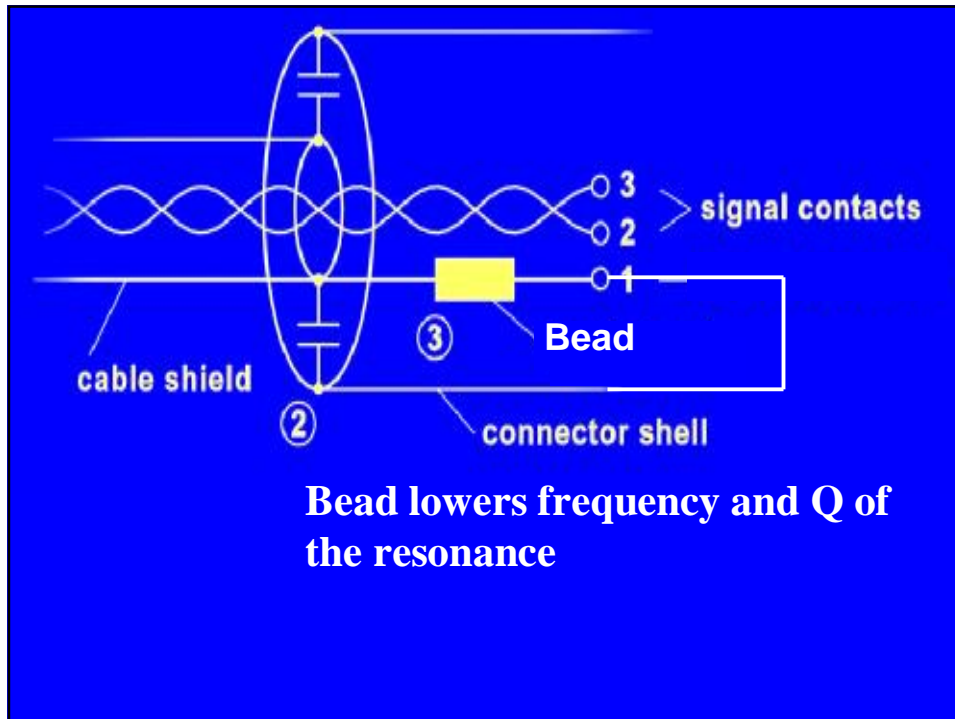


## New EMC Connectors

- Female has same internal construction
  - Additional spring improves shell contact with mating connector







## 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.

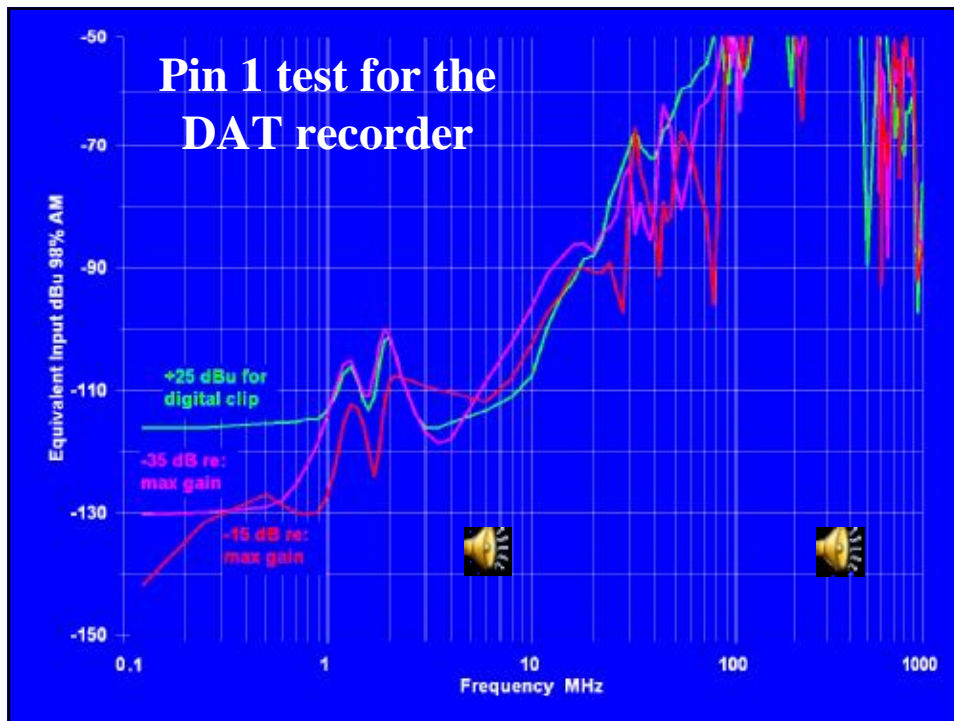
## Benefits of the EMC Connector

- **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**

**this DAT recorder has a serious  
Pin 1 problem, and Mating XL  
shells do not make good contact**



**So the EMC connector can't help!**



## Acknowledgements

- Ron Steinberg
- Neil Muncy
- David Josephson
- Dr. Leo Irakliotis
- Henry Ott
- Steve Kusiceil
- Fair-Rite Products

**RFI In Audio Systems  
Pin 1 Problems,  
Poor Shielding, and Poor  
Input/Output Filtering**

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