RFI, Unintentional Antennas, and Ferrites

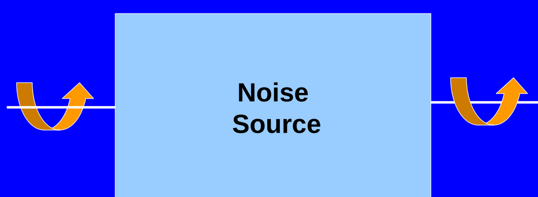
Jim Brown K9YC
Audio Systems Group, Inc.
Santa Cruz
jim@audiosystemsgroup.com

Primary RFI Mechanisms

- Common-mode noise on signal wiring
  - Pin 1 problems
  - Improper shield termination within equipment
  - A form of common-mode coupling
- Differential noise on signal pairs
  - Inadequate filtering on I/O wiring
- Inadequate shielding of equipment
- Coupling on power and control wiring

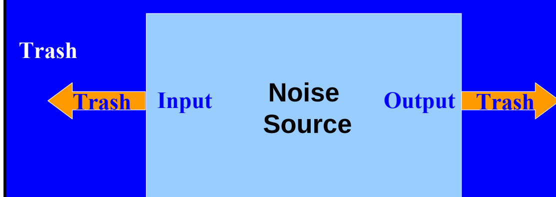
Common Mode Coupling

- I/O wiring acts as long wire antenna
- Noise current flows lengthwise on wiring



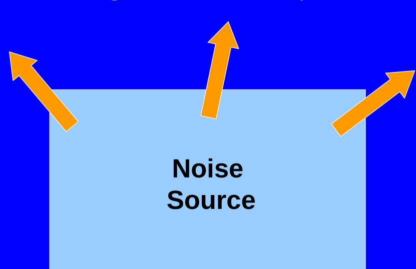
Differential Mode Coupling

- I/O wiring is not band-pass filtered
- Noise is between + and – terminals of wiring



Poor Equipment Shielding

- Internal wiring radiates directly



The Principle of Reciprocity – Coupling Works Both Ways

- If the coupling is passive, what helps minimize <u>received</u> interference will generally also help reduce <u>transmitted</u> noise
- Relative <u>strength</u> of coupling depends on impedances of the coupled circuit, and may not be equal in both directions

Common Mode Coupling

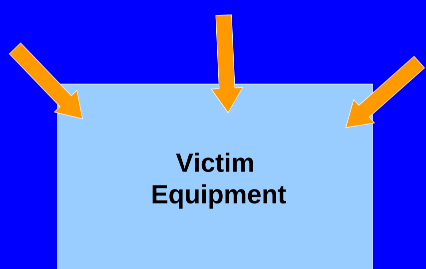
- I/O wiring acts as long wire antenna

Differential Mode Coupling

- I/O wiring is not band-pass filtered

Poor Equipment Shielding

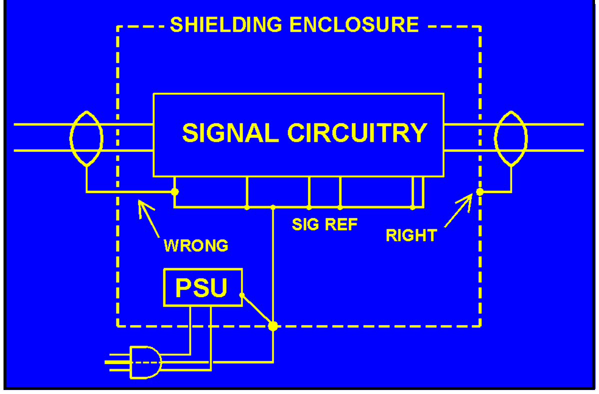
- Internal wiring is receiving antenna



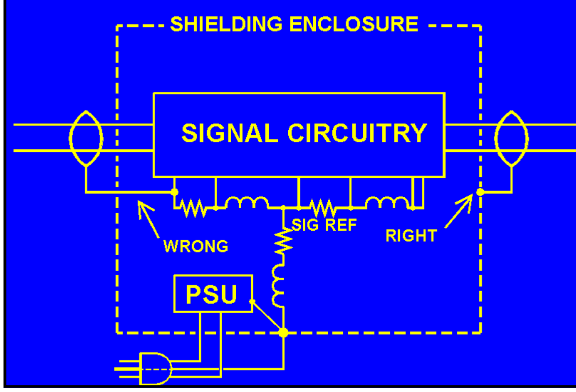
Common Mode Coupling

- The “Pin 1 Problem”
  - First acknowledged in the pro audio world
  - Pin 1 is the shield of XL connectors
  - A major problem in <u>all</u> kinds of systems
- Cable shields should go to the <u>chassis</u>, <u>not</u> the circuit board
- Old fashioned connectors were mounted to the chassis
- Modern connectors mount to the PC board

Pin 1 in Balanced Interfaces

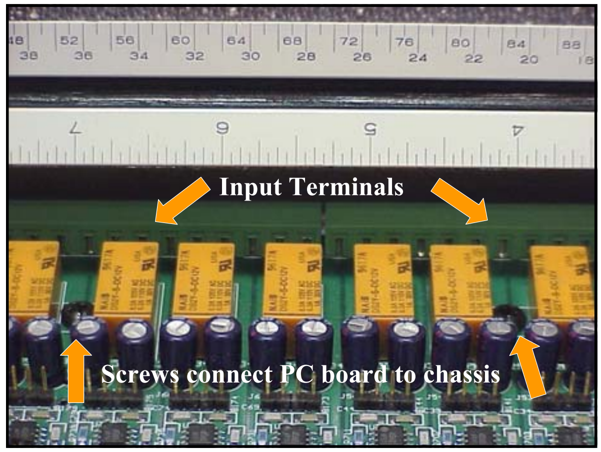


Pin 1 in Balanced Interfaces



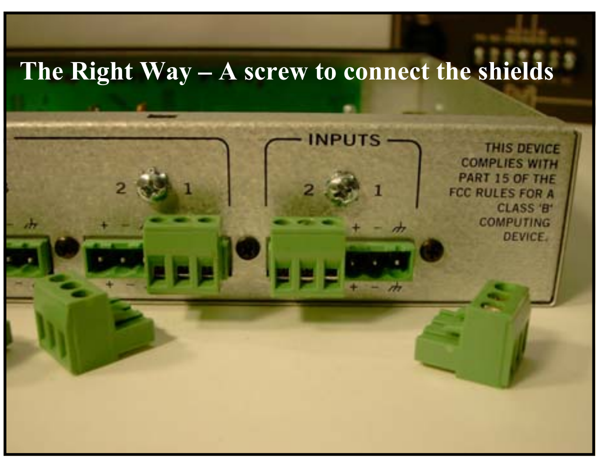
The G terminal goes to the enclosure, right?

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



A Pin 1 Problem in Obsolete Equipment, and a Really Long Path to the Chassis

Let's look behind the panel.

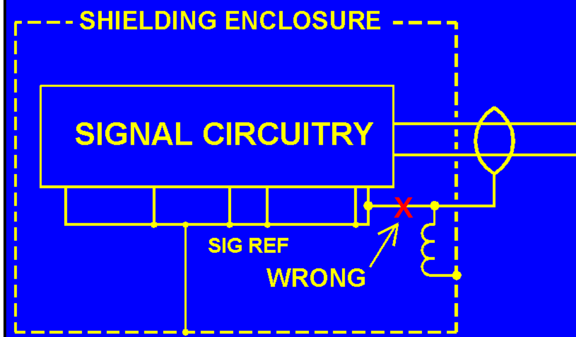


A classic RF pin 1 problem in a microphone

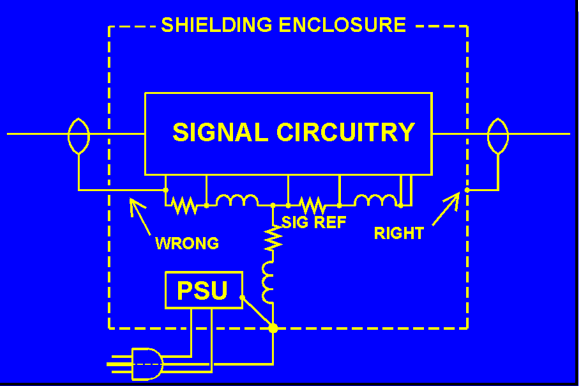
A classic RF pin 1 problem in a microphone

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

The Pin 1 Problem in Microphones



Pin 1 in Unbalanced Interfaces



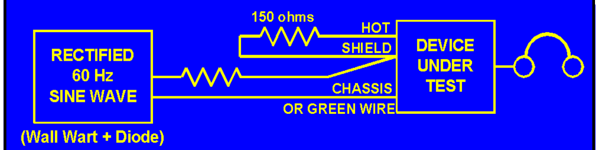
Some Classic Pin 1 Problems

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

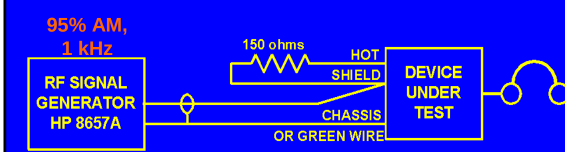
Testing for Pin 1 Problems

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



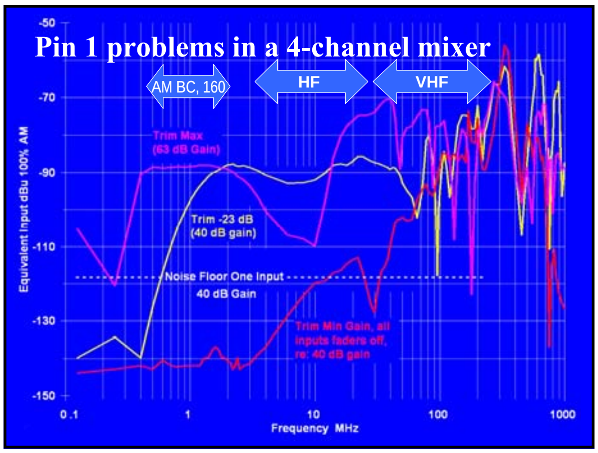
- Drive between "audio ground" and chassis
- Listen to the output
- If you hear it, you have a problem

RF Pin 1 Test Setup for Equipment

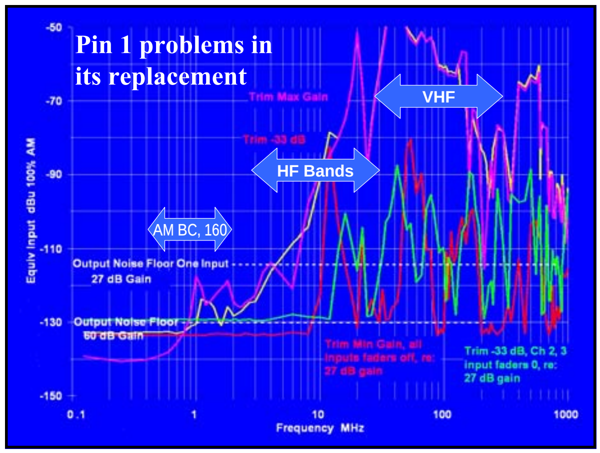


- Drive between "audio ground" and chassis
- Listen to the output
- If you hear 1 kHz, you have a problem

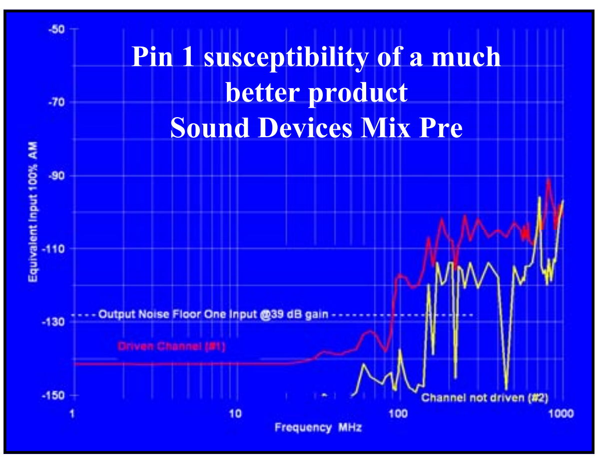
Pin 1 problems in a 4-channel mixer



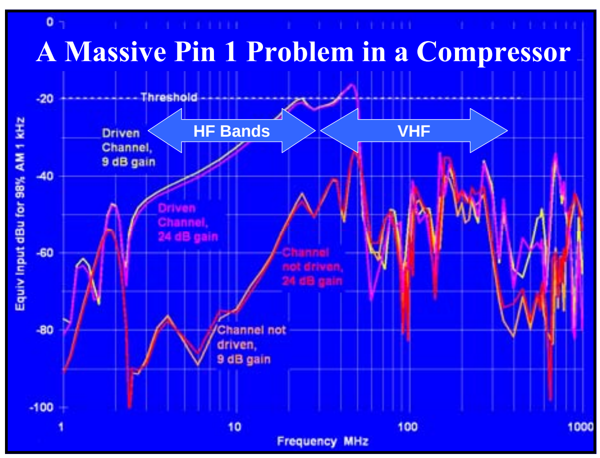
Pin 1 problems in its replacement



Pin 1 susceptibility of a much better product Sound Devices Mix Pre



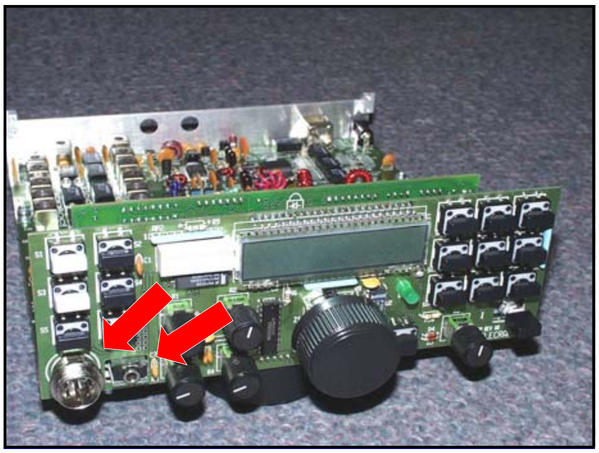
A Massive Pin 1 Problem in a Compressor

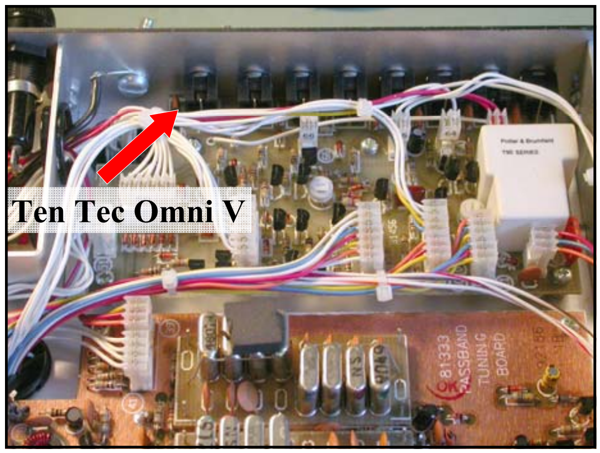


RF in the Shack is a Pin 1 Problem

- 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

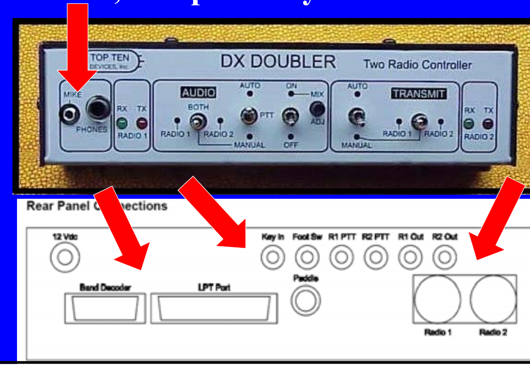




A Pin 1 Problem

RF Feedback on 15 Meters

Multiple Pin 1 problems cause hum, buzz, and probably RF feedback



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!

Hook-Up Cables are Antennas!

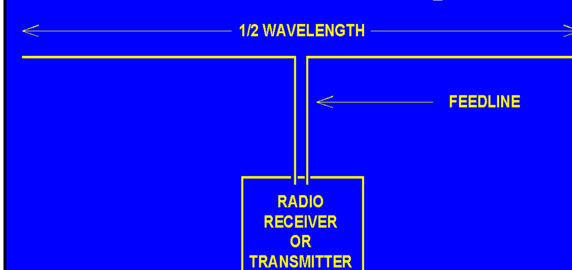
Hook-Up Cables are Antennas!

- Audio hookup cables
- Loudspeaker cables
- MATV Cables
- Computer Cables
- Video hookup cables
- Telephone cables
- Power cables

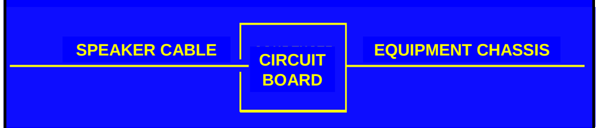
Antennas Inside the Ham Shack

- Mic cables
- Rig control cables
- Audio Interface Cables
- Computer Cables
- Power cables
- Keyer cables

A "Textbook" λ /2 Dipole

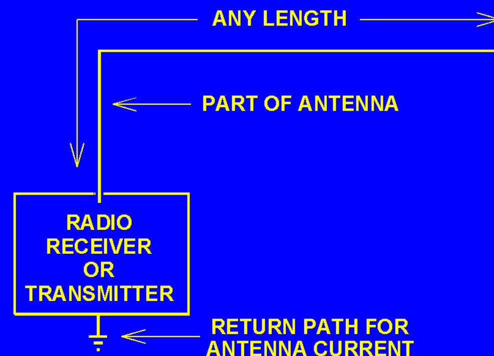


Battery Operated Equipment and its Cable can form a Dipole

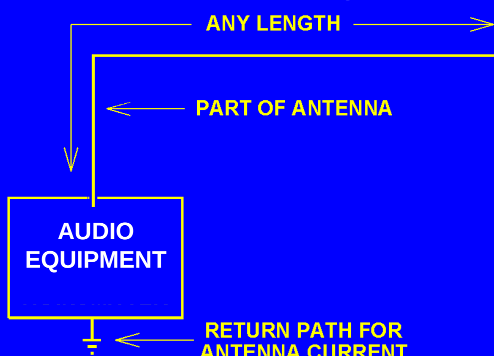


- It doesn't need to be an ideal quarter wave to work – it will just be less efficient and its directivity may change!

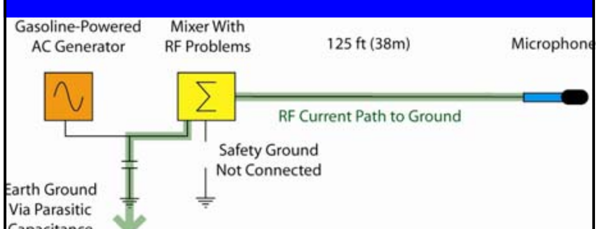
Basic Random Long Wire



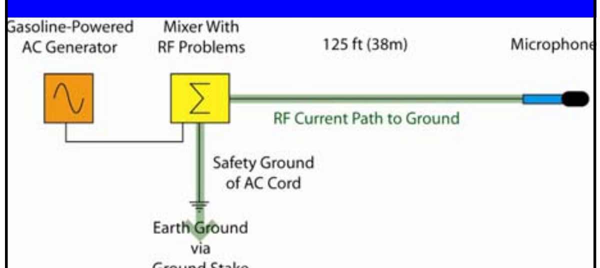
Basic Random Long Wire



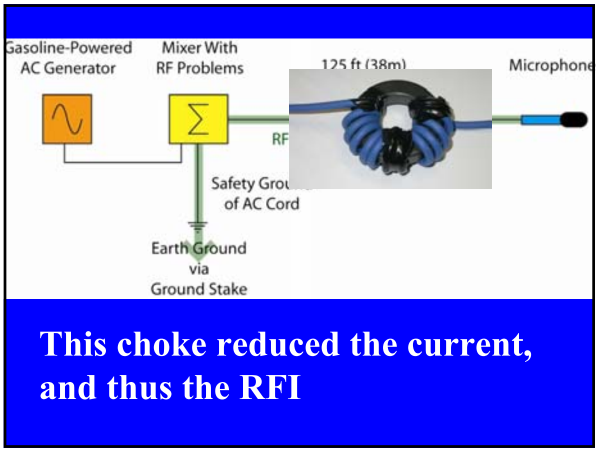
Example: 50kW on 720 kHz (WGN) to test mics and input gear for RFI



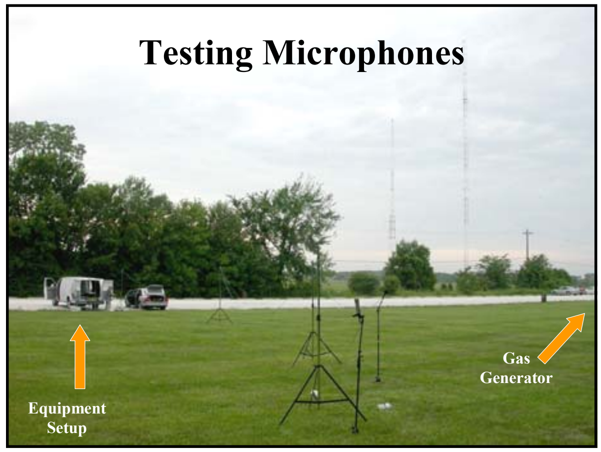
A poor RF ground (only the capacitance), so not much interference



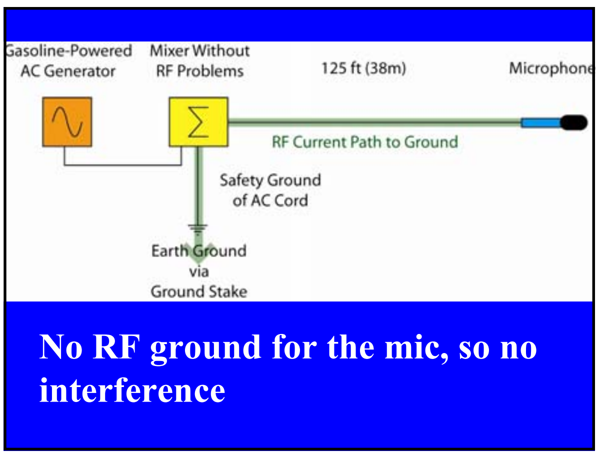
A better RF ground (the ground stake), so much more interference



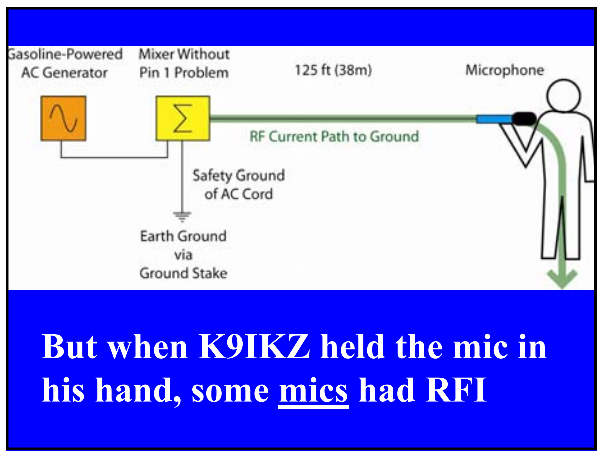
Gasoline-Powered AC Generator
Mixer With RF Problems
Microphone
RF
of AC Cord
Earth Ground via Ground Stake
This choke reduced the current, and thus the RFI



Testing Microphones
Equipment Setup
Gas Generator

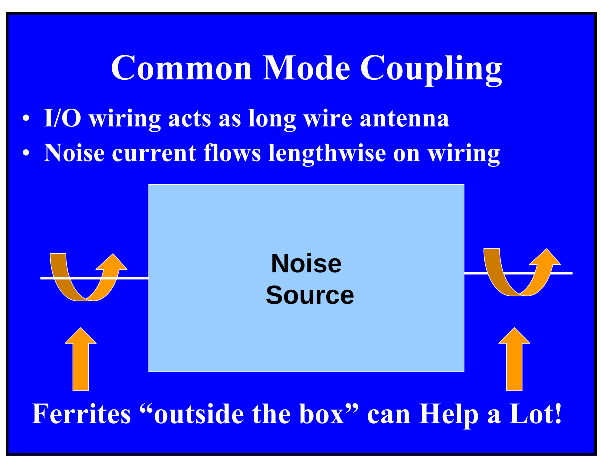


Gasoline-Powered AC Generator
Mixer Without RF Problems
125 ft (38m)
Microphone
RF Current Path to Ground
Safety Ground of AC Cord
Earth Ground via Ground Stake
No RF ground for the mic, so no interference



Gasoline-Powered AC Generator
Mixer Without Pin 1 Problem
125 ft (38m)
Microphone
RF Current Path to Ground
Safety Ground of AC Cord
Earth Ground via Ground Stake
But when K9IKZ held the mic in his hand, some mics had RFI

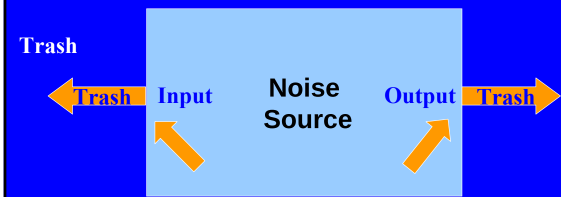
Ferrites can block the current!



Common Mode Coupling
• I/O wiring acts as long wire antenna
• Noise current flows lengthwise on wiring
Noise Source
Ferrites "outside the box" can Help a Lot!

Differential Mode Coupling

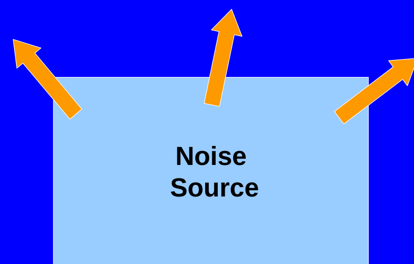
- I/O wiring is not band-pass filtered
- Noise is between + and – terminals of wiring



Ferrites can be used <u>inside</u> the box as part of low pass filters

Poor Equipment Shielding

- Internal wiring radiates directly



Ferrites don't help at all!

Different sizes and shapes

What's a Ferrite?

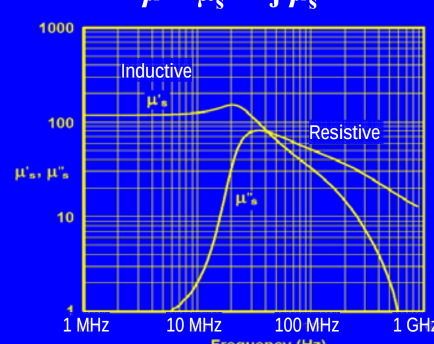
- A ceramic consisting of an iron oxide
  - manganese-zinc – 1-30 MHz (AM broadcast, hams)
  - nickel-zinc – 30 MHz-1 GHz (FM, TV, cell phones)
- Has permeability (μ) much greater than air
  - Better path for magnetic flux than air
  - Multiplies inductance of a wire passed through it
- Is increasingly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

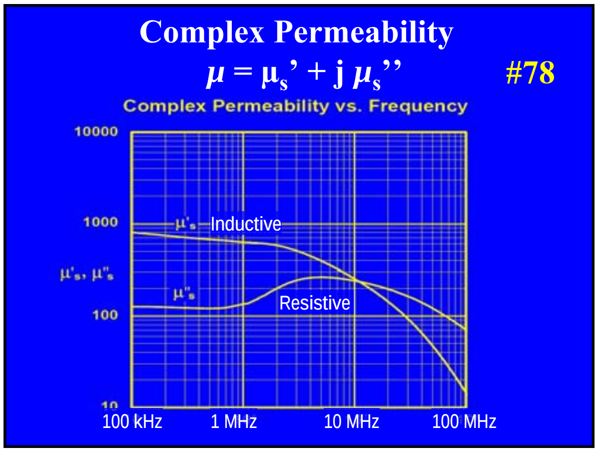
A (too) simple equivalent circuit of a wire passing through a ferrite

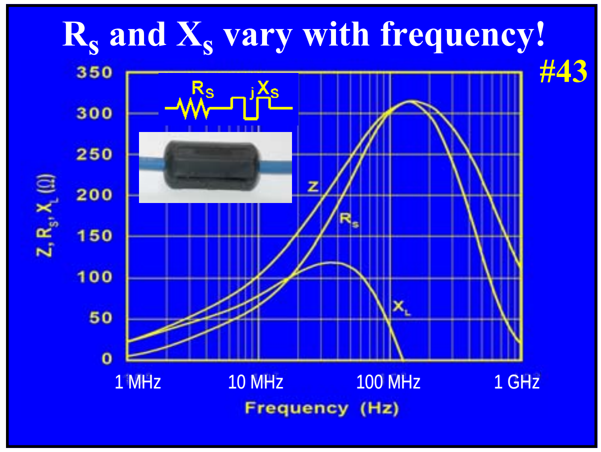
Complex Permeability

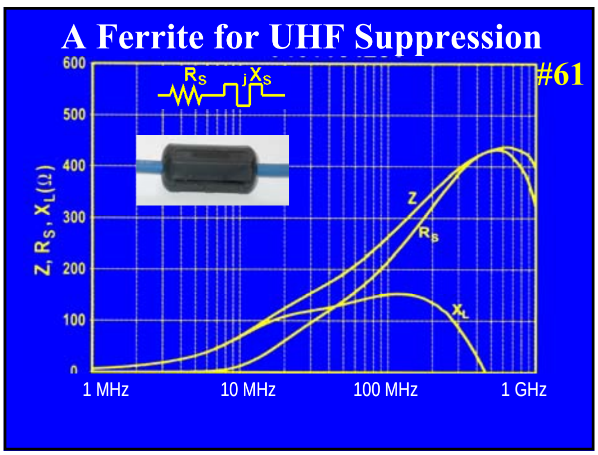
$$\mu = \mu_s' + j\,\mu_s''$$

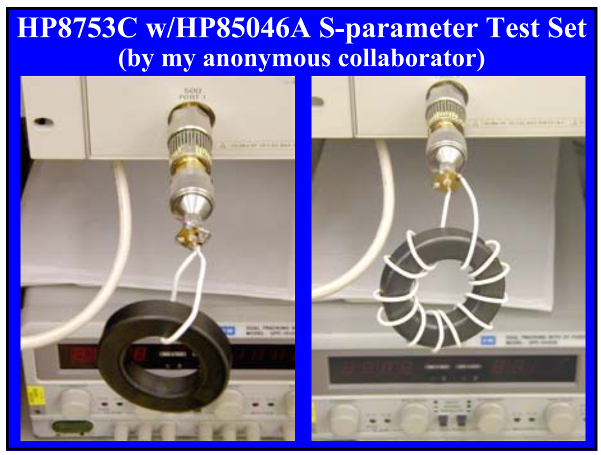
#61



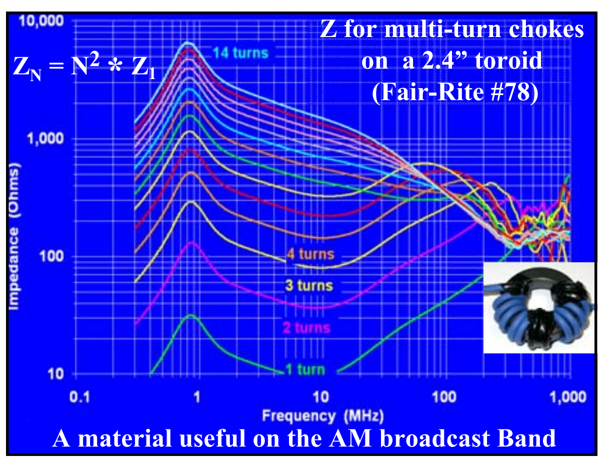

Complex Permeability
μ = μs' + j μs''
#78
Complex Permeability vs. Frequency
10000
1000
100
10
μ's, μ''s
μ's Inductive
μ''s
Resistive
100 kHz
1 MHz
10 MHz
100 MHz

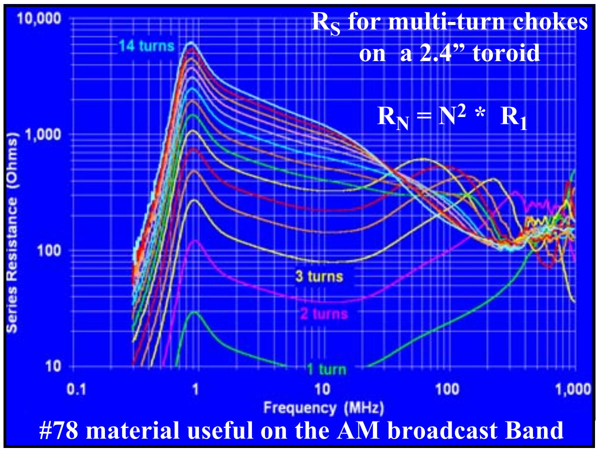

Rs and Xs vary with frequency!
#43
Rs jXs
Z, Rs, XL (Ω)
350
300
250
200
150
100
50
0
Z
Rs
XL
1 MHz
10 MHz
100 MHz
1 GHz
Frequency (Hz)

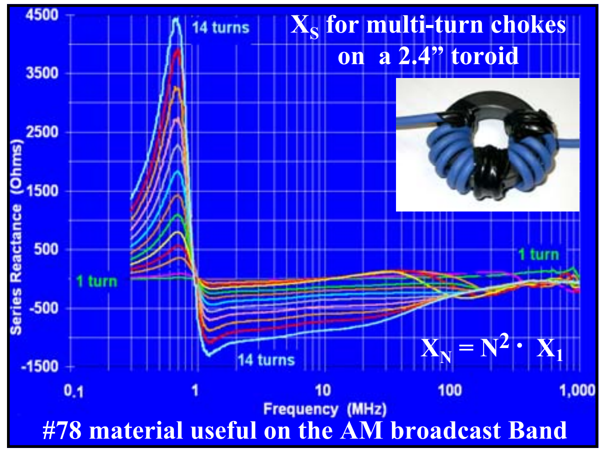

A Ferrite for UHF Suppression
#61
Rs jXs
Z, Rs, XL (Ω)
600
500
400
300
200
100
0
Z
Rs
XL
1 MHz
10 MHz
100 MHz
1 GHz

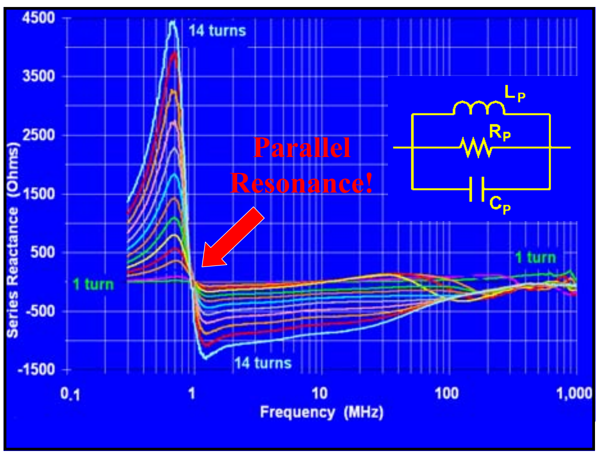

HP8753C w/HP85046A S-parameter Test Set
(by my anonymous collaborator)


AEA CIA-HF


Z for multi-turn chokes
on a 2.4" toroid
(Fair-Rite #78)
ZN = N2 * Z1
10,000
1,000
100
10
Impedance (Ohms)
14 turns
4 turns
3 turns
2 turns
1 turn
0.1
1
10
100
1,000
Frequency (MHz)
A material useful on the AM broadcast Band







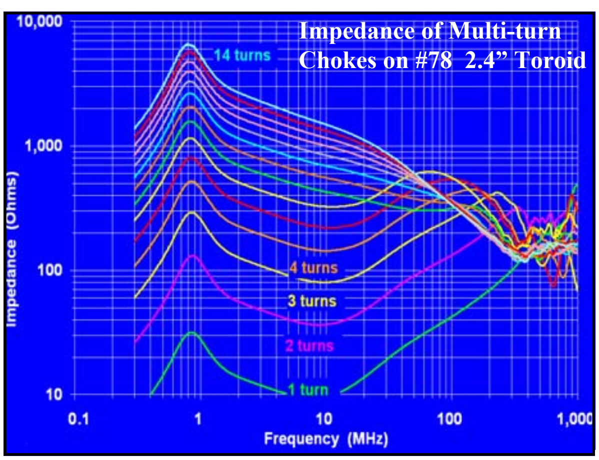
What Causes this Resonance?

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

  $V_P = \mu\varepsilon$ (that is, permeability * permittivity)

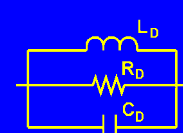
- Resonance occurs when the cross-section is a half-wavelength
- Frequency of the resonance depends on:
  - Velocity of propagation (depends on the “mix”)
  - Dimensions of the cross-section of the flux path



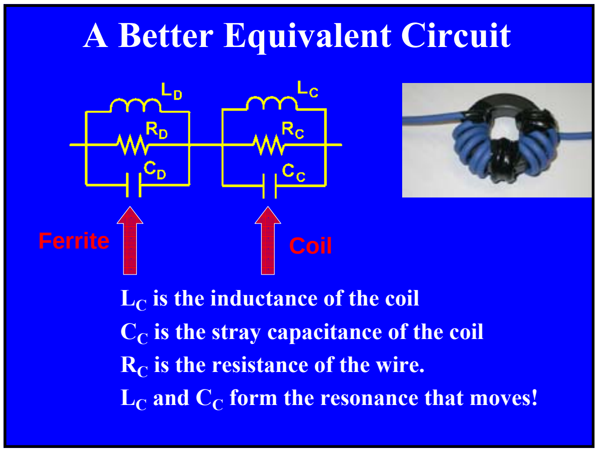
This One is Also Too Simple

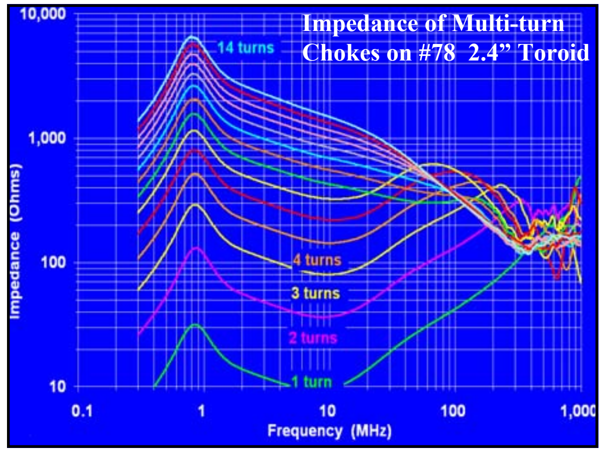
It is adequate at <u>low</u> frequencies, but look at high frequencies – there is another resonance up there!

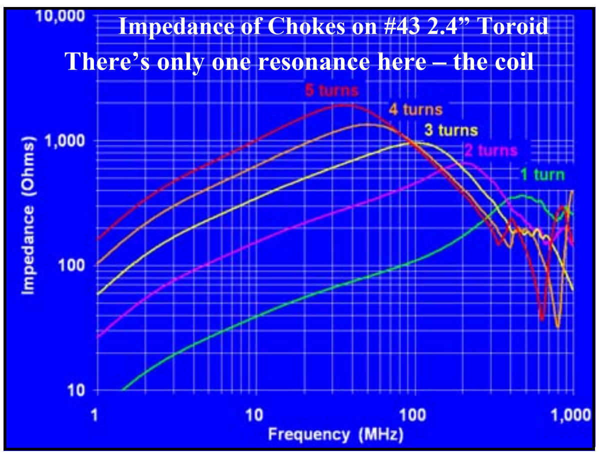
L_D and C_D describe the *dimensional resonance.* R_D accounts for the *losses* in the ferrite.

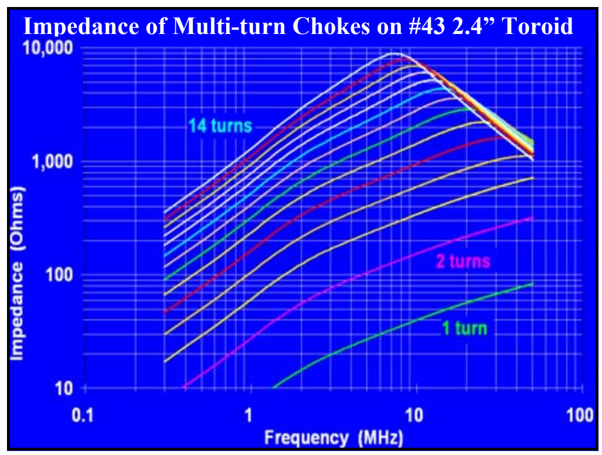


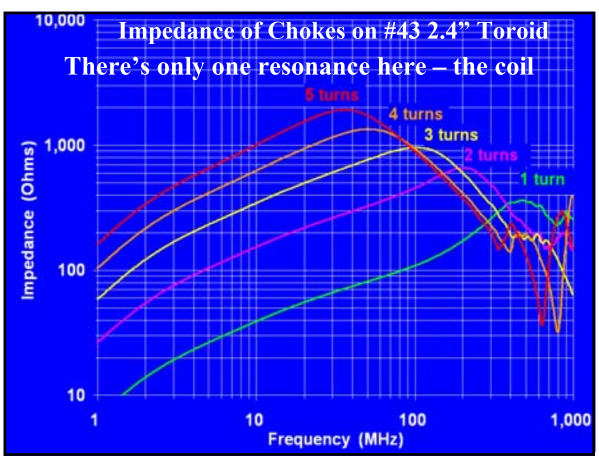
We need a more complex equivalent circuit.

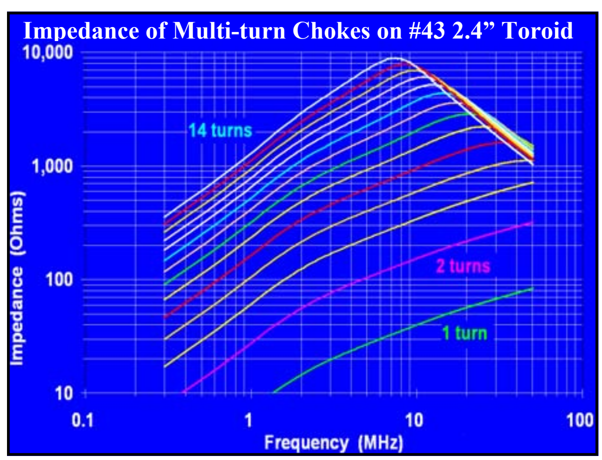

A Better Equivalent Circuit
LD
RD
CD
LC
RC
CC
Ferrite
Coil
LC is the inductance of the coil
CC is the stray capacitance of the coil
RC is the resistance of the wire.
LC and CC form the resonance that moves!


Impedance of Multi-turn
Chokes on #78 2.4" Toroid
14 turns
4 turns
3 turns
2 turns
1 turn
Impedance (Ohms)
10,000
1,000
100
10
0.1
1
10
100
1,000
Frequency (MHz)


Impedance of Chokes on #43 2.4" Toroid
There's only one resonance here – the coil
5 turns
4 turns
3 turns
2 turns
1 turn
Impedance (Ohms)
10,000
1,000
100
10
1
10
100
1,000
Frequency (MHz)


Impedance of Multi-turn Chokes on #43 2.4" Toroid
14 turns
2 turns
1 turn
Impedance (Ohms)
10,000
1,000
100
10
0.1
1
10
100
Frequency (MHz)

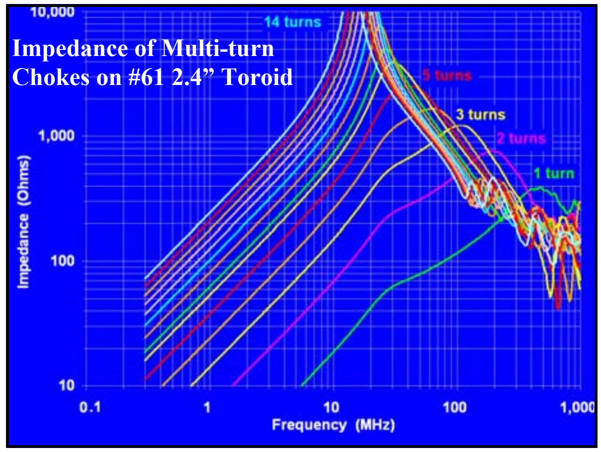

Impedance of Chokes on #43 2.4" Toroid
There's only one resonance here – the coil
5 turns
4 turns
3 turns
2 turns
1 turn
Impedance (Ohms)
10,000
1,000
100
10
1
10
100
1,000
Frequency (MHz)


Impedance of Multi-turn Chokes on #43 2.4" Toroid
14 turns
2 turns
1 turn
Impedance (Ohms)
10,000
1,000
100
10
0.1
1
10
100
Frequency (MHz)

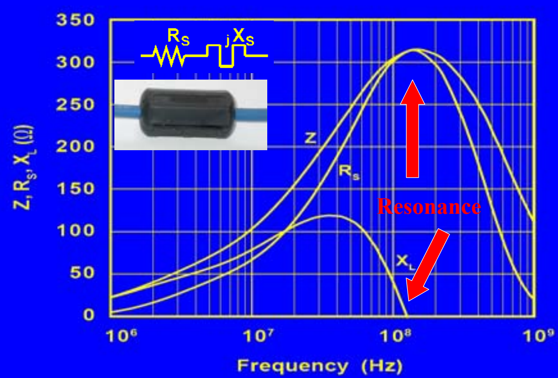
Why no Dimensional Resonance?

It's a different material! The first material, mix #78, was MnZn, while this one is NiZn

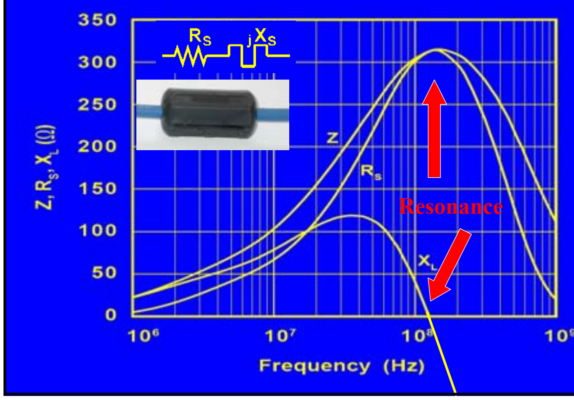
- V_P in #43 is much higher, so dimensional resonance would occur at VHF rather than MF
- At VHF, there is so much loss that it damps the standing waves that produce dimensional resonance



Data Sheets Show the Resonance



Data Sheets Show the Resonance



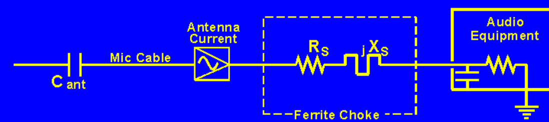
Where's the Capacitance here?

Where's the Capacitance here?

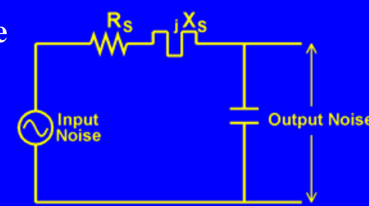
From the wire at one end of the choke to the wire at the other end, through the permittivity of the ferrite (it is a dielectric!)

So How do We Use These Tools?

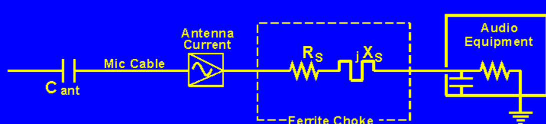
A Choke Applied to Audio Cable



It's a voltage divider!



The Choke can Resonate with the Antenna



A short antenna looks capacitive

X_L can cancel some or all of $X_{C\ ant}$

Current will increase, <u>unless</u> R_S limits it – so, for effective suppression:

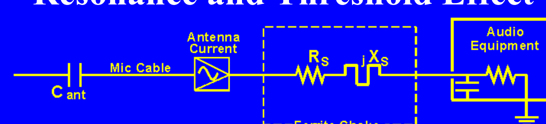
R_S should always be large!

Criteria for Good Suppression

You May Not Need an Elephant Gun

- Most RFI detection is square law, so:
  - A 10 dB reduction in RF level reduces audible interference by 20 dB

Resonance and Threshold Effect



Example:

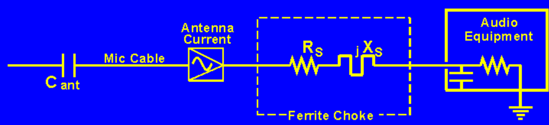
Without the choke, the total antenna circuit is $300\angle{-60°}\Omega$ (that is, capacitive)

and we add a choke that is $300\angle{60°}\Omega$ (inductive),

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

Our choke has not reduced the current!

Threshold Effect



Additional R_S will begin to reduce the current. Increasing R_T to 425Ω (3 dB) reduces detected RF by 6 dB, and increasing R_T to 600Ω (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.

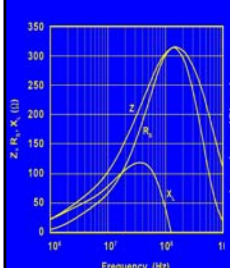
Criteria for Good Suppression

- Outside the box – common-mode coupling
- In practical systems, the threshold is typically 300 - 1,000 ohms
- R_S of the choke should be >1,000 ohms

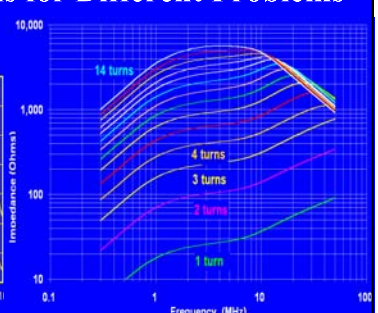
Inside the Box

- For differential mode suppression, form a simple voltage divider
  - Ferrite bead in series
  - Capacitive (or resistive) load
  - A few hundred ohms (or less) from the ferrite can be very effective

Different Tools for Different Problems

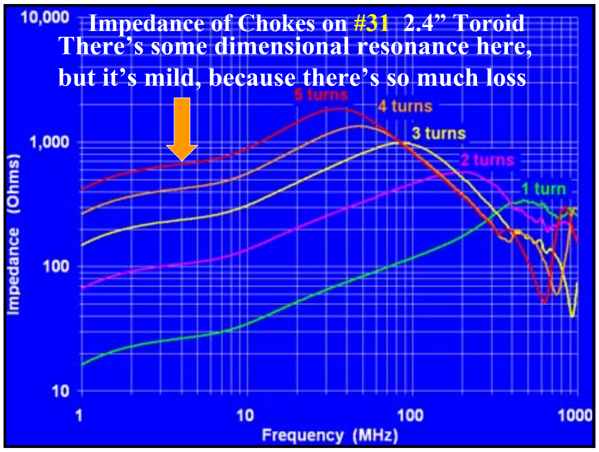


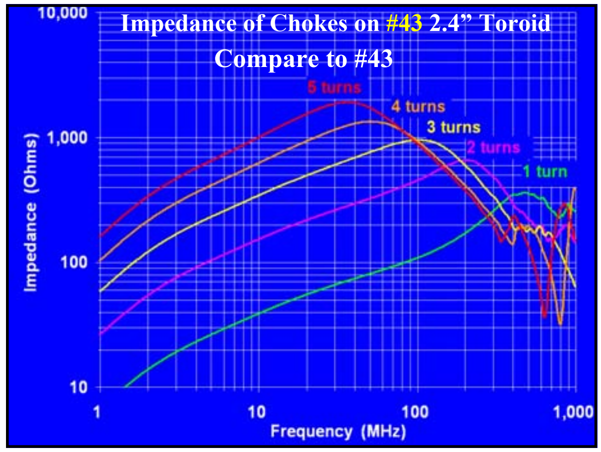
A Simple Bead (#43) works for VHF

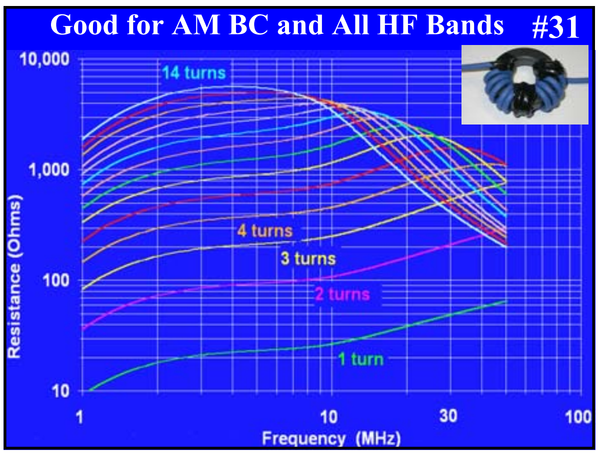


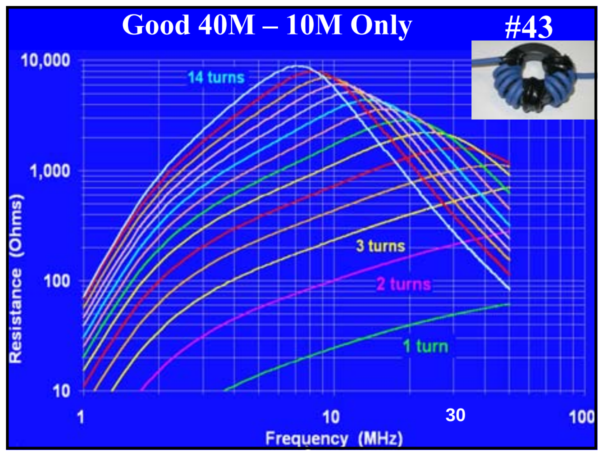
A Multi-turn Choke (#31) is needed for lower frequencies

A Really Nice New Mix



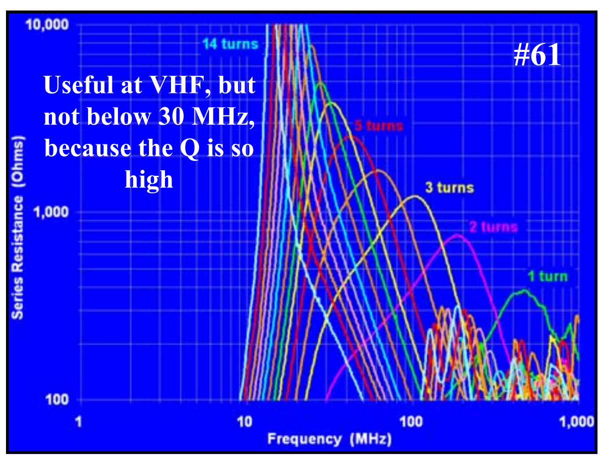


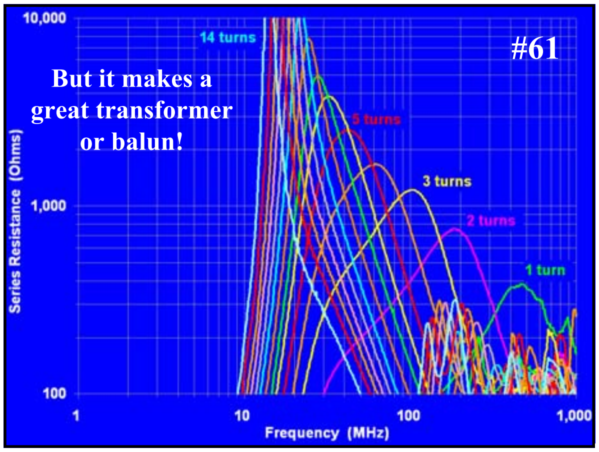


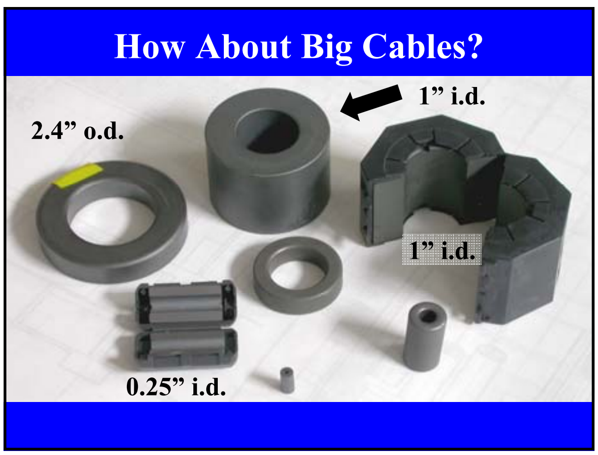


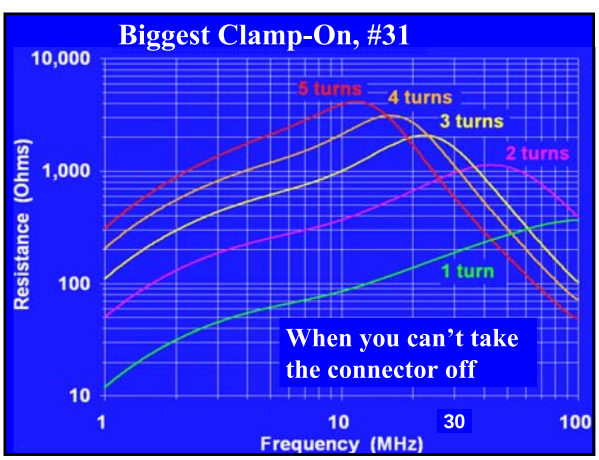
A Really Nice New Mix

- Fair-Rite #31
- Greater suppression bandwidth
  - one more octave
  - one more ham band
- Much better HF suppression
- Equally good VHF suppression









Suppression Guidelines

- Multiple chokes can be placed in series to cover multiple frequency ranges
- $Z_T = Z_1 + Z_2$
- The cable between the choke and the equipment can act as an antenna
- Always place the choke covering the higher frequency range nearest to the equipment

Saturation

- Ferrites saturate at high power levels, reducing μ
- If both conductors of high power circuits are wound through core, the fields cancel, so only common mode current contributes to saturation
  - This allows ferrites to be effective on loudspeaker and power wiring

These ferrites surround all three conductors of center-tapped single phase service, so don't saturate

Temperature

- μ decreases with increasing temperature
- Suppression occurs with dissipation
- High power can result in heating

They can look alike, but be very different

They're brittle!

Three Kinds of Ham RFI

- Interference <u>from</u> ham radio to other non-ham systems
- Interference <u>to</u> ham radio
- RF in the shack

Basic Interference Mechanisms

- Pin 1 problems (both ways!)
  - Fix them
  - Chokes can help
- Coupled on input and output wiring
  - Low pass filters
  - Chokes can help
- Radiated directly to/from circuitry
  - Shield equipment and bond cable shields to equipment shield
  - Good interior design to minimize loops
  - Chokes cannot help

What Needs to Be Choked for Ham RFI to Home Entertainment Systems?

- Anything that can act as an antenna!
  - RF coax lead-ins
  - Video cables
  - Audio cables
  - Power cables

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

Identifying RFI to the Ham Bands

- Check your own house first!
  - Kill power to your house and listen with battery power
- With power restored, listen with a talkie that covers HF

Common RF Noise Sources at Home

- Anything Digital
- Anything with a microprocessor
- Anything with a clock (or oscillator)
- Anything with a motor or switch
  - Computers
  - Appliances
  - Home Entertainment
  - Power supplies
  - Radios

Other Notorious RFI Sources

- Electric fences
- Battery chargers for:
  - Power tools (drills, etc.)
  - Golf carts
  - Lawn mowers
- Power supplies for:
  - Low voltage lighting
  - Computers
  - Home electronics

Some Ethernet Birdies

- 3,511 kHz
- 10,106 kHz
- 10,122 kHz
- 14,030 kHz
- 21,052 kHz
- 28,014 kHz
- 28,105 kHz
- 28,181 kHz
- 28,288 kHz
- 28,319 kHz
- 28,350 kHz
- 28,380 kHz

All frequencies are approximate

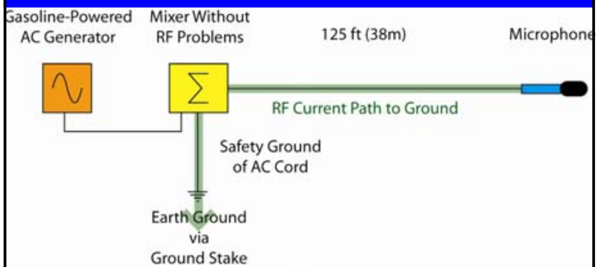
Ethernet Birdies

- Identify by killing power to router or hub
- Even when you fix your own, you may hear your neighbors (I did in Chicago)
- Methods of radiation
  - The ethernet cable is a (long wire) antenna
  - Direct radiation from the switch, hub, router, computer, and their power supplies
  - Power supply cables are antennas

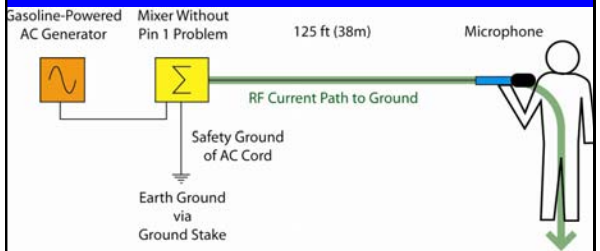
Ethernet Birdies

- Chokes will kill the common mode radiation (long wire) from the cable
- Use choke(s) on each cable (and each end of long cables) (Each end talks)
- Use multiple chokes if needed for wide frequency ranges, putting the highest frequency choke nearest to noise source
- Choke the power supply too!

Remember this?



No path for RF current through the mic, so no interference



But when K9IKZ held the mic in his hand, some mics had RFI

If There's No RF Current

- Sensors that get their power from the signal circuit (no local power)
  - Smoke alarms
  - Temperature probes
  - Humidity probes
  - Microphones
- Power over Ethernet devices

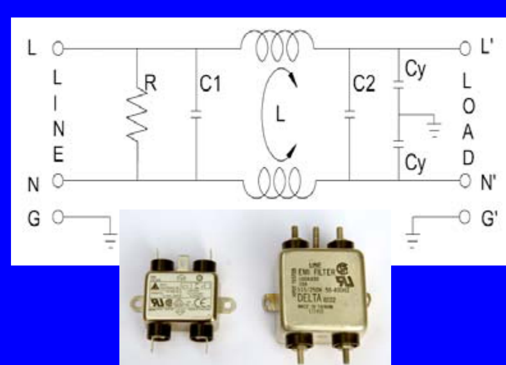
If There's No RF Current

- It's a voltage between the signal conductors that's causing the problem
- Chokes won't help (current already zero)
- Use a capacitor across the signal input
  - Small value to avoid degrading the signal
  - Short leads

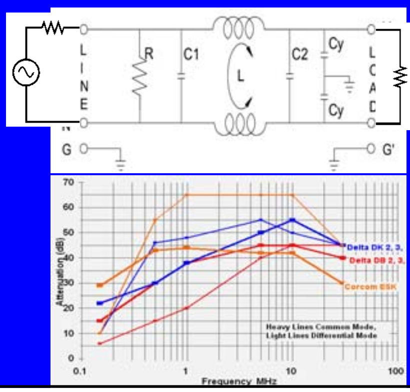
Power Line Filters Can Help, but Don't Overdo It

- Shunt capacitance couples noise to the "ground" wire
- The ground wire will act like an antenna

Line Filters Attenuate RF Noise



Performance Depends on Impedances



The Biggest Myths

Myth: "I need a better ground"

Fact: A connection to earth will almost never reduce noise or RFI, and it will often make it worse, because the "ground wire" can act as an antenna.

Fact: A connection to earth rarely affects antenna performance, but it is very important for lightning protection.

The Biggest Myths

Myth: "I need a separate RF ground"

Fact: Separate grounds are unsafe – they can kill someone, increase lightning damage, even start a fire.

Fact: Separate grounds are more likely to cause problems than to fix them.

Fact: For safety, all grounds must be bonded together

The Biggest Myths

Myth: "I can fix these ground loops with a ground lifter"

Fact: Ground lifts are unsafe – they can kill someone or start a fire.

The Biggest Myths

Myth: "I need a power conditioner"

Fact: "Dirty power" is rarely the cause of hum, buzz, RFI, or bad sound.

Fact: The greatest effect of power conditioners is to transfer money from the pocket of the buyer to the pocket of the seller.

RFI to Telephones

- Try ferrite chokes first
  - Telephone wiring
  - Power supply
- Common mode chokes
  - K-Com bifilar-wound choke, about 15 mH
  - A lot more choke than you can easily do yourself
  - http://www.k-comfilters.com

Ferrites and HF Mobile

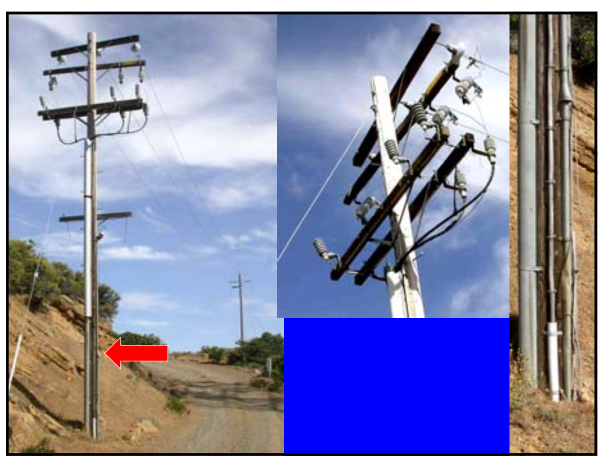
- Suppress noise in your receiver
  - Choke the antennas that radiate noise by adding chokes to power and signal cables connecting noise sources
- Suppress RFI to the car's computers
  - Choke the antennas that receive your RF and couple it to the car's systems
- They're the same antennas!

Ferrites and HF Mobile

- Use measured data in the tutorial as a guide in winding chokes
  - This is HF, so use #31 material
- Cores saturate with big current
  - No saturation if both conductors go through the core, even at high power
  - Ham rigs only 1-2A on receive
  - Saturation based on (Amps) x (Turns), so take care with multiple turns on only one lead!

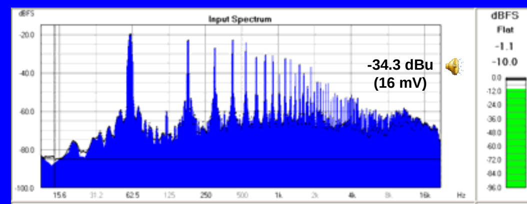
The HF Mobile Bonding Problem

- Car bodies are often badly bonded
  - Too much paint!
- The car body is a counterpoise for your antenna, carrying RF current
- Bad bonding will couple RF to car electronic systems bonded to the body
- Bad bonding will couple noise to your receive antenna
- Ferrites can't help this!



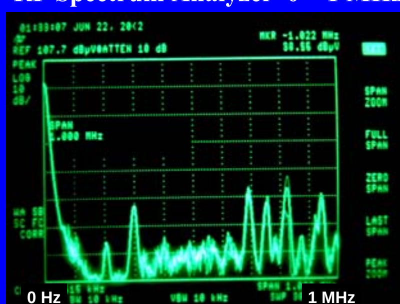
Audio (and Video) "Ground Loops"

Typical Noise Spectrum on "Ground"



Measured between two outlets in my office and ham shack

RF Spectrum Analyzer 0 – 1 MHz

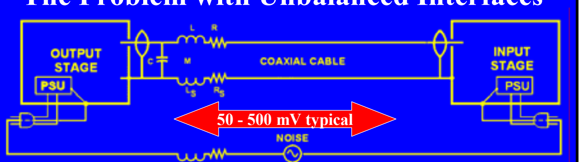


Measured between two different outlets in my office, one a conventional outlet, and one an IG outlet, into a 75 ohm load

Unbalanced Signal Wiring

- Audio and control wiring of ham gear
- RS-232 interfaces
- Video gear
- Consumer audio equipment (even "gilt-edged" high futility gear)

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
- Reduce the noise voltage between the ends of the cable

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

To Reduce Hum and Buzz

- **Reduce the shield resistance**
  - Use cable with beefy copper shield
  - Use a shorter cable
- **Minimize the voltage between grounds**
  - Plug all gear into the same outlet
  - Bond chassis together with beefy copper
- **Ham gear doesn't require much power**
  - One 20A 120V circuit can run several radios <u>and</u> computers
  - One 20A 240V circuit in the same quad box can run two power amps at rated power

Acknowledgements

- **Ron Steinberg (K9IKZ)**
- **Leo Irakliotis (KC9GLI)**
- **Neil Muncy (ex-W3WJE)**
- **Fair-Rite Products**

Excellent EMC Seminars

- **Taught by Henry Ott (WA2IRQ)**
  - October 16-18, 2007
  - Ramada Inn, East Hanover, NJ
  - Details at http://www.hottconsultants.com

References

- **Henry Ott, *Noise Reduction Techniques in Electronic Systems,* Wiley Interscience, 1988**
- **E. C. Snelling, *Soft Ferrites, Properties and Applications,* CRC Press, 1969**
- **E. C. Snelling and A. D. Giles, *Ferrites for Inductors and Transformers,* Research Study Press, 1983**
- ***Fair-Rite Products Catalog* This 200-page catalog is a wealth of product data and applications guidance on practical ferrites.   http://www.fair-rite.com**
- ***Ferroxcube Catalog and Applications Notes* More online from another great manufacturer of ferrites. http://www.ferroxcube.com**

References

- ***Noise Susceptibility in Analog and Digital Signal Processing Systems*, N. Muncy**, JAES, June 1995
- ***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*, J. Brown** (AES Preprint 5897)
- ***A Novel Method of Testing for Susceptibility of Audio Equipment to Interference from Medium and High Frequency Broadcast Transmitters*, J. Brown** (AES Preprint 5898)

References

- ***New Understandings of the Use of Ferrites in the Prevention and Suppression of RF Interference to Audio Systems* , J. Brown** (AES Preprint 6564)
- ***ARRL RFI Book***
- Marv Loftness**, *AC Power Interference Handbook* (ARRL)**
- ***Understanding How Ferrites Can Prevent and Eliminate RF Interference to Audio Systems*, J. Brown** Self-published tutorial (on my website)

Applications notes, tutorials, and my AES papers are on my website for free download
http://audiosystemsgroup.com/publish

RFI,
Unintentional Antennas,
and Ferrites

Jim Brown K9YC
Audio Systems Group, Inc.
Santa Cruz
k9yc@audiosystemsgroup.com
http://audiosystemsgroup.com