RFI and Ferrites

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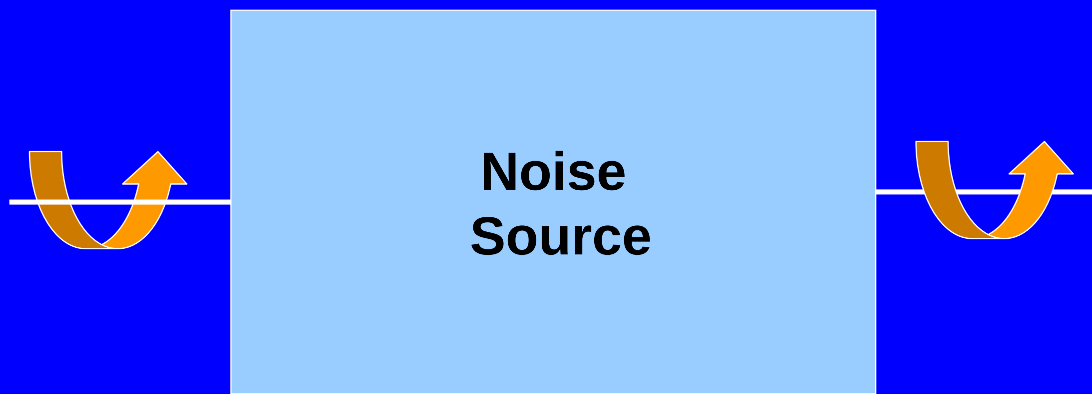
Primary Interference Mechanisms

- 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

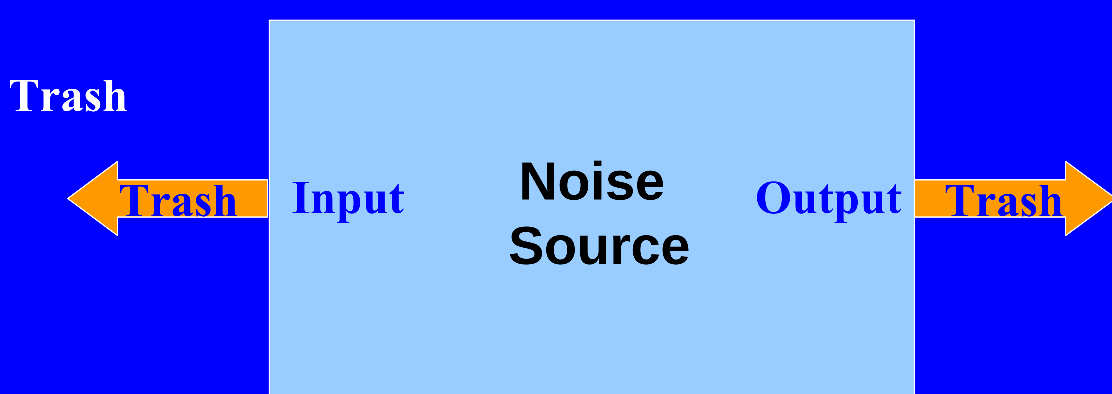
Common Mode Coupling

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



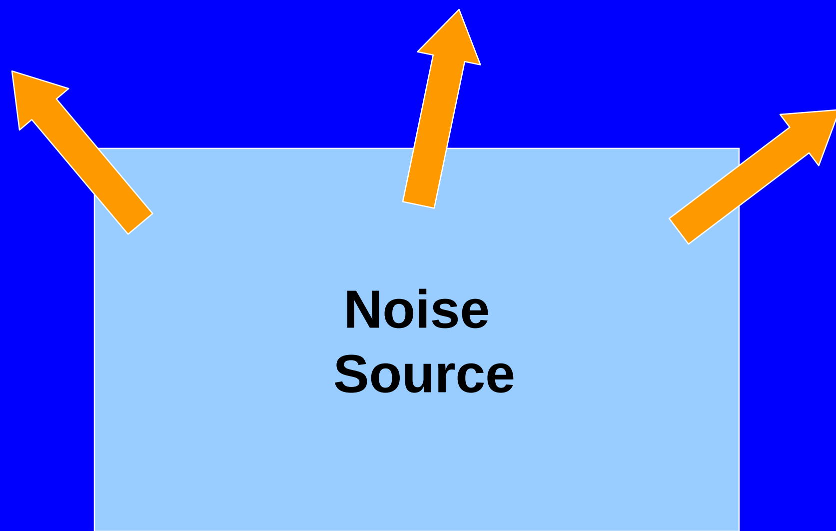
Differential Mode Coupling

- 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 received interference will generally also help reduce transmitted noise
- Relative strength of coupling depends on impedances of the coupled circuit, and may not be equal in both directions

Common Mode Coupling

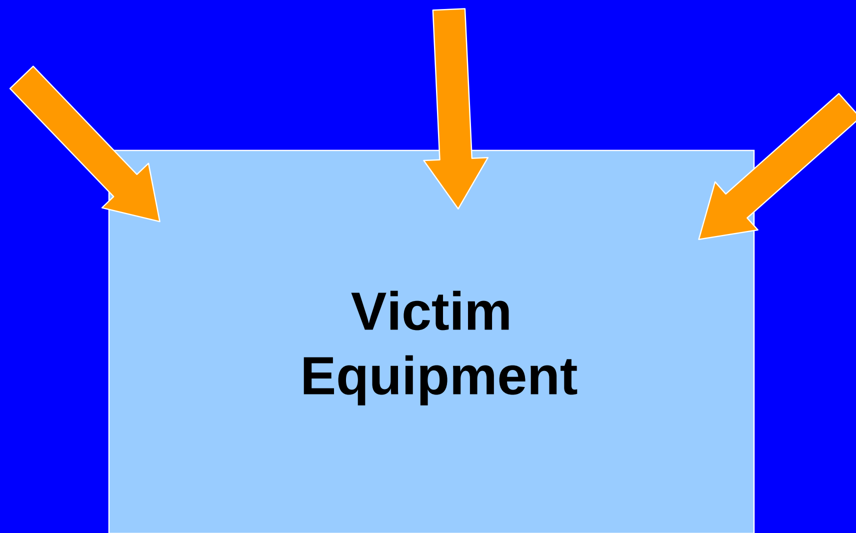
- I/O wiring acts as long wire antenna

Differential Mode Coupling

- I/O wiring is not band-pass filtered

Poor Equipment Shielding

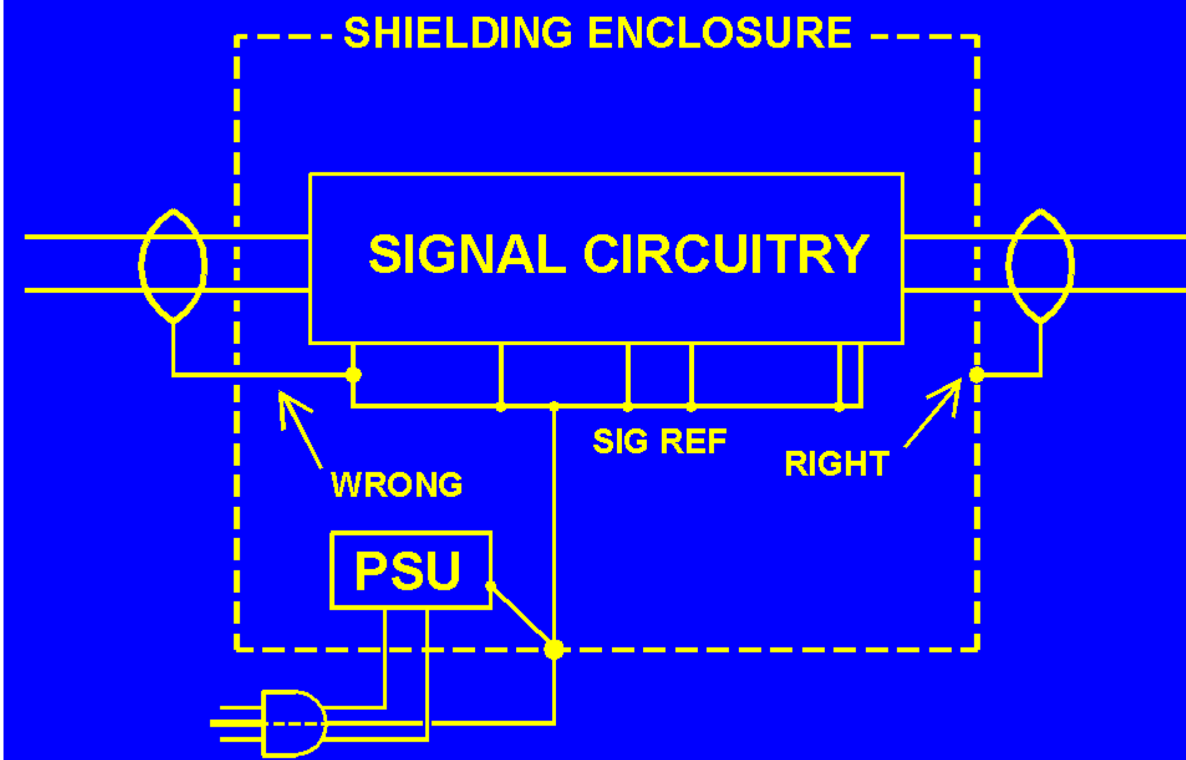
- Internal wiring is receiving antenna



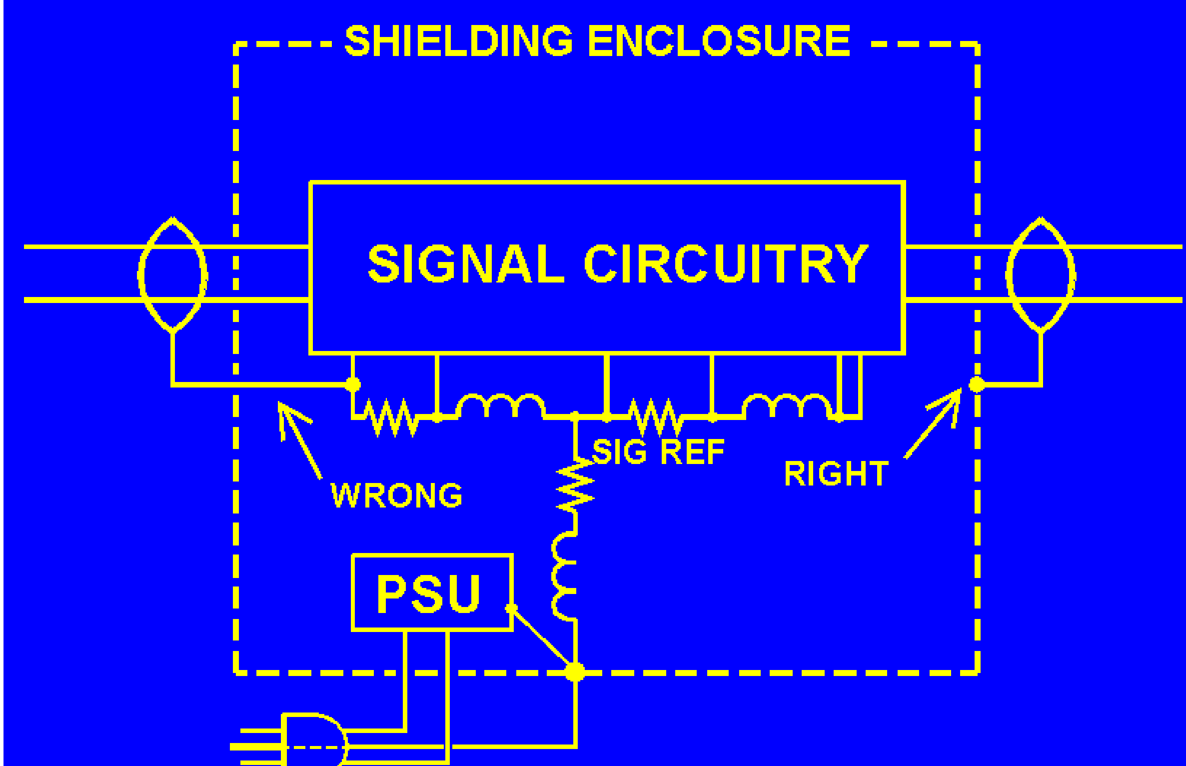
Common Mode Coupling

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

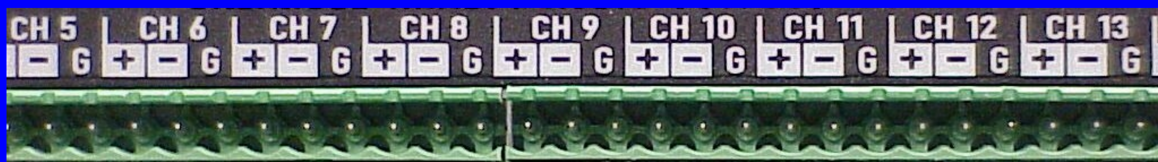
Pin 1 in Balanced Interfaces



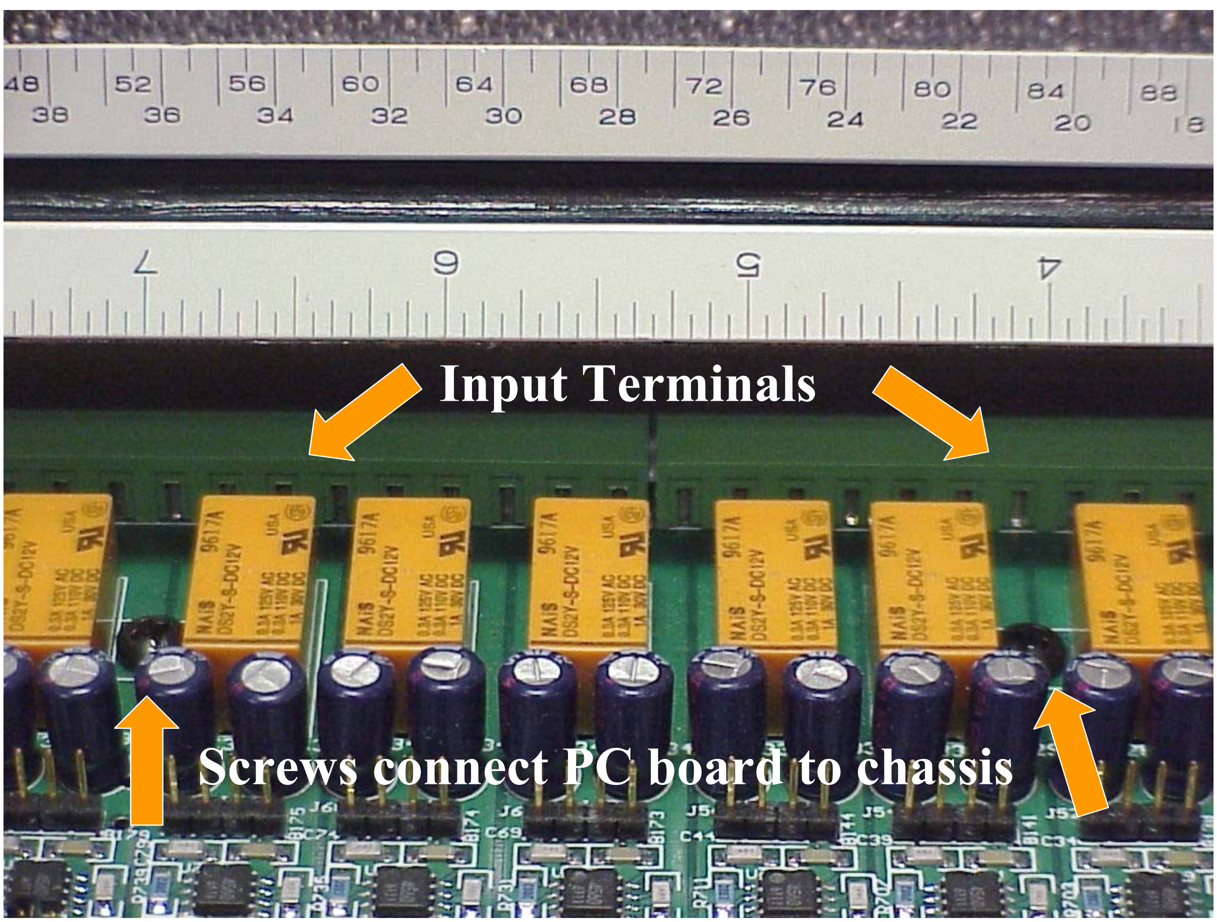
Pin 1 in Balanced Interfaces



The G terminal goes to the enclosure, right?



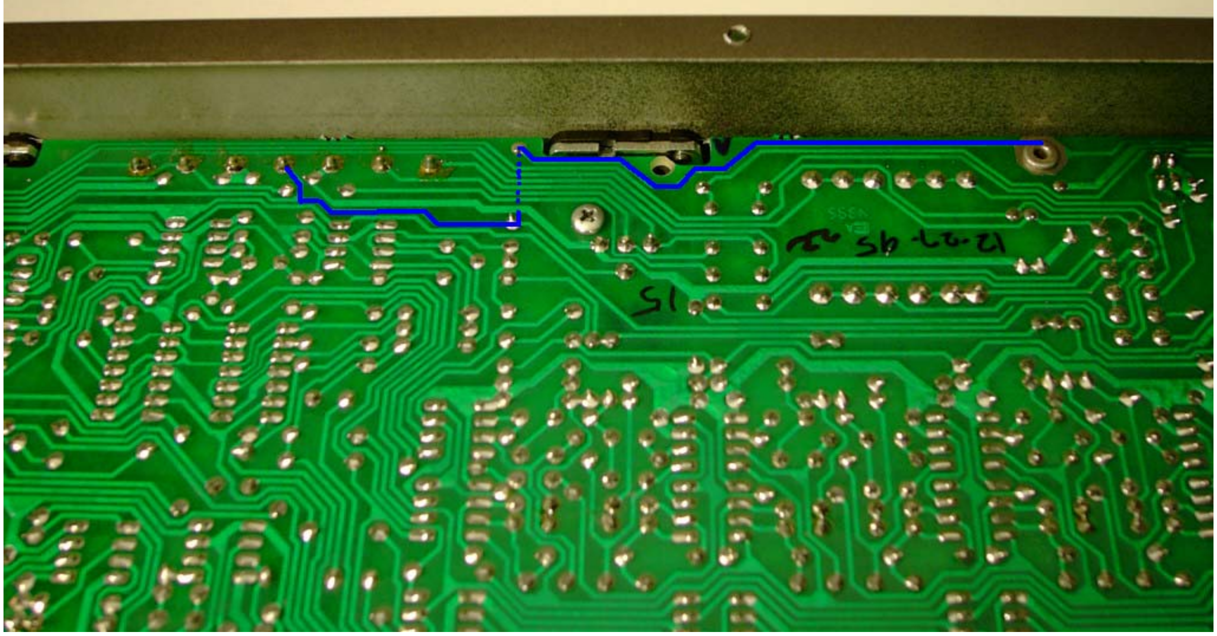
Well, sort of, but it's a long and torturous journey!



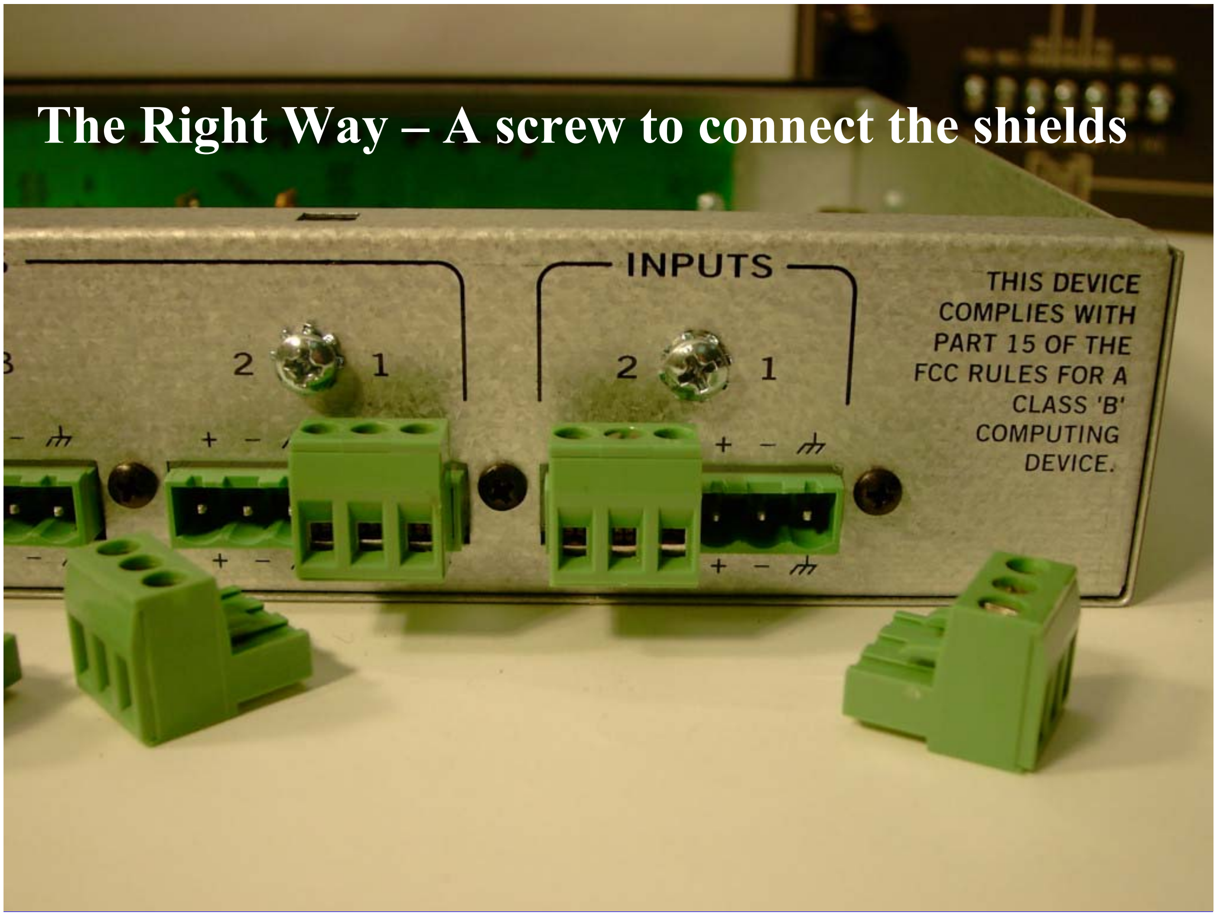
A Pin 1 Problem in Obsolete Equipment, and a Really Long Path to the Chassis

Let's look behind the panel.

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



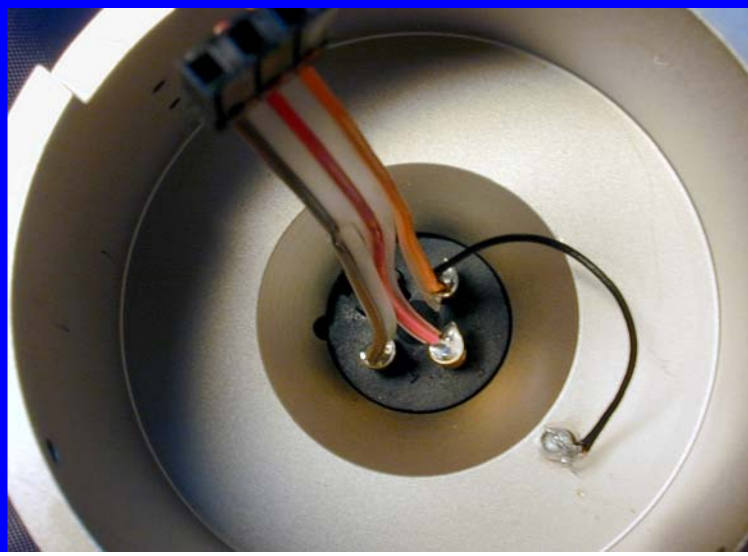
The Right Way – A screw to connect the shields



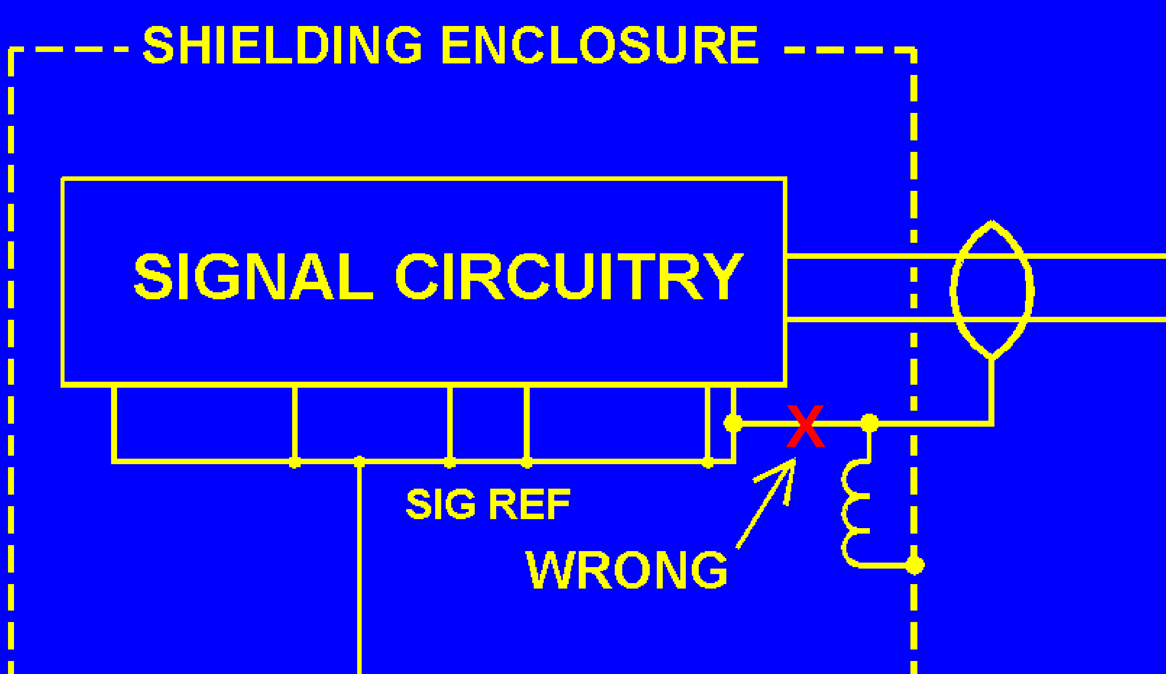
A classic RF pin 1 problem in a microphone

A classic RF pin 1 problem in a microphone

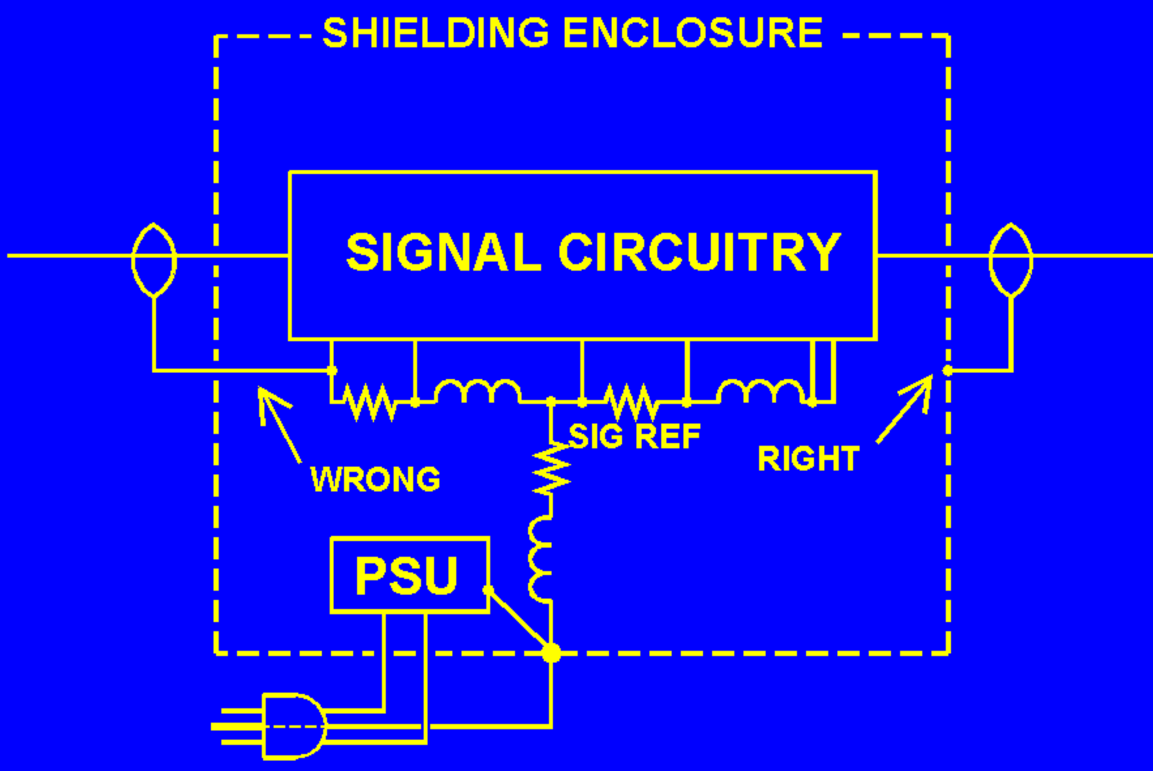
- Black wire goes to enclosure (good)
- Far too LONG - Inductance makes it high impedance
  - 7.5 Ω @ 100 MHz, 60 Ω at 850 MHz
- Orange wire goes to circuit board common
- Common impedance couples RF to circuit board



The Pin 1 Problem in Microphones



Pin 1 in Unbalanced Interfaces



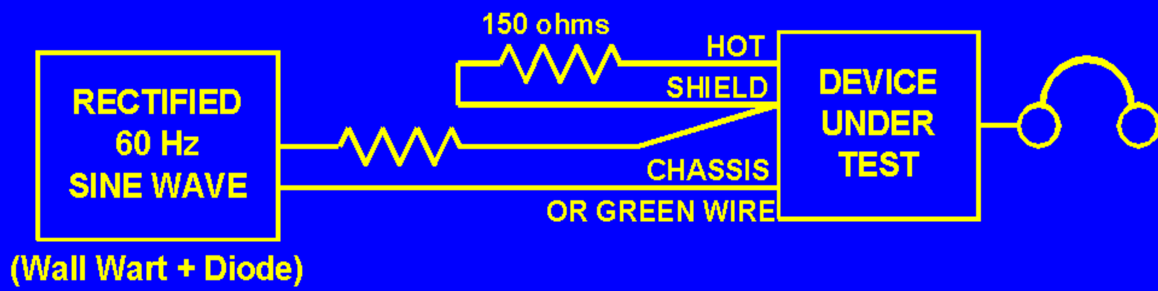
Some Classic Pin 1 Problems

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

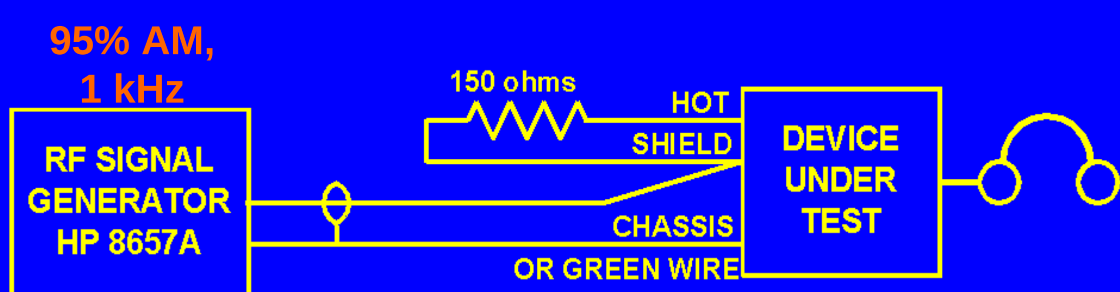
Testing for Pin 1 Problems

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

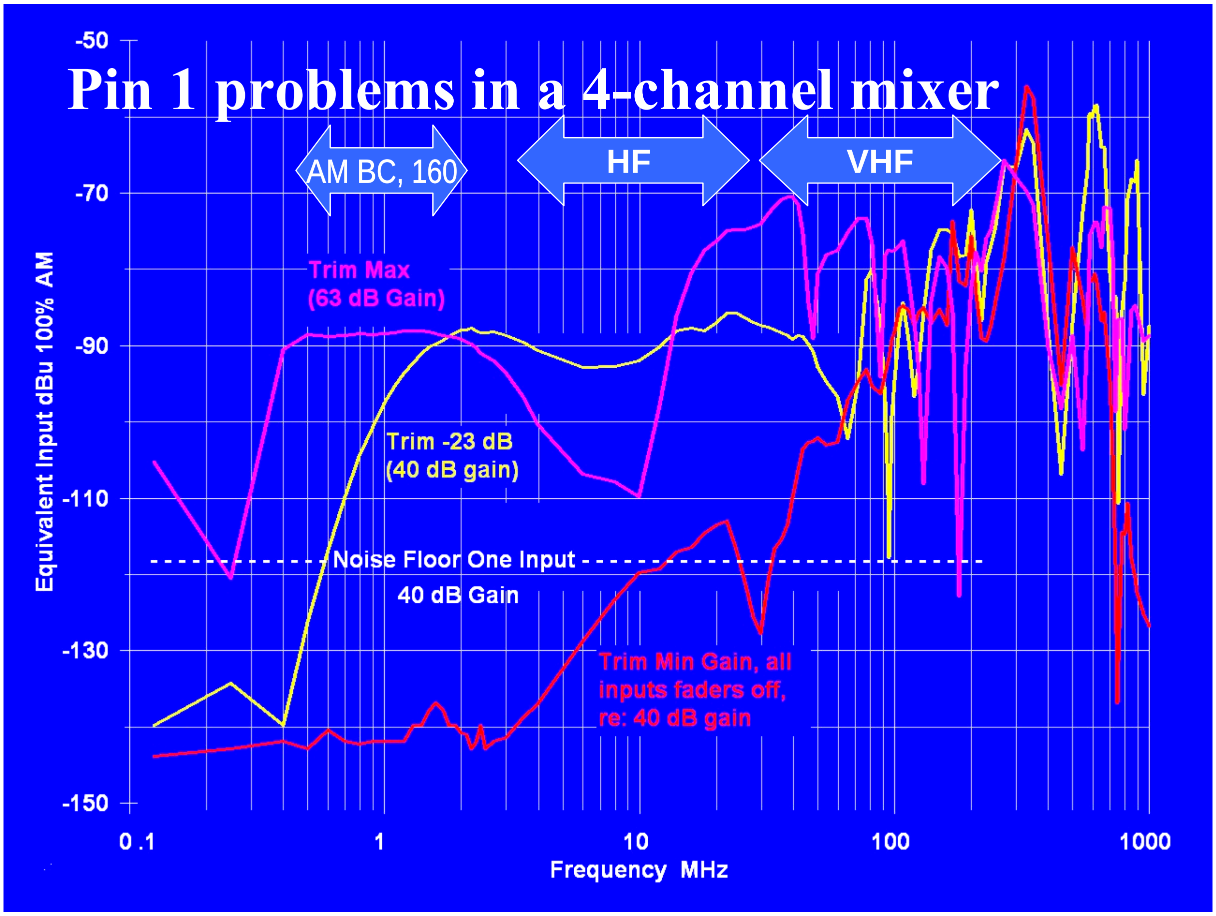


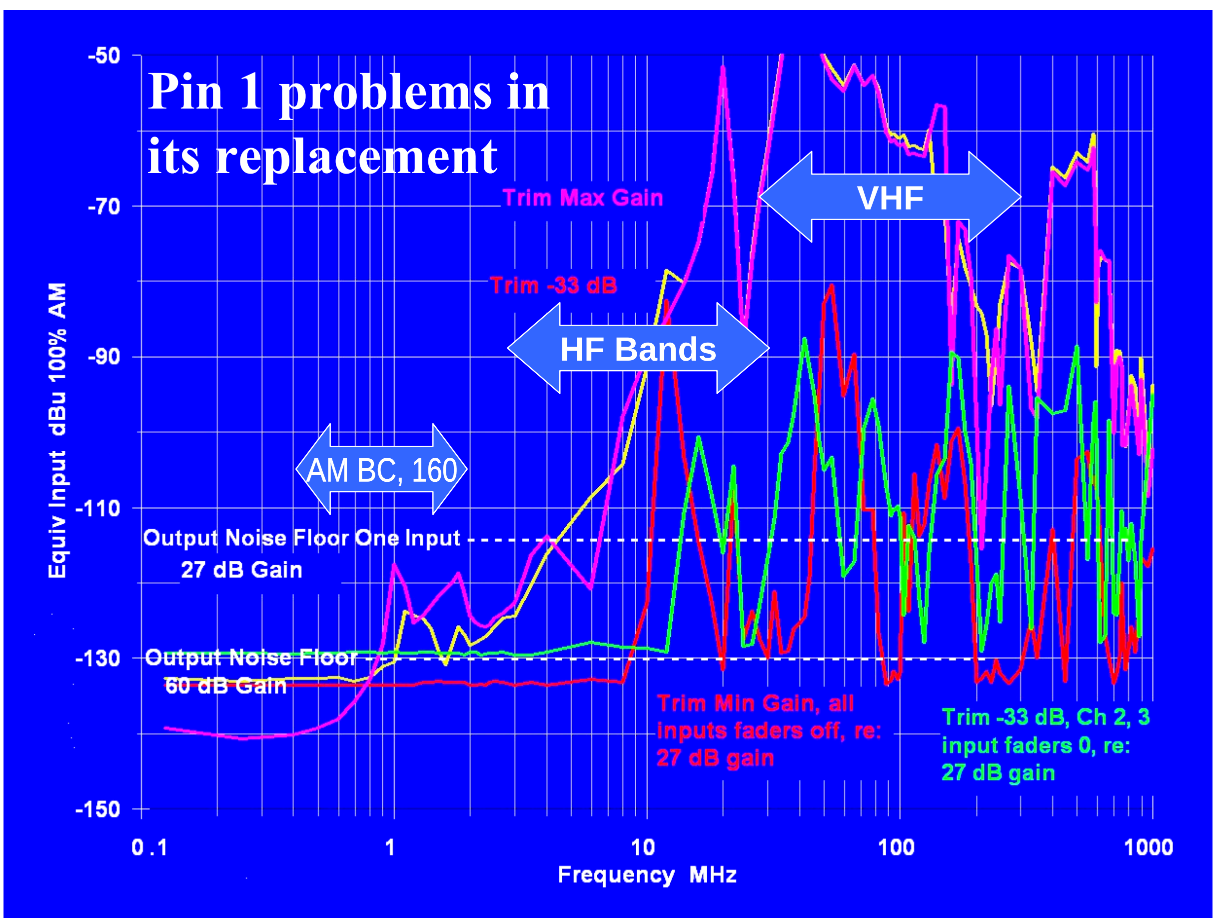
- Drive between "audio ground" and chassis
- Listen to the output
- If you hear it, you have a problem

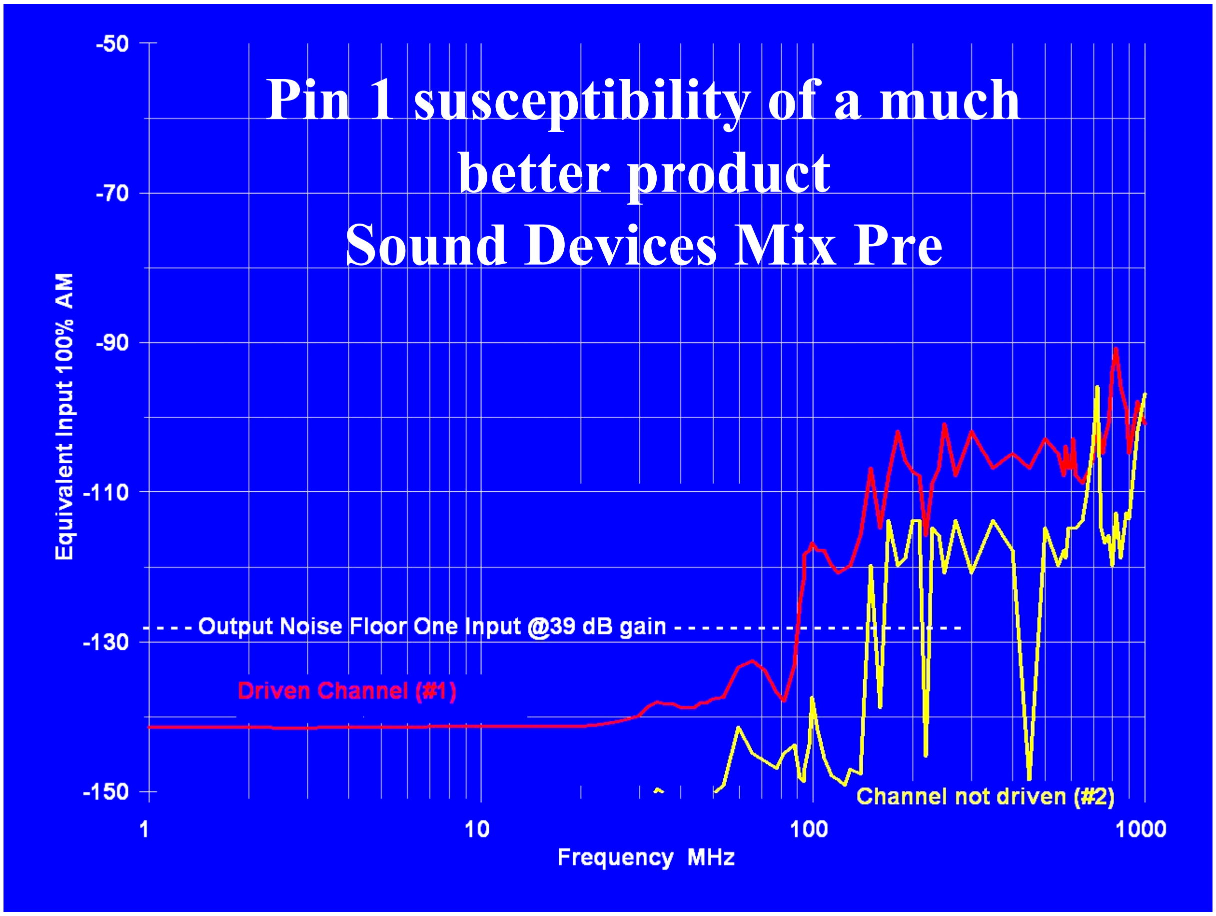
RF Pin 1 Test Setup for Equipment



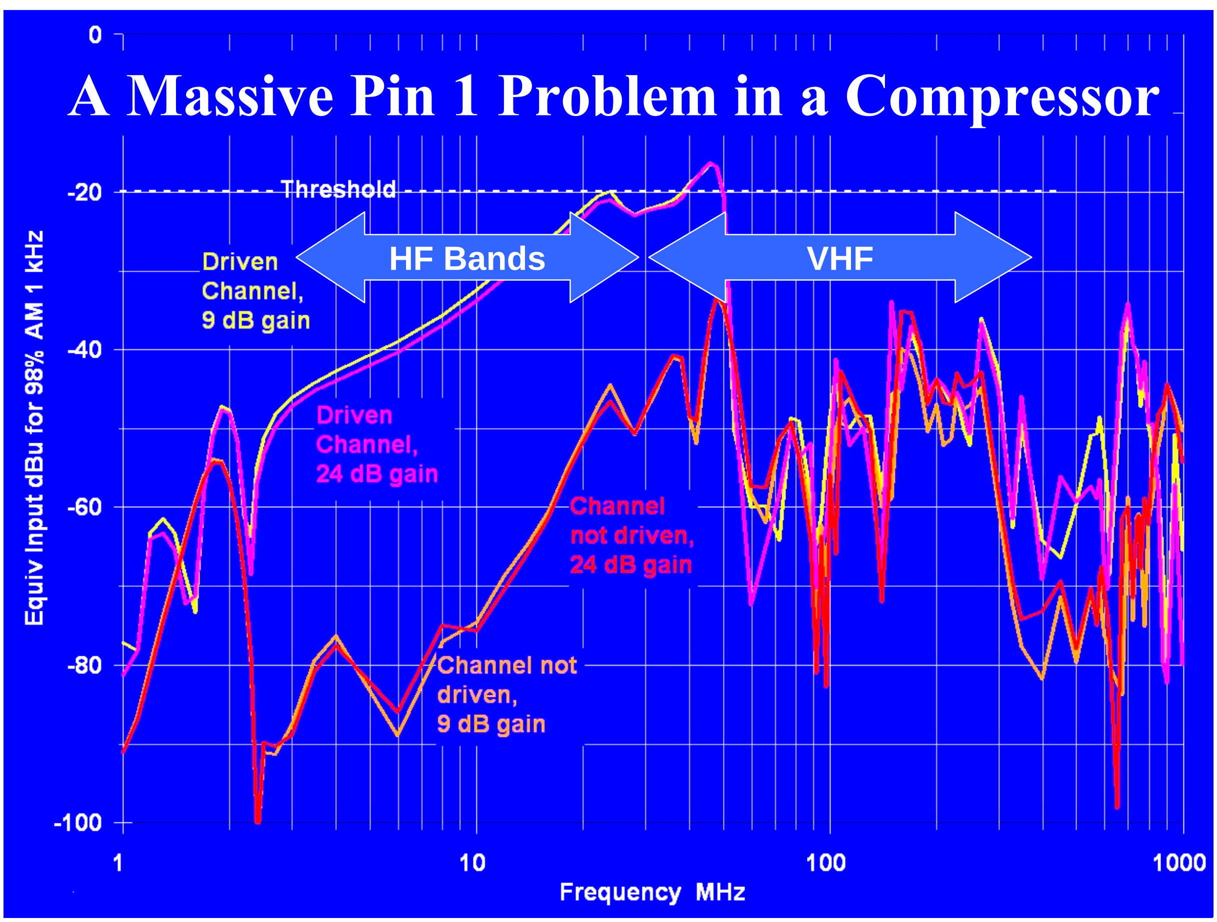
- Drive between "audio ground" and chassis
- Listen to the output
- If you hear 1 kHz, you have a problem


Pin 1 problems in a 4-channel mixer
AM BC, 160
HF
VHF
Trim Max
(63 dB Gain)
Trim -23 dB
(40 dB gain)
Noise Floor One Input
40 dB Gain
Trim Min Gain, all
inputs faders off,
re: 40 dB gain
Equivalent Input dBu 100% AM
-50
-70
-90
-110
-130
-150
0.1
1
10
100
1000
Frequency MHz


Pin 1 problems in
its replacement
Trim Max Gain
Trim -33 dB
VHF
HF Bands
AM BC, 160
Output Noise Floor One Input
27 dB Gain
Output Noise Floor
60 dB Gain
Trim Min Gain, all
inputs faders off, re:
27 dB gain
Trim -33 dB, Ch 2, 3
input faders 0, re:
27 dB gain
Equiv Input dBu 100% AM
-50
-70
-90
-110
-130
-150
0.1
1
10
100
1000
Frequency MHz



Pin 1 susceptibility of a much better product
Sound Devices Mix Pre
-50
-70
-90
-110
-130
-150
Equivalent Input 100% AM
Output Noise Floor One Input @39 dB gain
Driven Channel (#1)
Channel not driven (#2)
1
10
100
1000
Frequency MHz

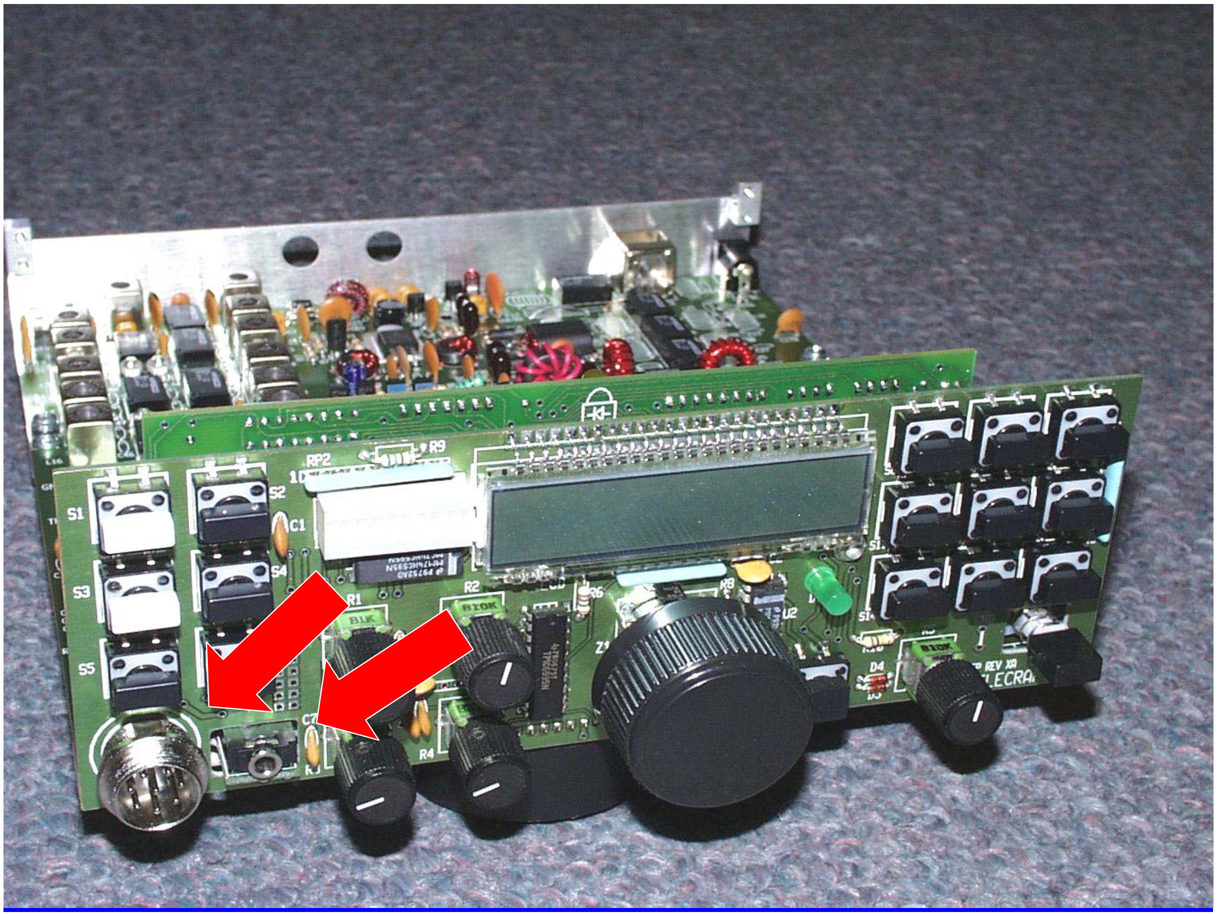


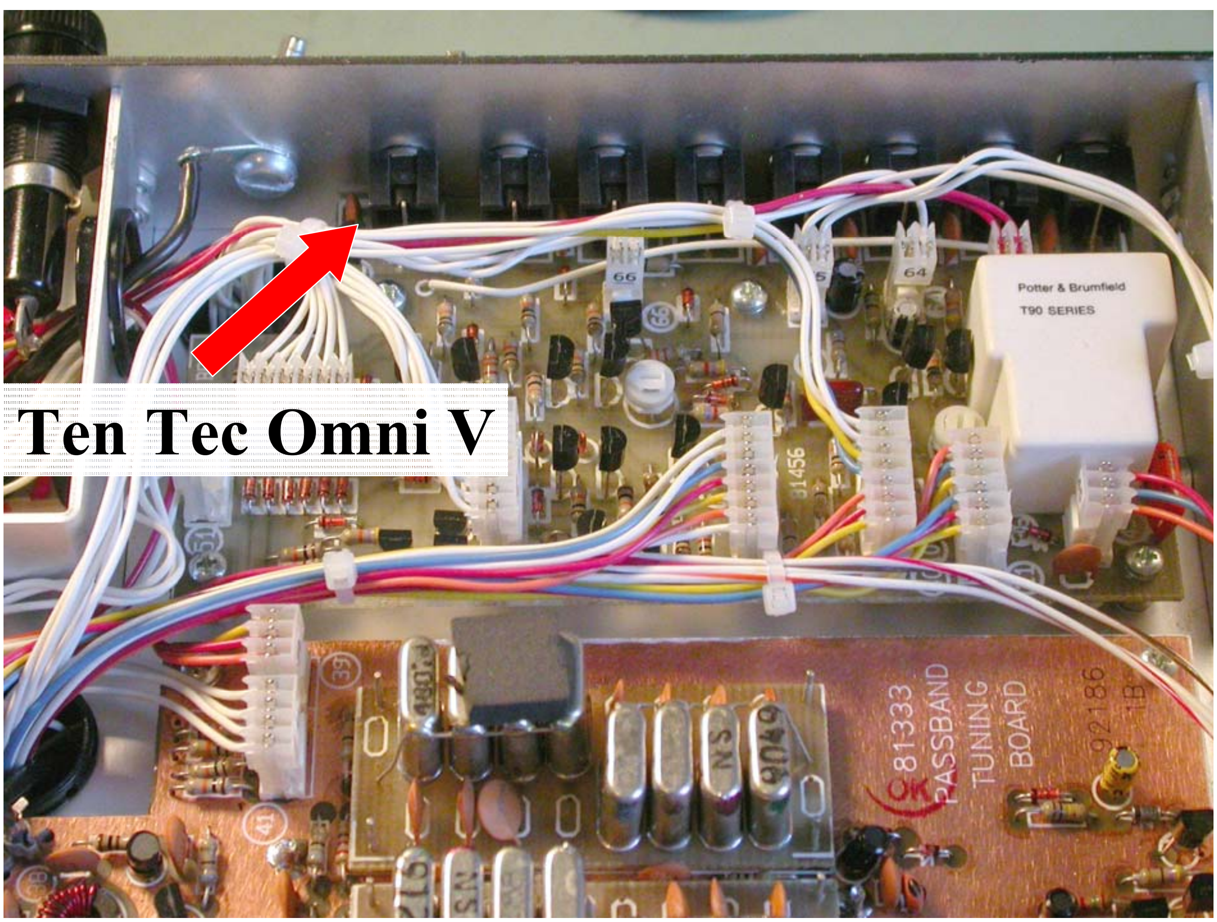
A Massive Pin 1 Problem in a Compressor
0
-20
-40
-60
-80
-100
Equiv Input dBu for 98% AM 1 kHz
Threshold
HF Bands
VHF
Driven Channel, 9 dB gain
Driven Channel, 24 dB gain
Channel not driven, 24 dB gain
Channel not driven, 9 dB gain
1
10
100
1000
Frequency MHz

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





Ten Tec Omni V

A Pin 1 Problem? Maybe

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?

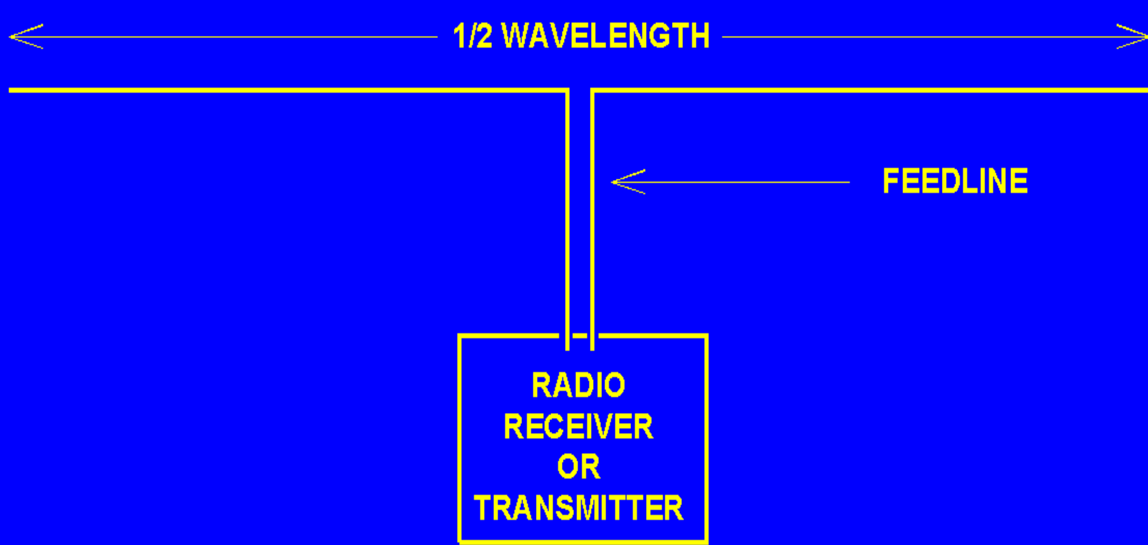
Yes, it's the DB9 and DB25 shells!

Consumer Cables are Antennas!

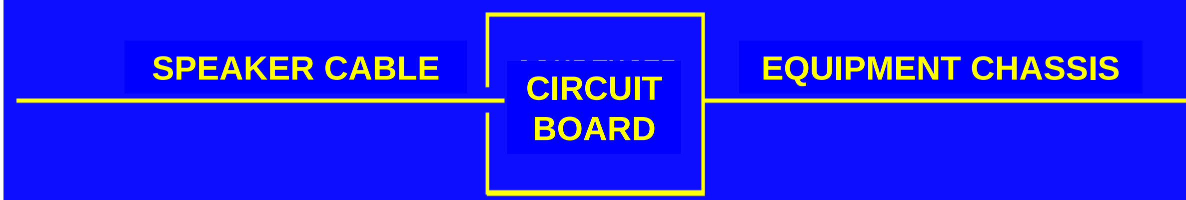
Consumer Cables are Antennas!

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

A “Textbook” λ /2 Dipole

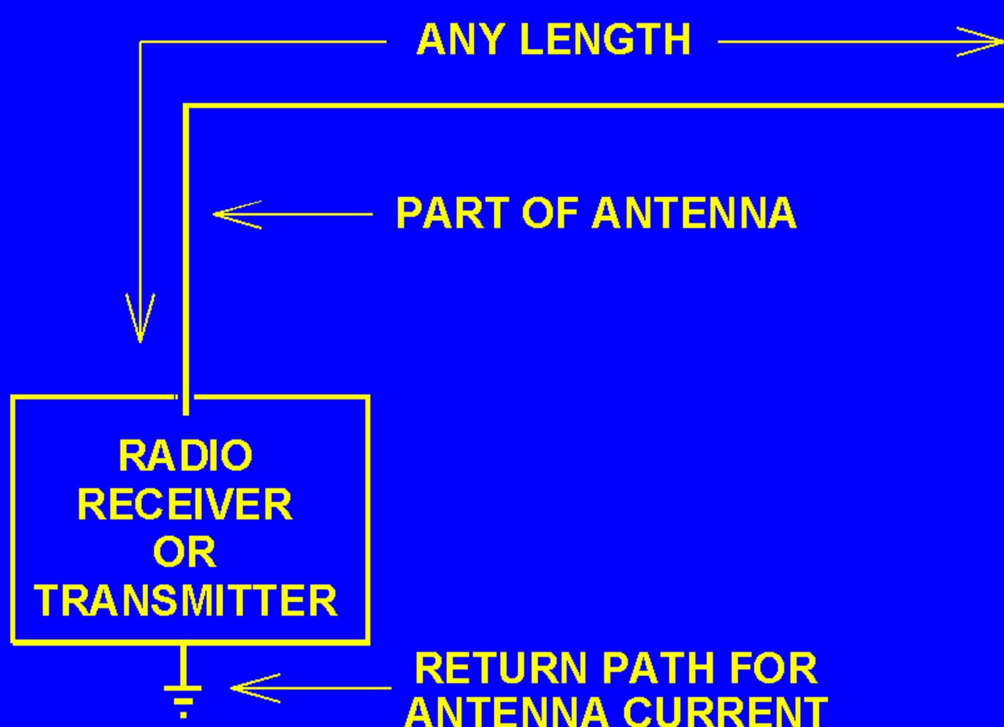


Battery Operated Equipment and its Cable can form a Dipole

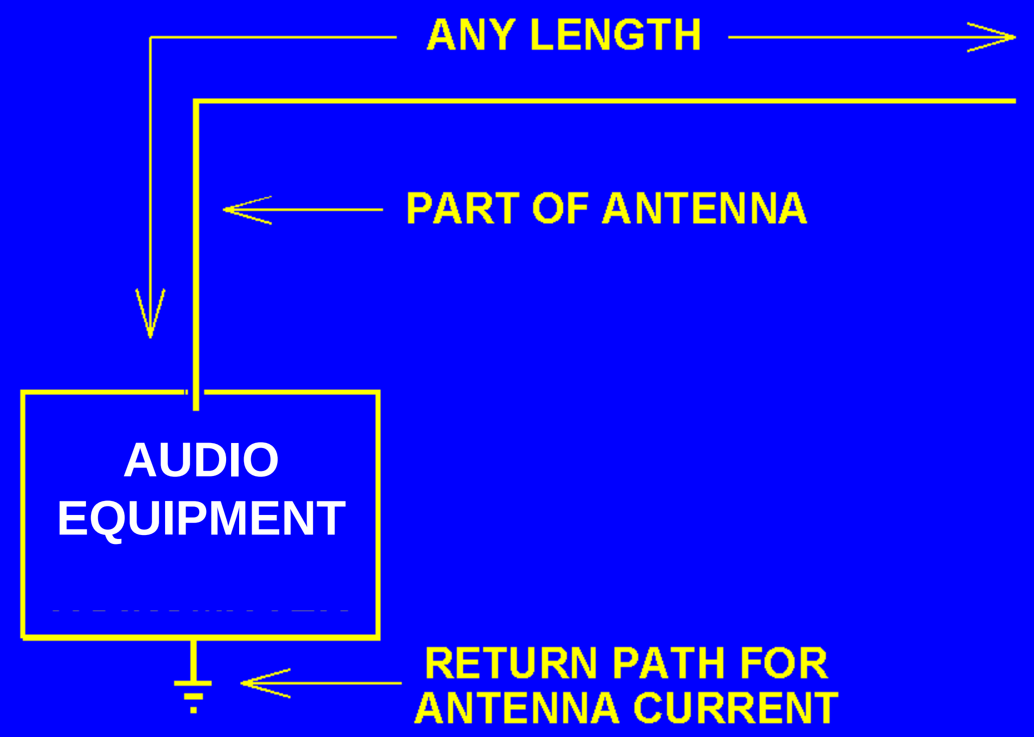


- It doesn’t need to be an ideal quarter wave to work – it will just be less efficient and its directivity may change!

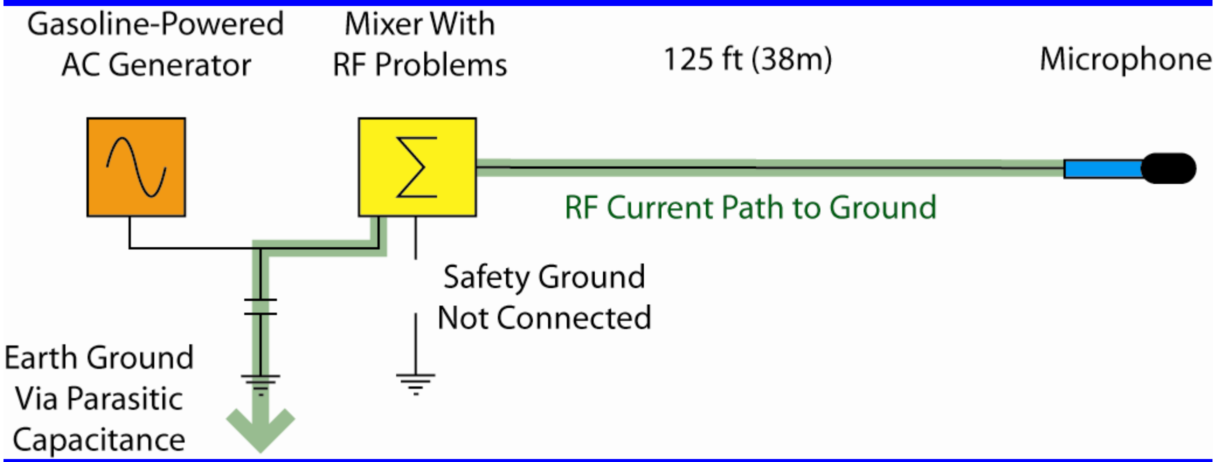
Basic Random Long Wire



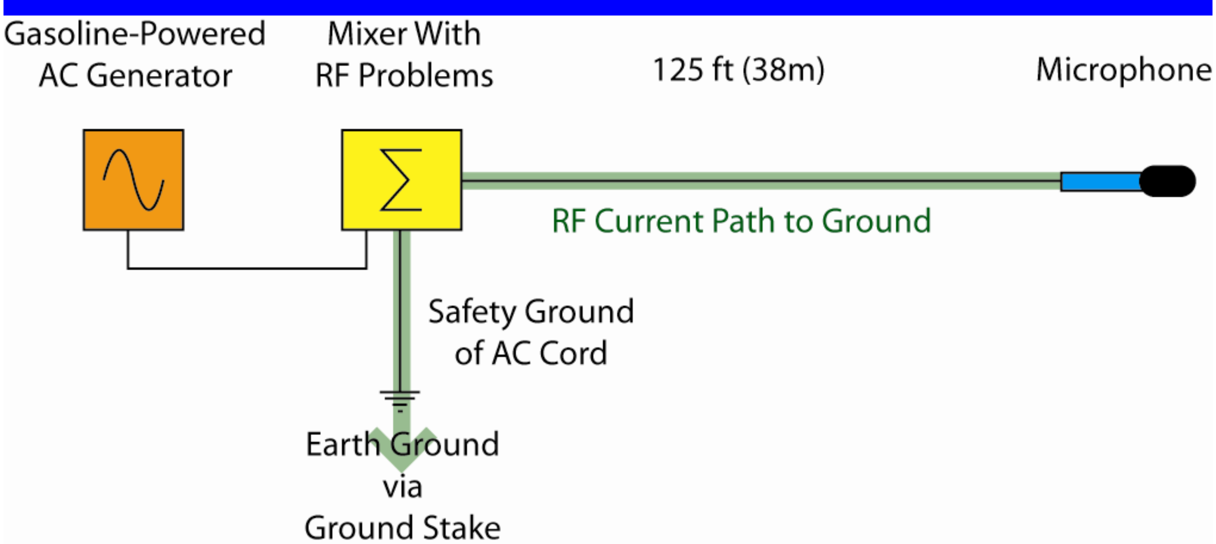
Basic Random Long Wire



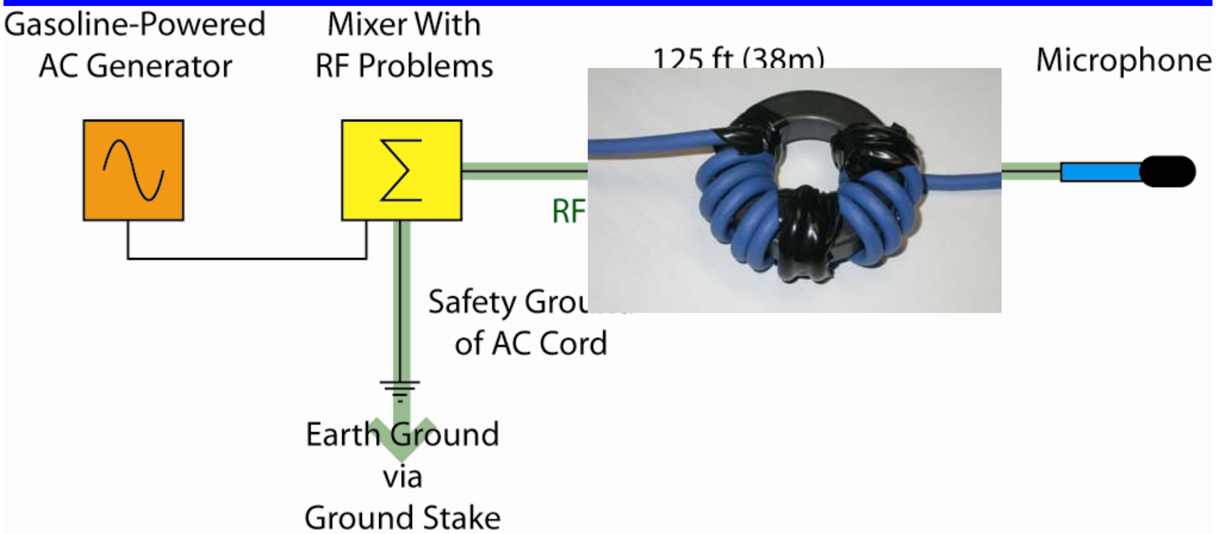
Example: 50kW on 720 kHz (WGN) to test mics and input gear for RFI



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

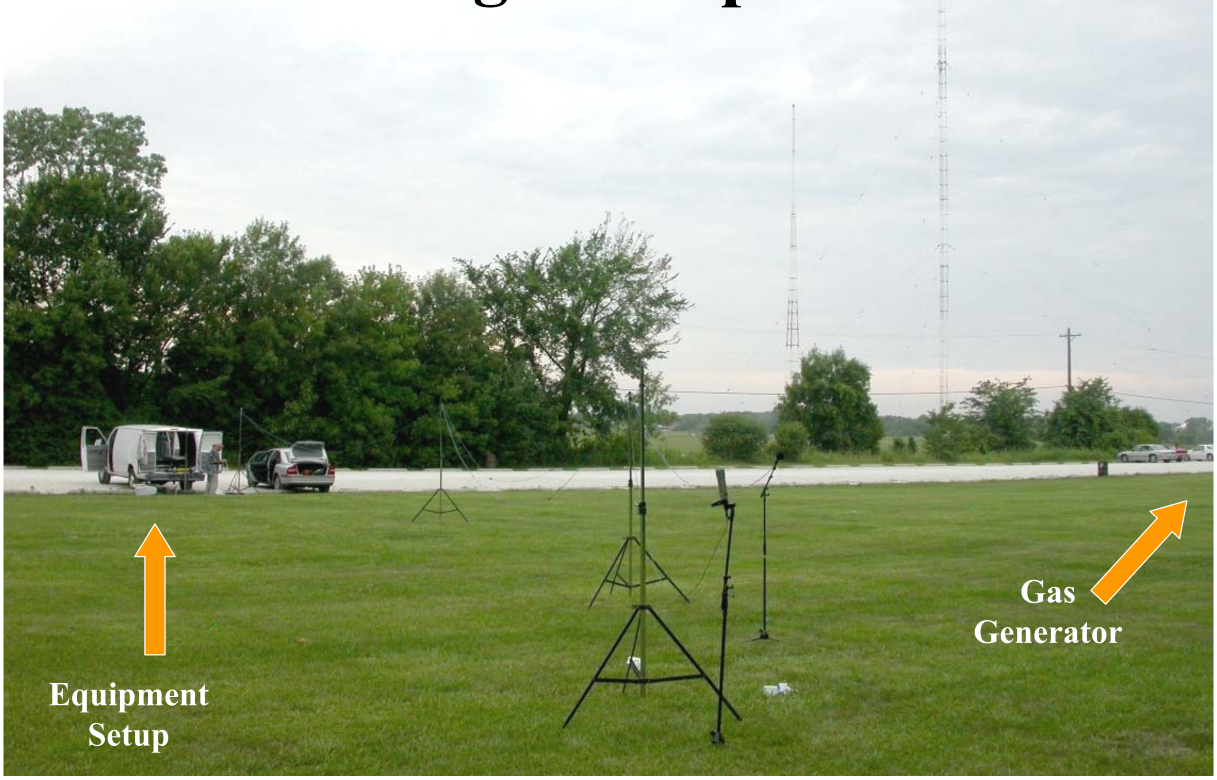


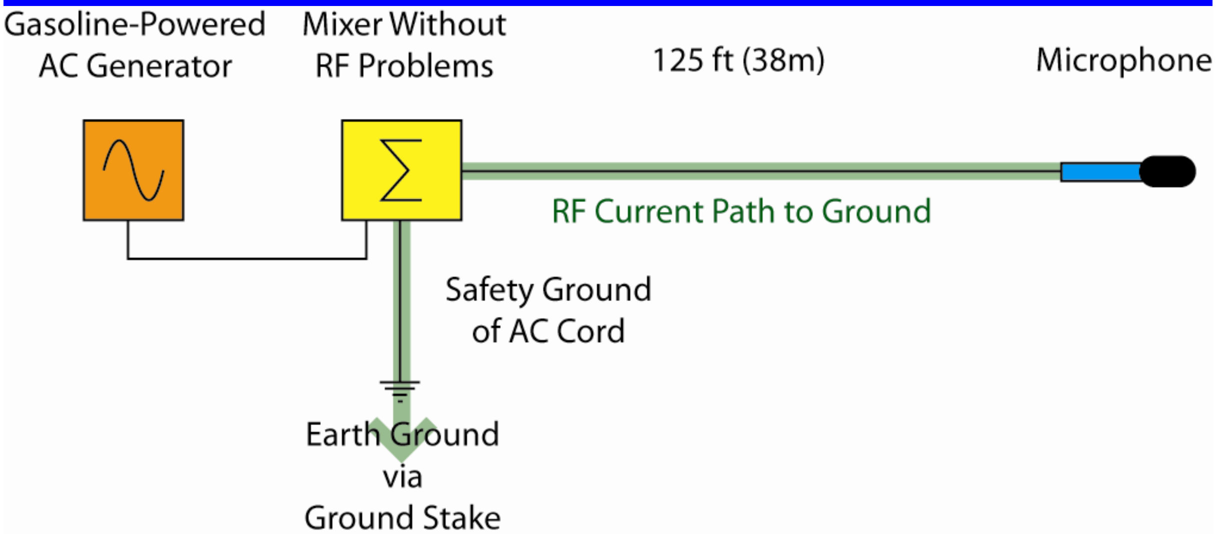
A better RF ground (the ground stake), so much more interference



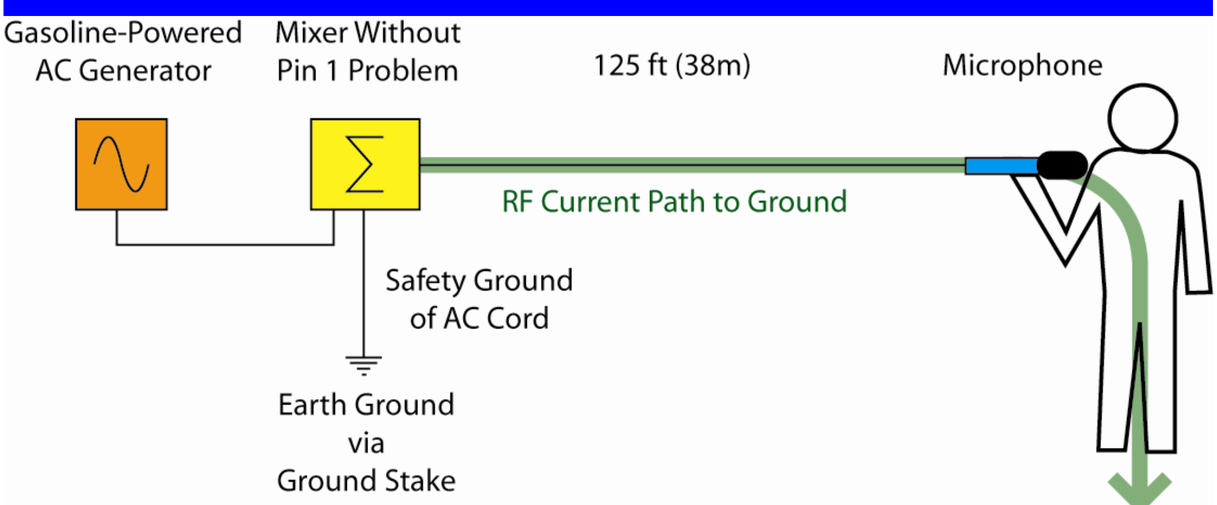
This choke reduced the current, and thus the RFI

Testing Microphones





No RF ground for the mic, so no interference

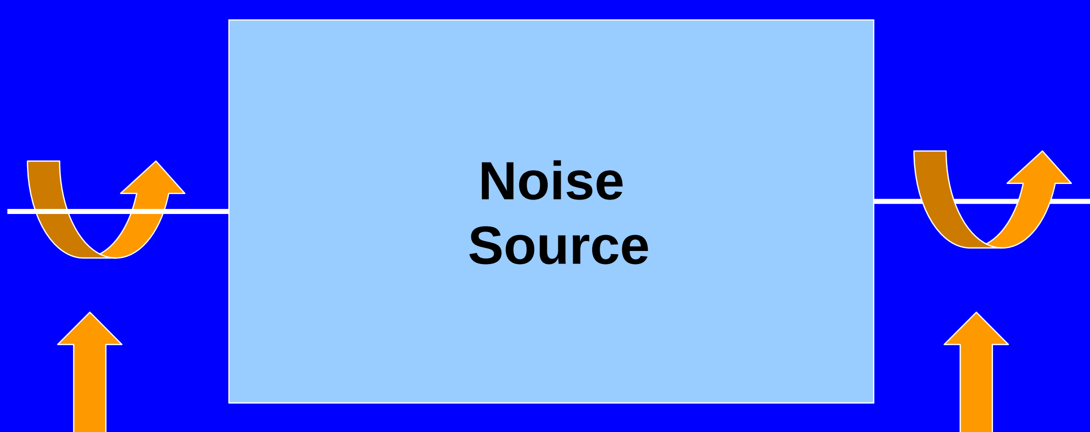


But when K9IKZ held the mic in his hand, some mics had RFI

Ferrites can block the current!

Common Mode Coupling

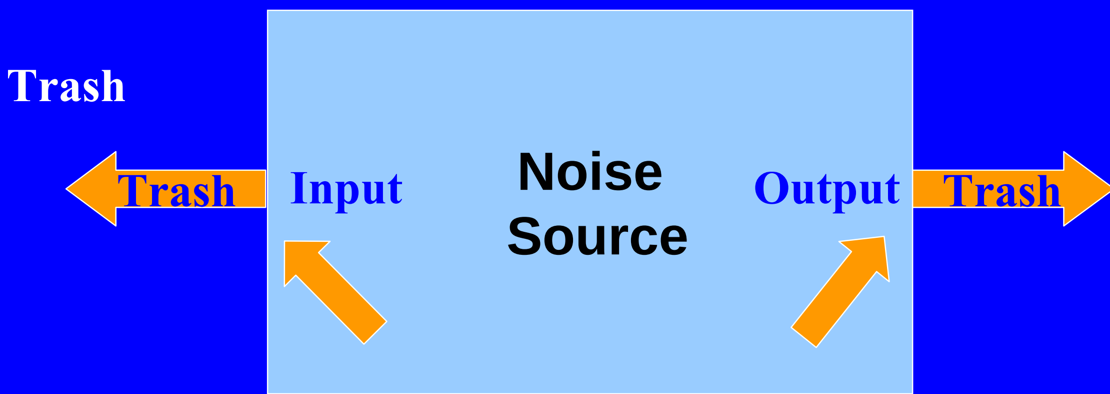
- I/O wiring acts as long wire antenna
- Noise current flows lengthwise on wiring



Ferrites “outside the box” can Help a Lot!

Differential Mode Coupling

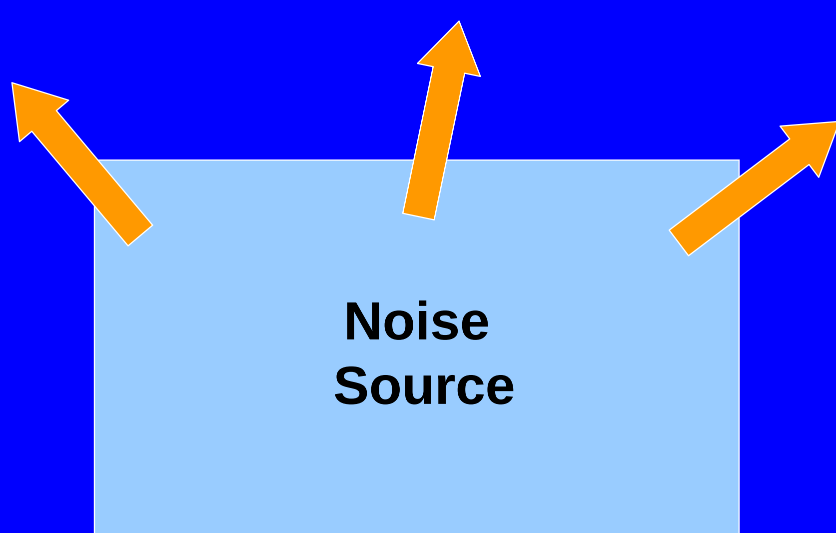
- I/O wiring is not band-pass filtered
- Noise is between + and – terminals of wiring



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?

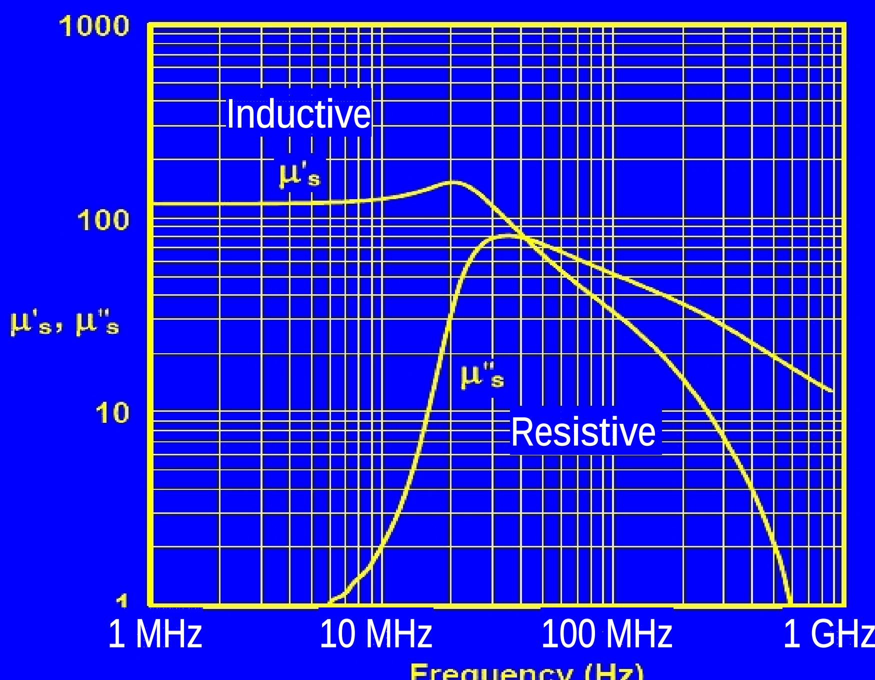
- A ceramic consisting of an iron oxide
  - manganese-zinc – 1-30 MHz (AM broadcast, hams)
  - nickel-zinc – 30 MHz-1 GHz (FM, TV, cell phones)
- Has permeability (μ) much greater than air
  - Better path for magnetic flux than air
  - Multiplies inductance of a wire passed through it
- Is increasingly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

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

Complex Permeability

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

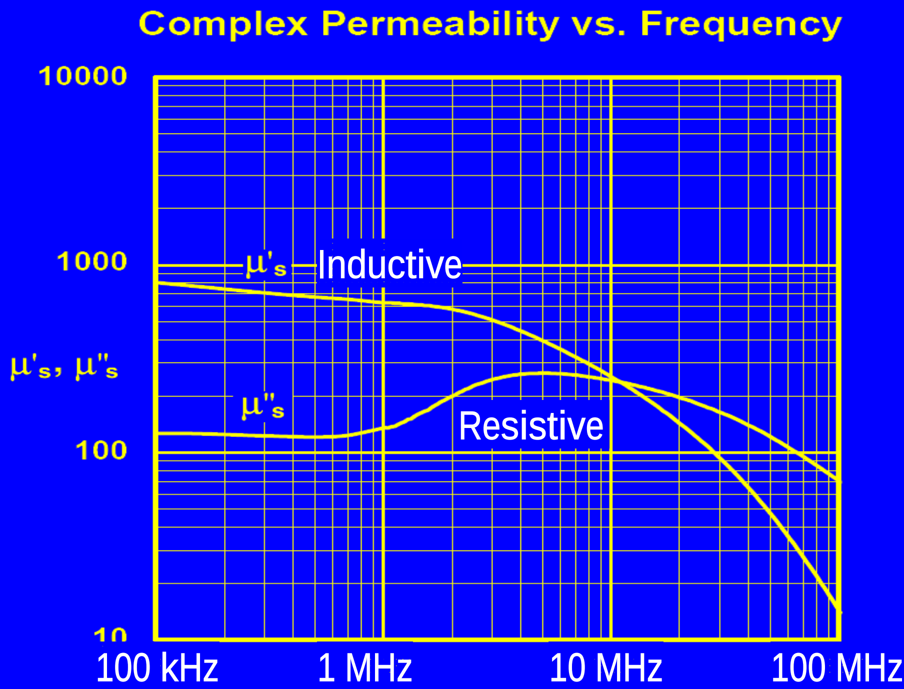
#61



Complex Permeability

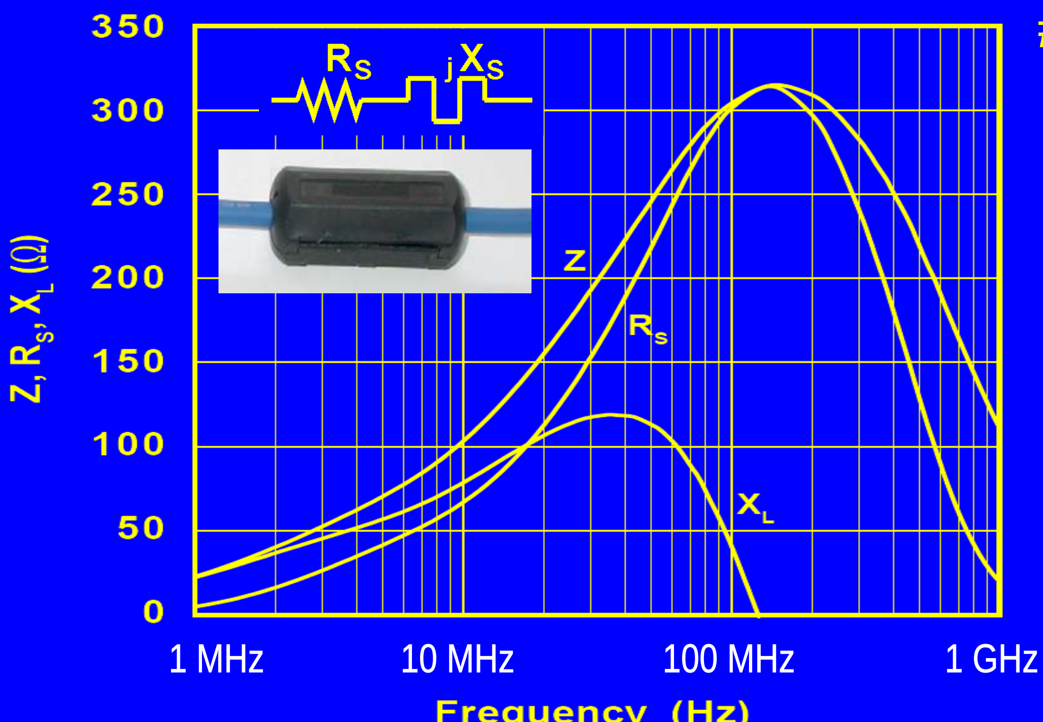
$$\mu = \mu_s' + j\,\mu_s''$$

#78

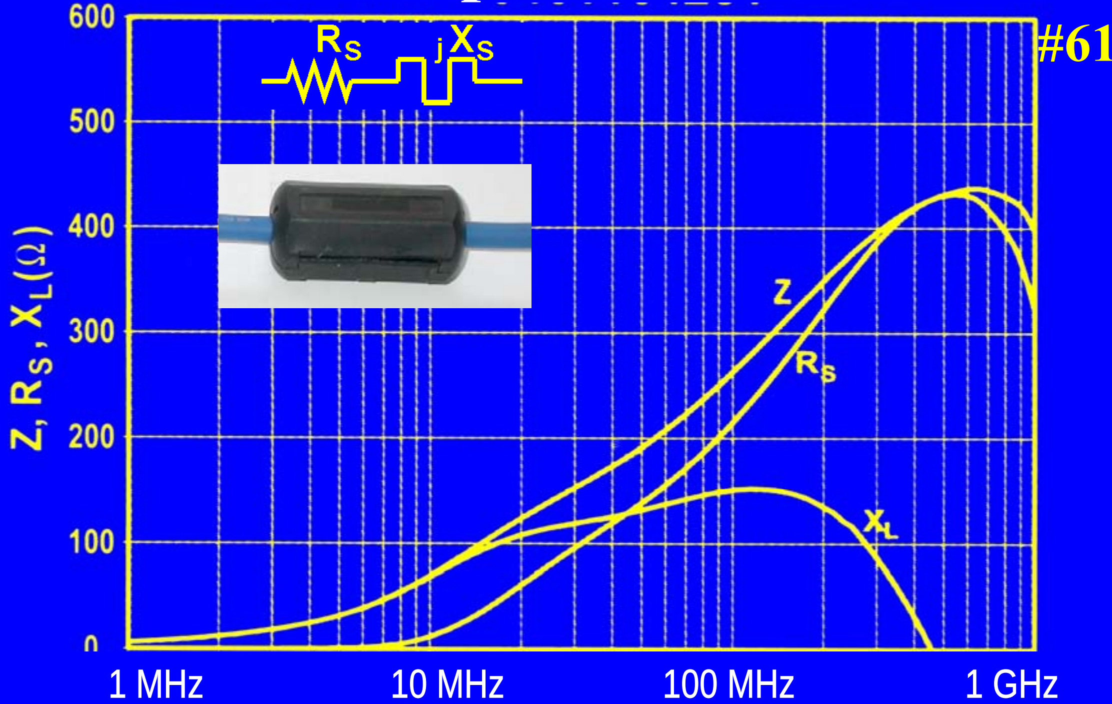


R_s and X_s vary with frequency!

#43

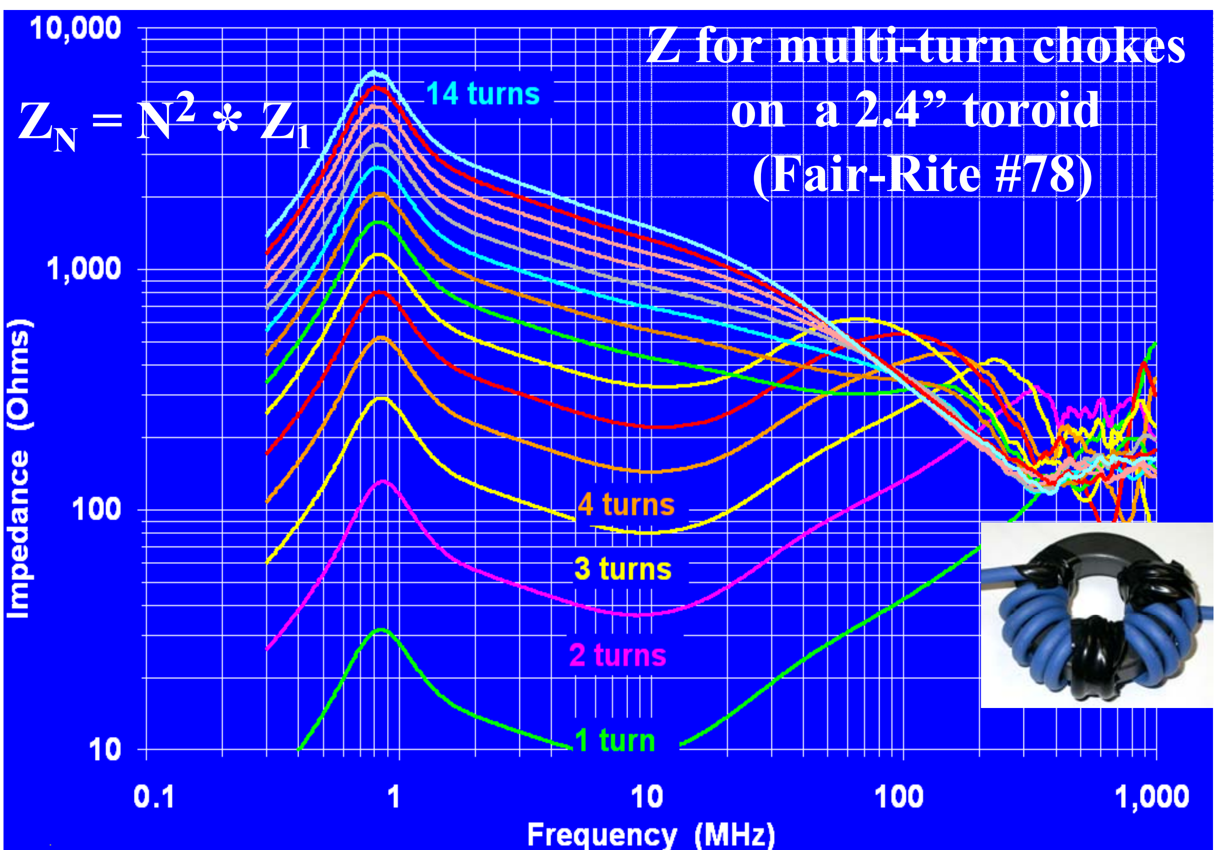


A Ferrite Optimized for UHF

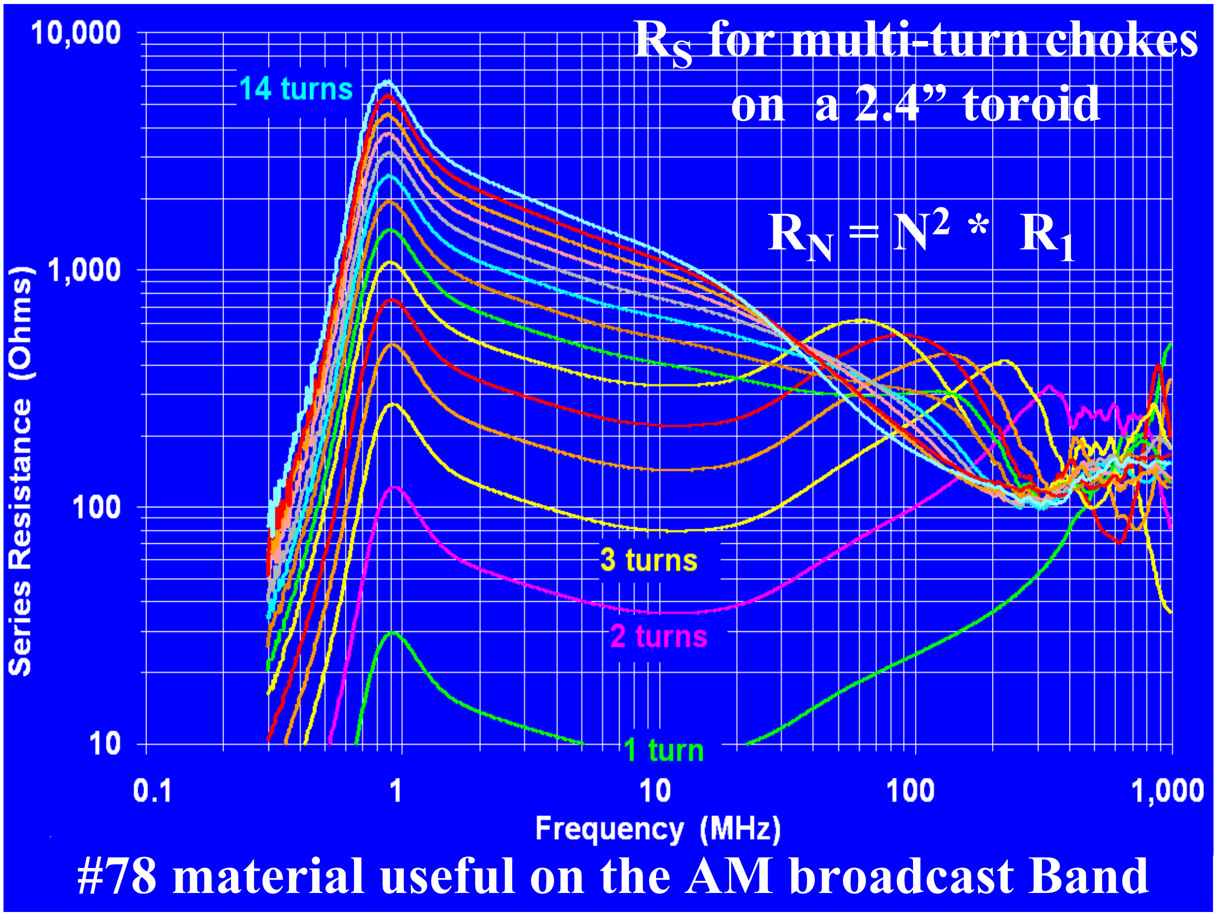


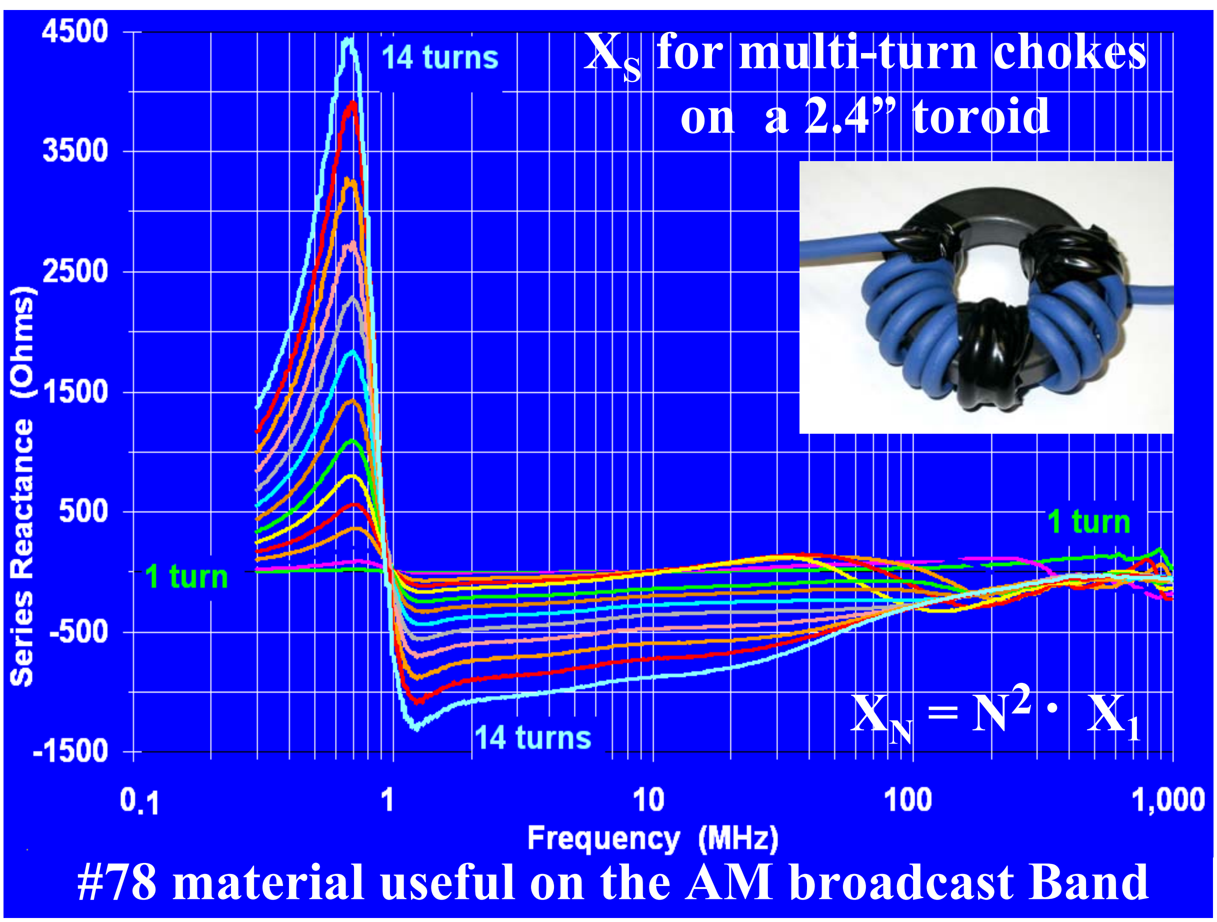
HP8753C w/HP85046A S-parameter Test Set
(by my anonymous collaborator)

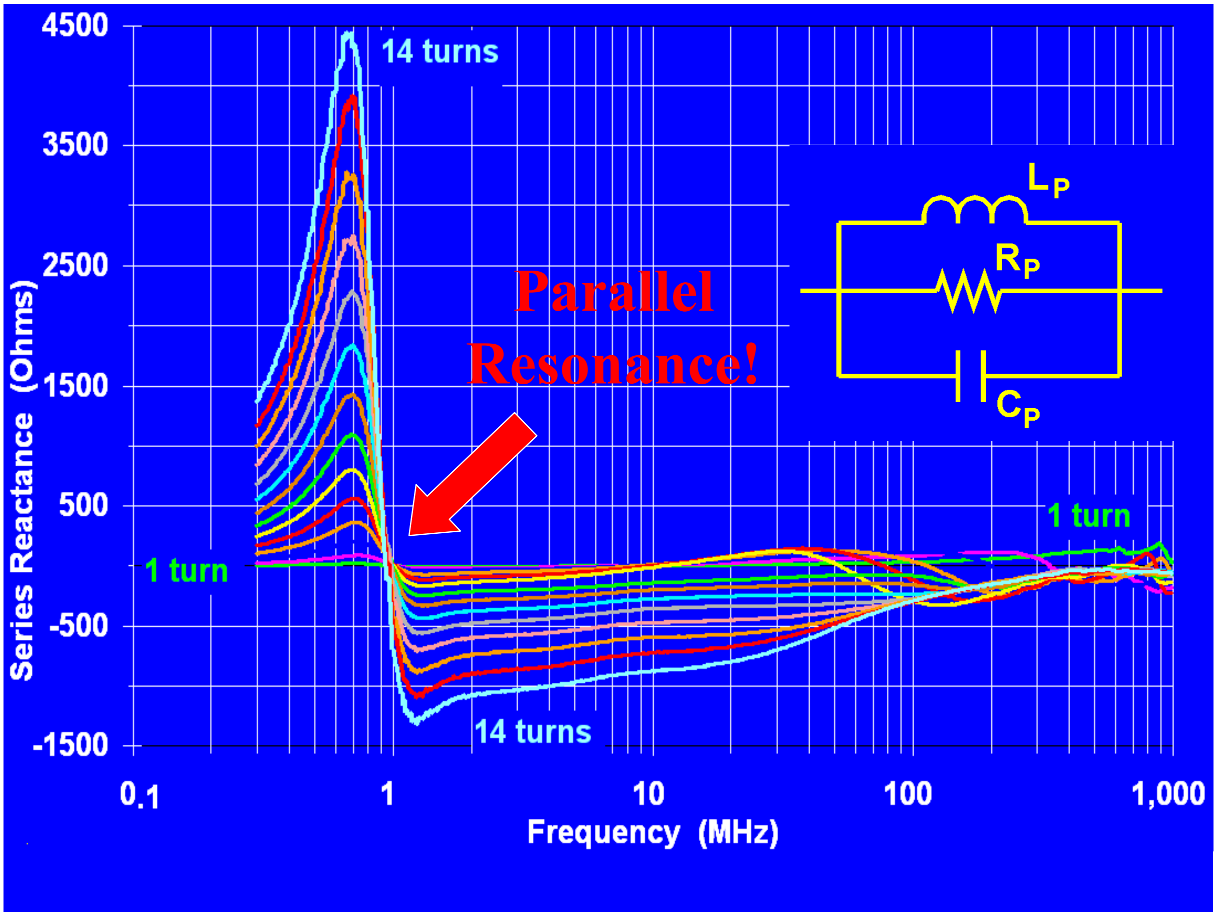
AEA CIA-HF



A material useful on the AM broadcast Band


RS for multi-turn chokes on a 2.4" toroid
RN = N2 * R1
14 turns
3 turns
2 turns
1 turn
10,000
1,000
100
10
Series Resistance (Ohms)
0.1
1
10
100
1,000
Frequency (MHz)
#78 material useful on the AM broadcast Band


XS for multi-turn chokes on a 2.4" toroid
XN = N2 · X1
14 turns
1 turn
1 turn
14 turns
4500
3500
2500
1500
500
-500
-1500
Series Reactance (Ohms)
0.1
1
10
100
1,000
Frequency (MHz)
#78 material useful on the AM broadcast Band



What Causes this Resonance?

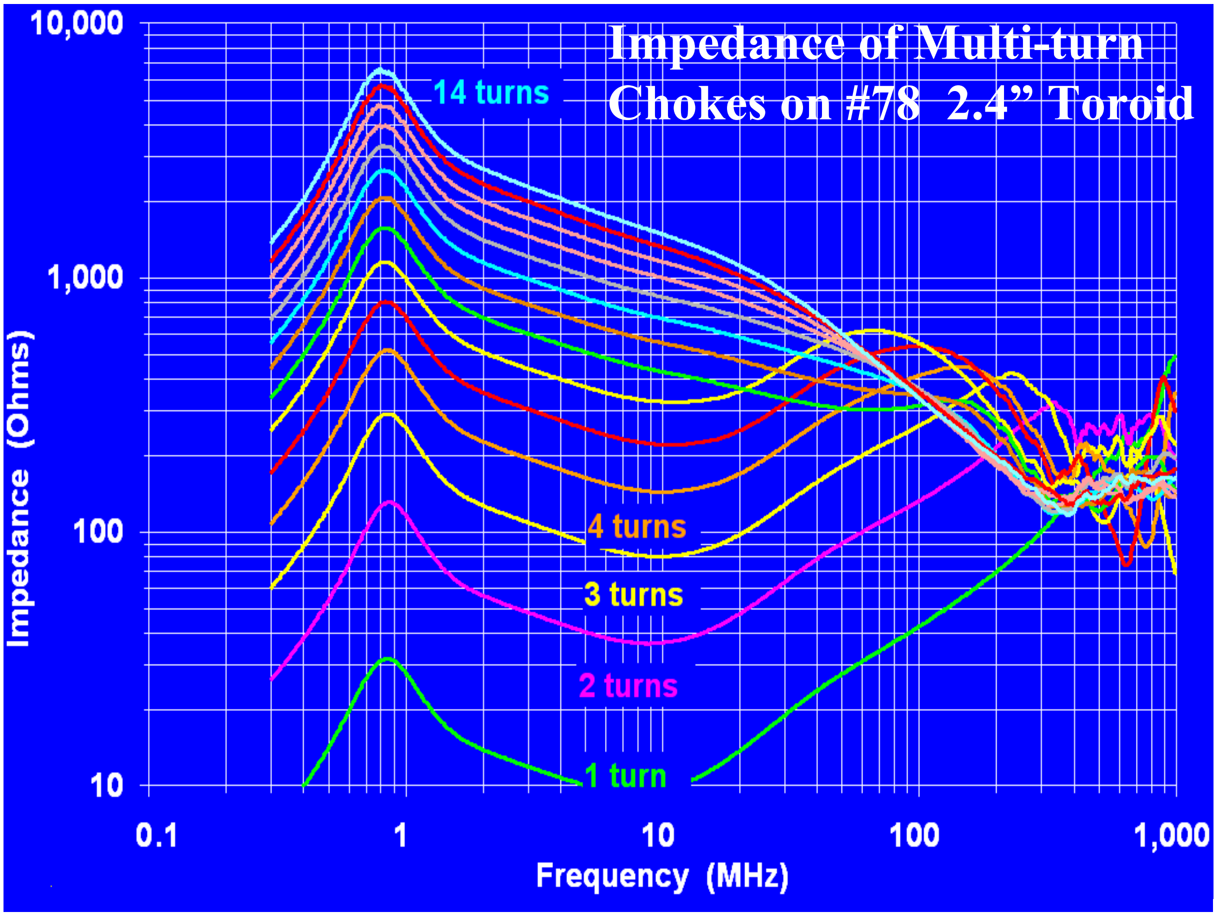
The ferrite material (called the "*mix*"), and

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)**

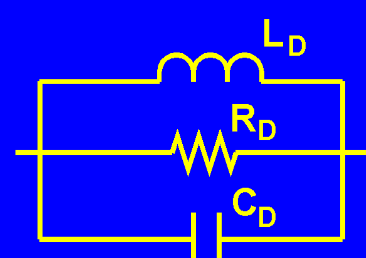
- **Resonance occurs when the cross-section is a half-wavelength**
- **Frequency of the resonance depends on:**
  - **Velocity of propagation (depends on the "mix")**
  - **Dimensions of the cross-section of the flux path**



This One is Also Too Simple

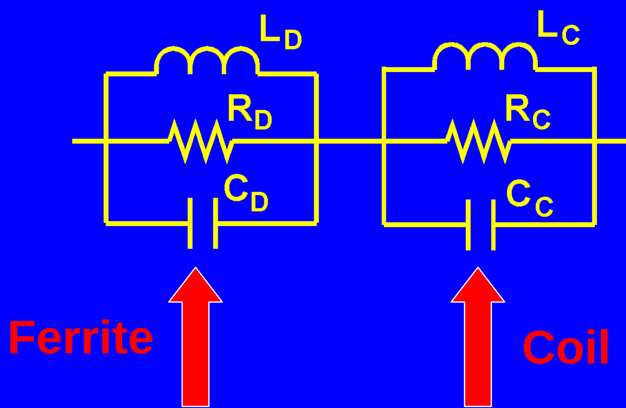
It is adequate at <u>low</u> frequencies, but look at high frequencies – there is another resonance up there!

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

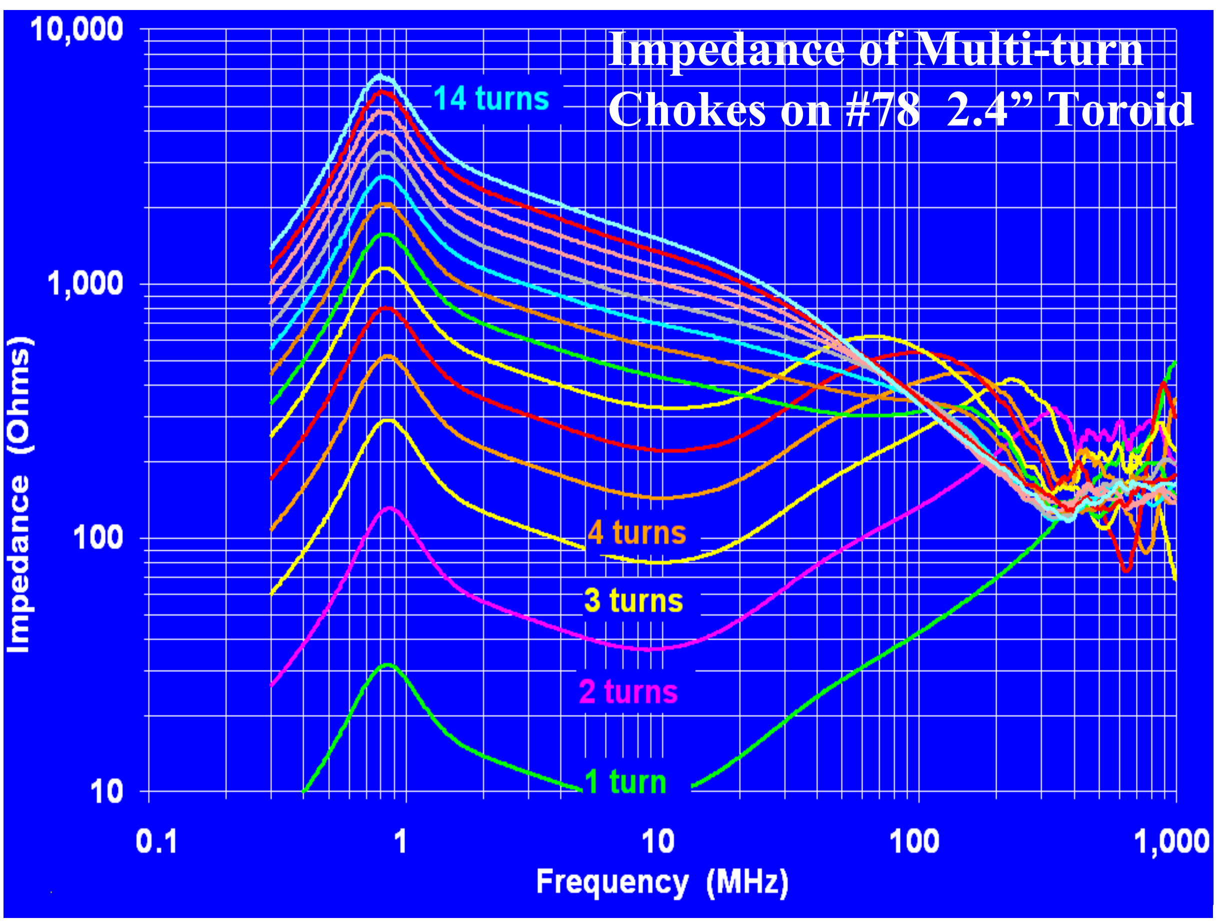


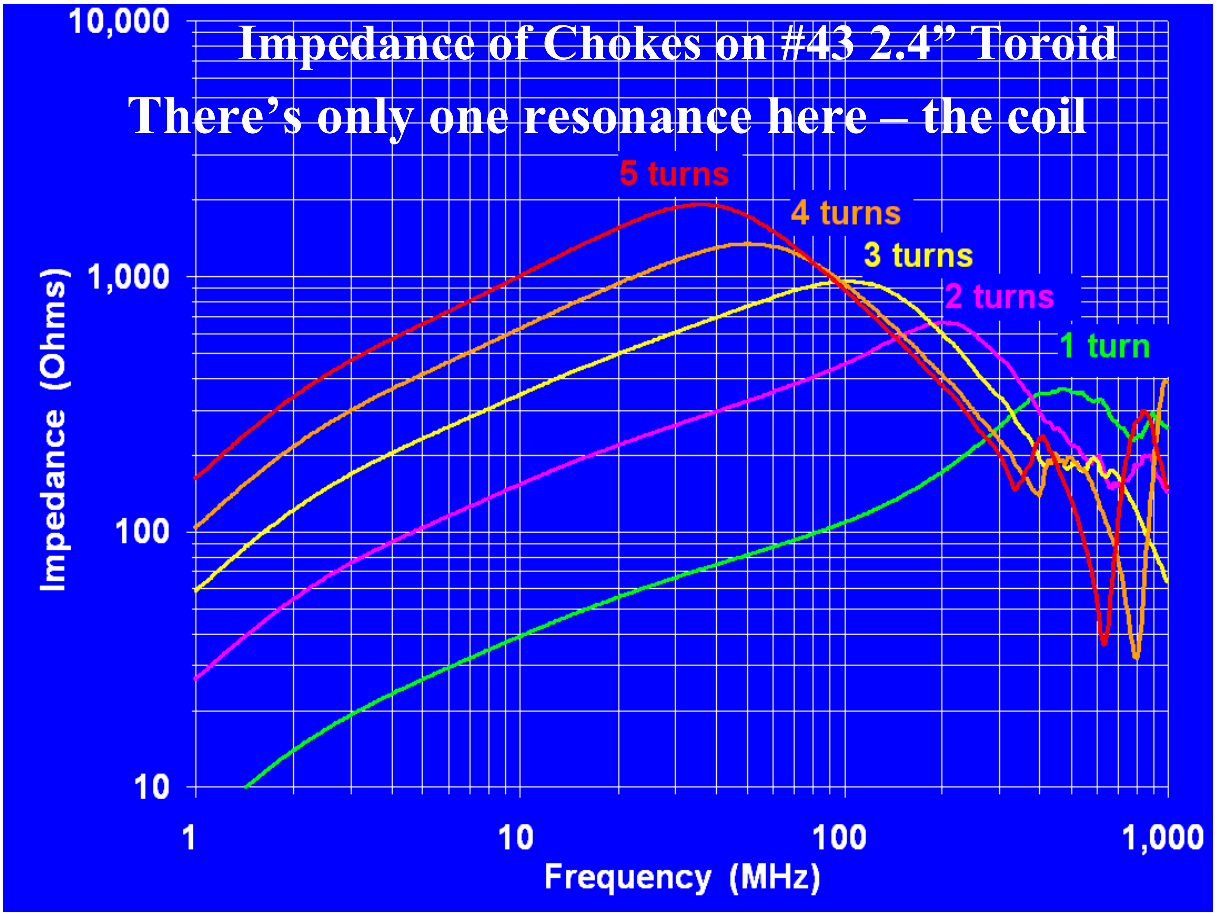
L_C is the inductance of the coil

C_C is the stray capacitance of the coil

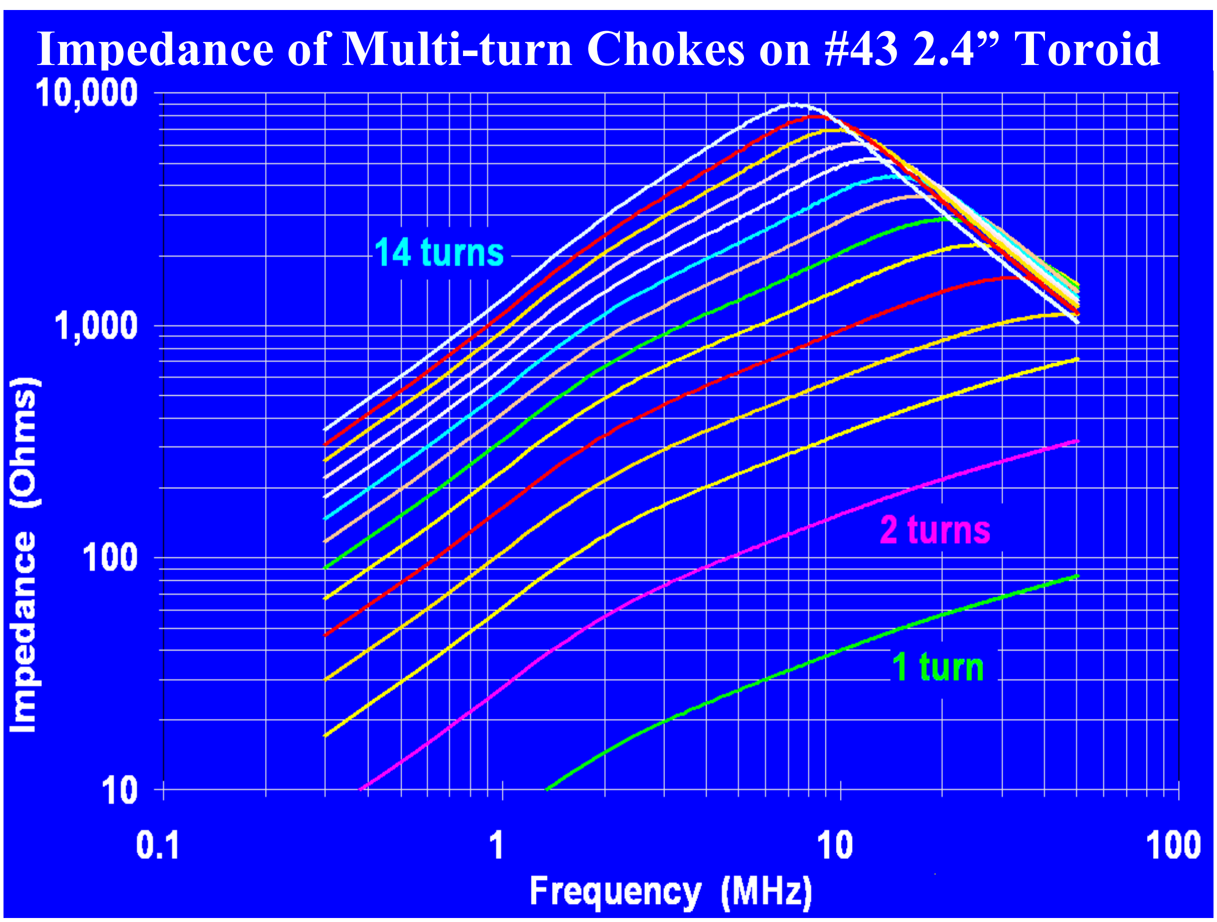
R_C is the resistance of the wire.

L_C and C_C form the resonance that moves!

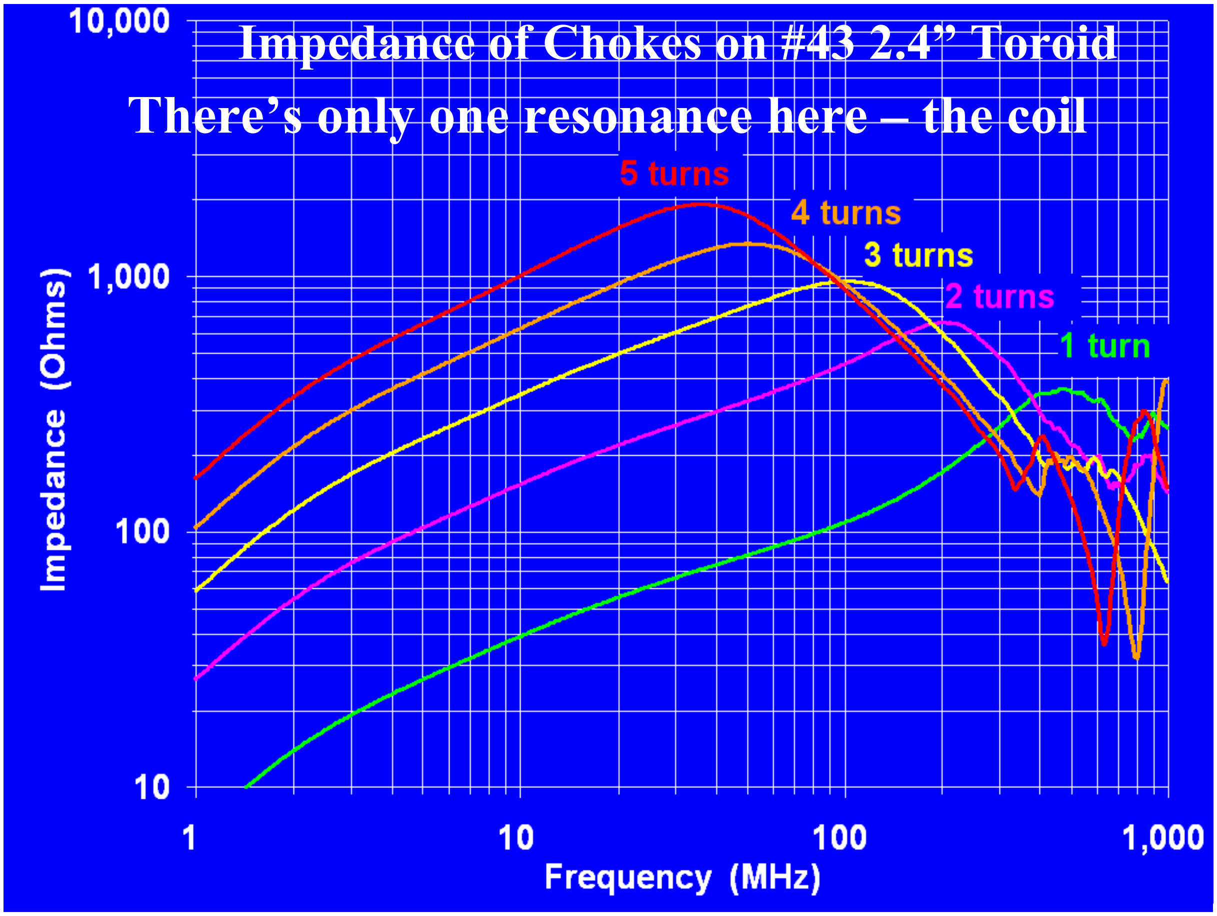


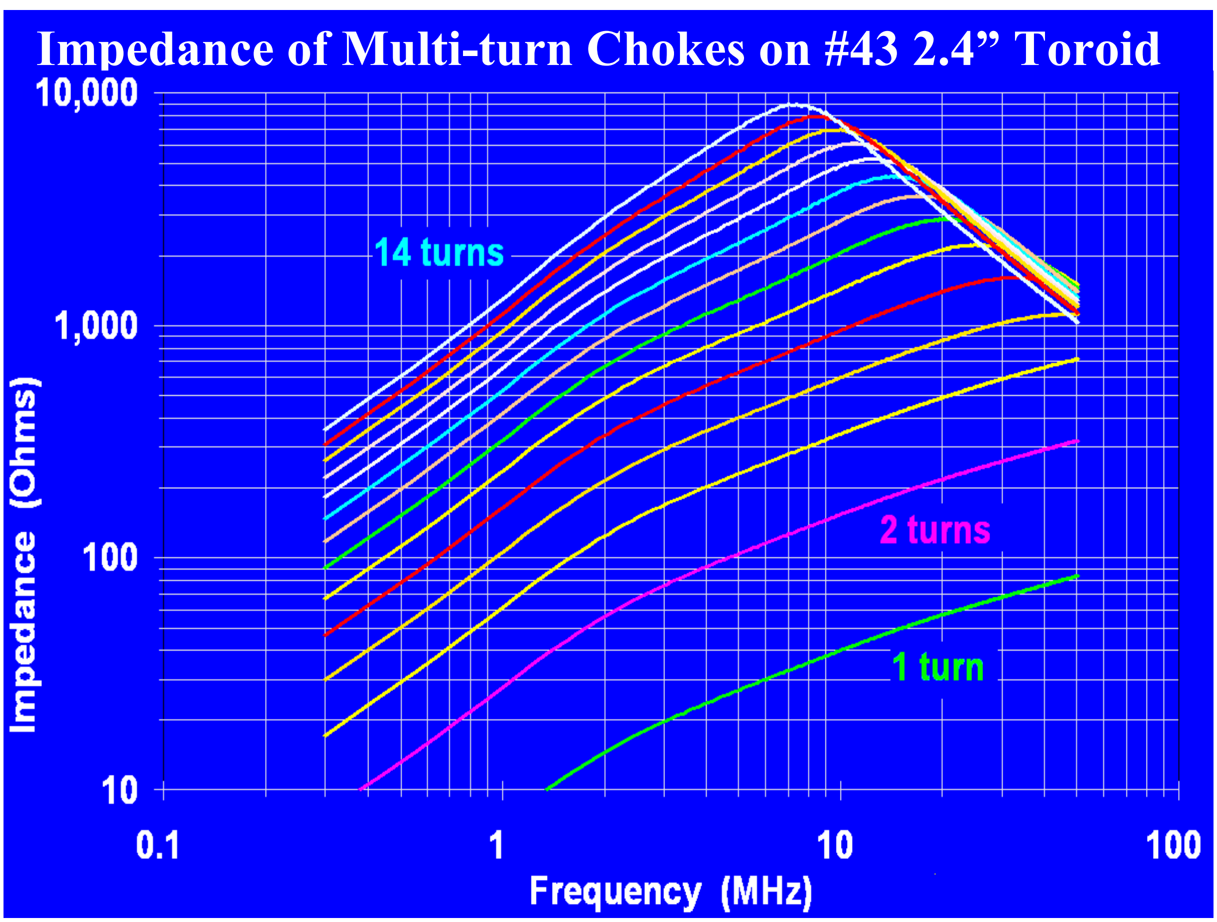


Impedance of Chokes on #43 2.4" Toroid
There's only one resonance here – the coil
5 turns
4 turns
3 turns
2 turns
1 turn
Impedance (Ohms)
10,000
1,000
100
10
1
10
100
1,000
Frequency (MHz)



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)

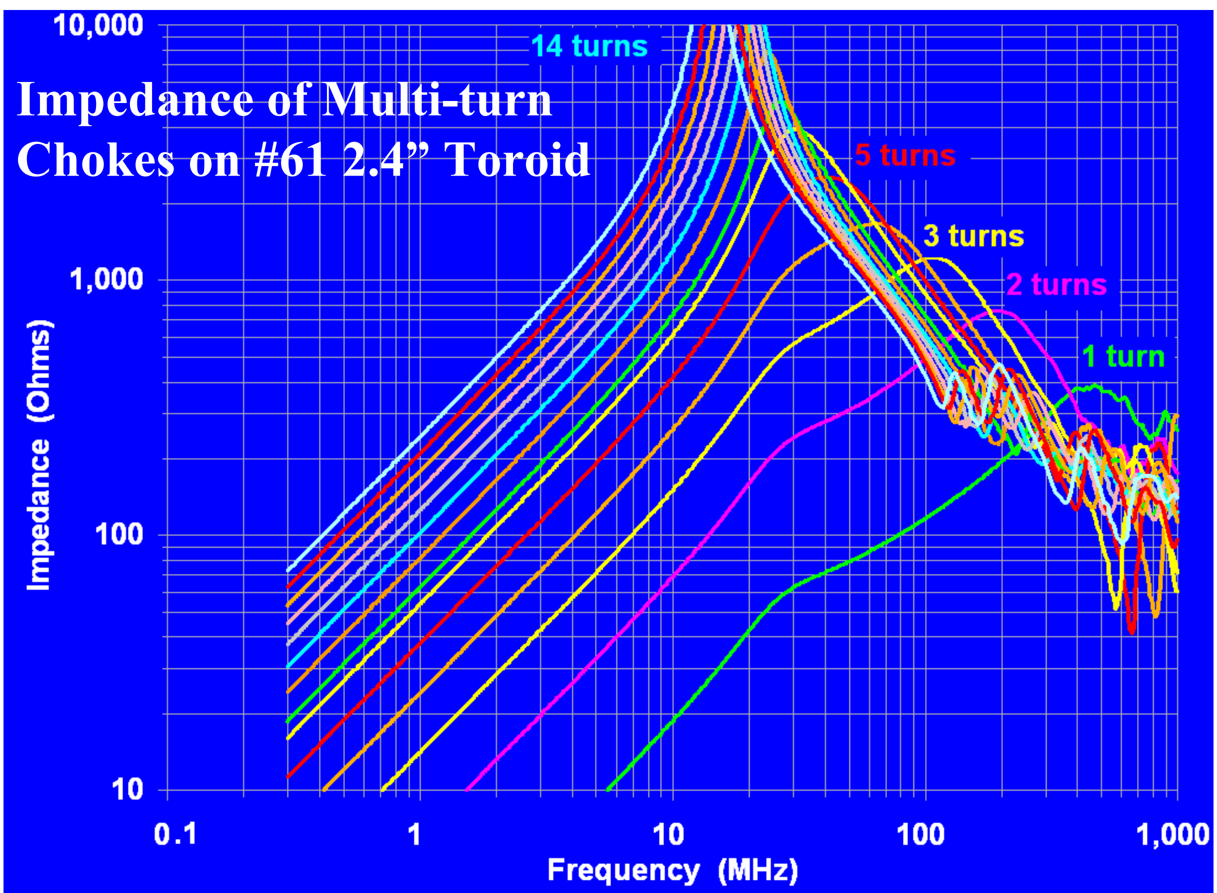

Impedance of Chokes on #43 2.4" Toroid
There's only one resonance here – the coil
5 turns
4 turns
3 turns
2 turns
1 turn
Impedance (Ohms)
10,000
1,000
100
10
1
10
100
1,000
Frequency (MHz)


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)

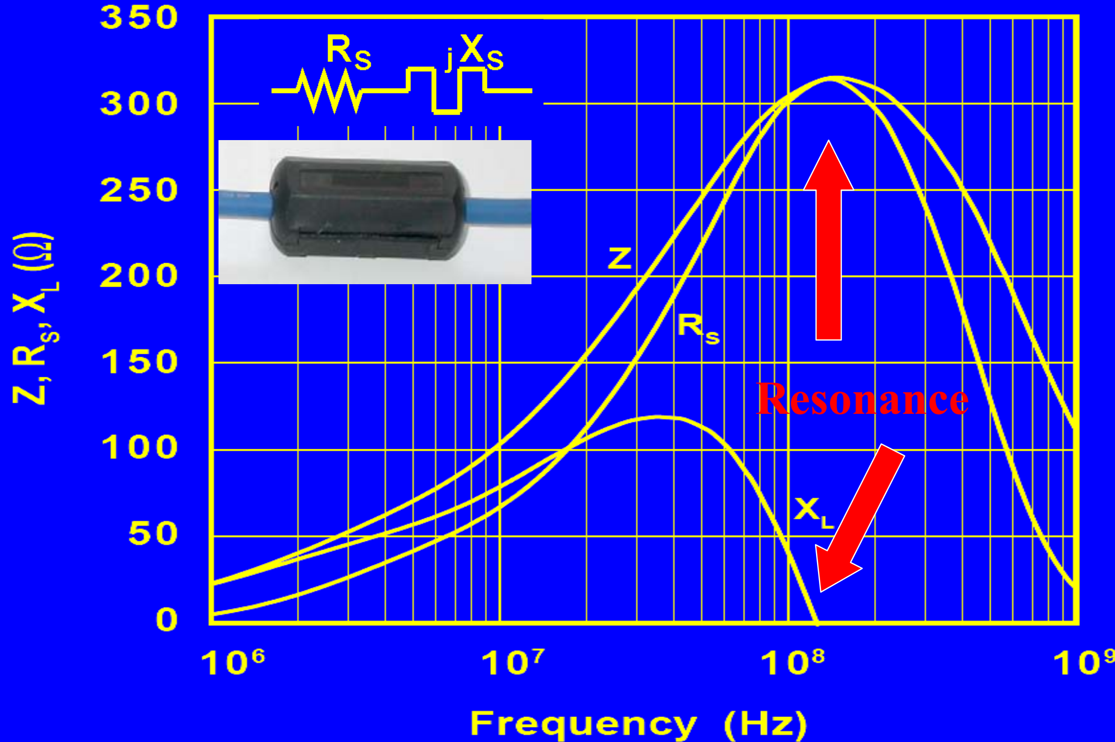
Why no Dimensional Resonance?

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



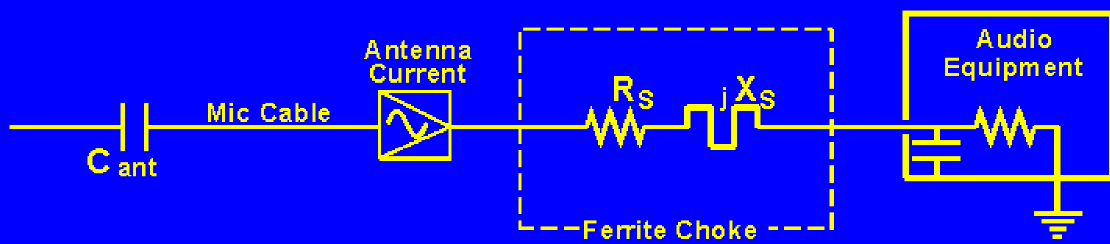
Where's the Capacitance here?

Where’s the Capacitance here?

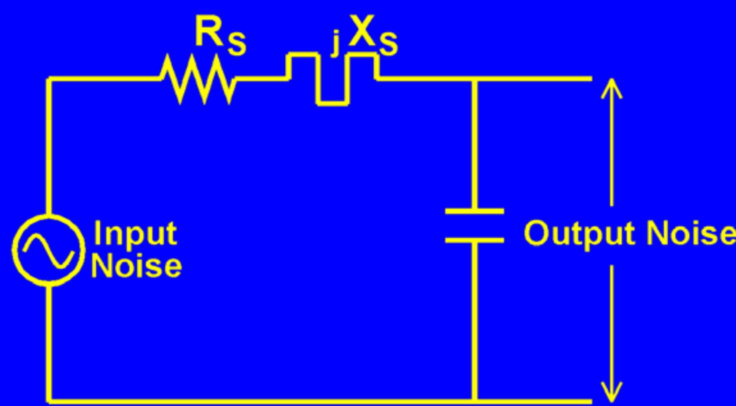
From the wire at one end of the choke to the wire at the other end, through the permittivity of the ferrite (it is a dielectric!)

So How do We Use These Tools?

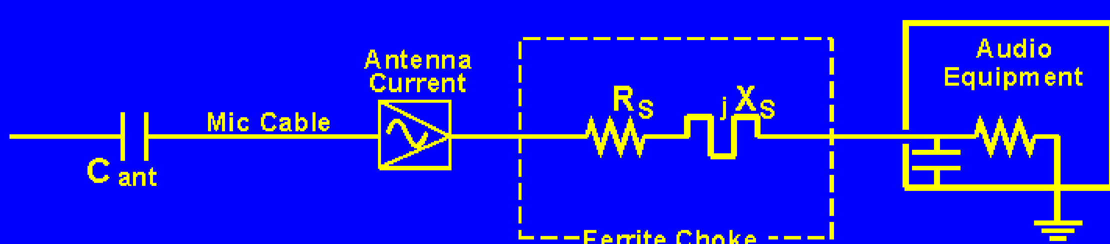
A Choke Applied to Audio Cable



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, unless R_S limits it – so, for effective suppression:

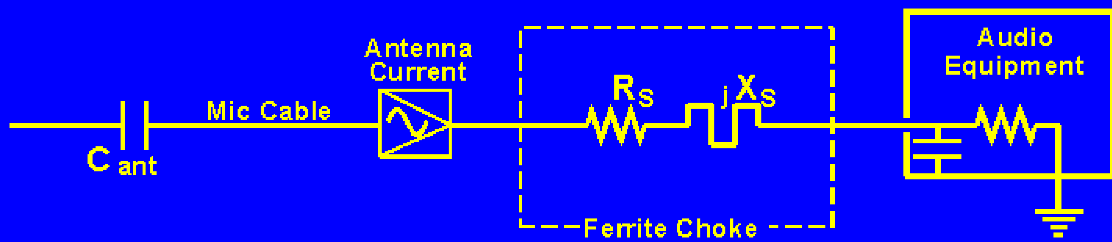
R_S should always be large!

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:

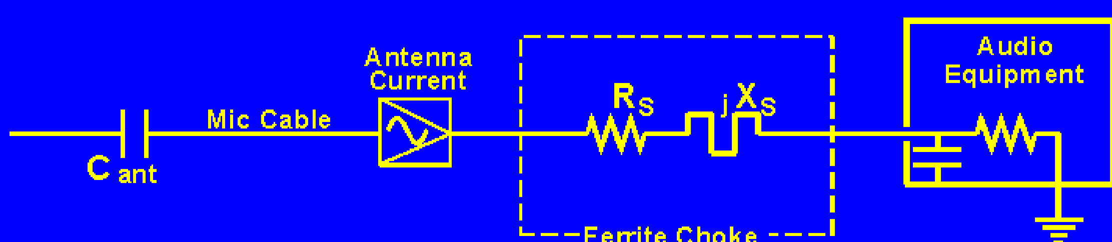
Without the choke, the total antenna circuit is 300∠-60°Ω (that is, capacitive)

and we add a choke that is 300∠60°Ω (inductive),

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

Our choke has not reduced the current!

Threshold Effect



Additional R_S <u>will</u> 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.

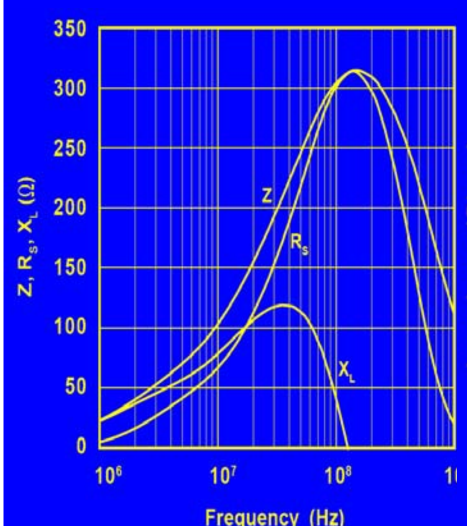
Criteria for Good Suppression

- 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

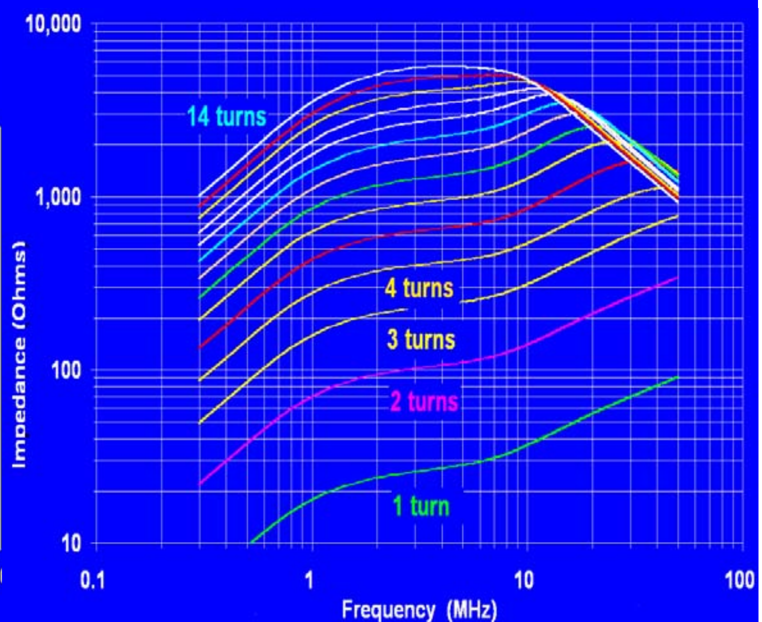
Inside the Box

- 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

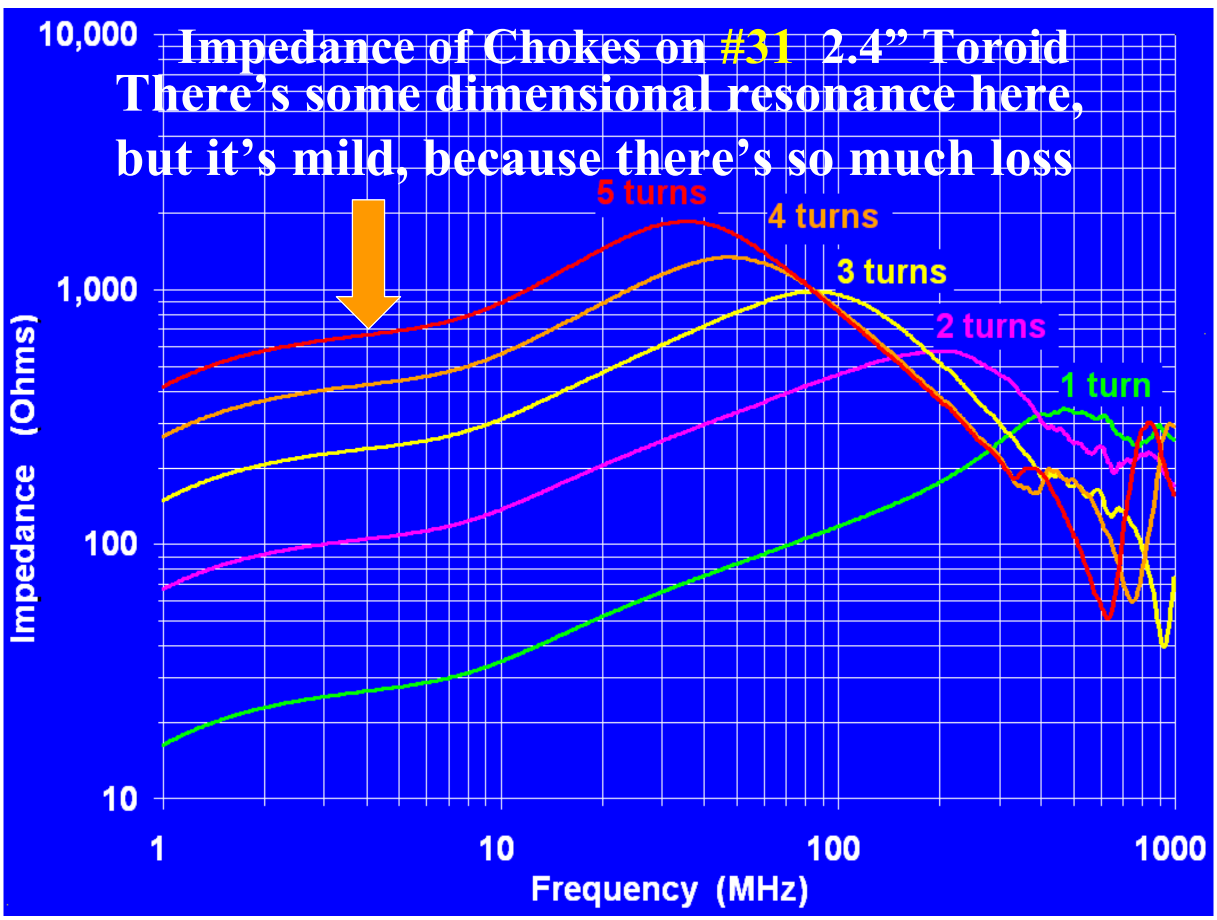


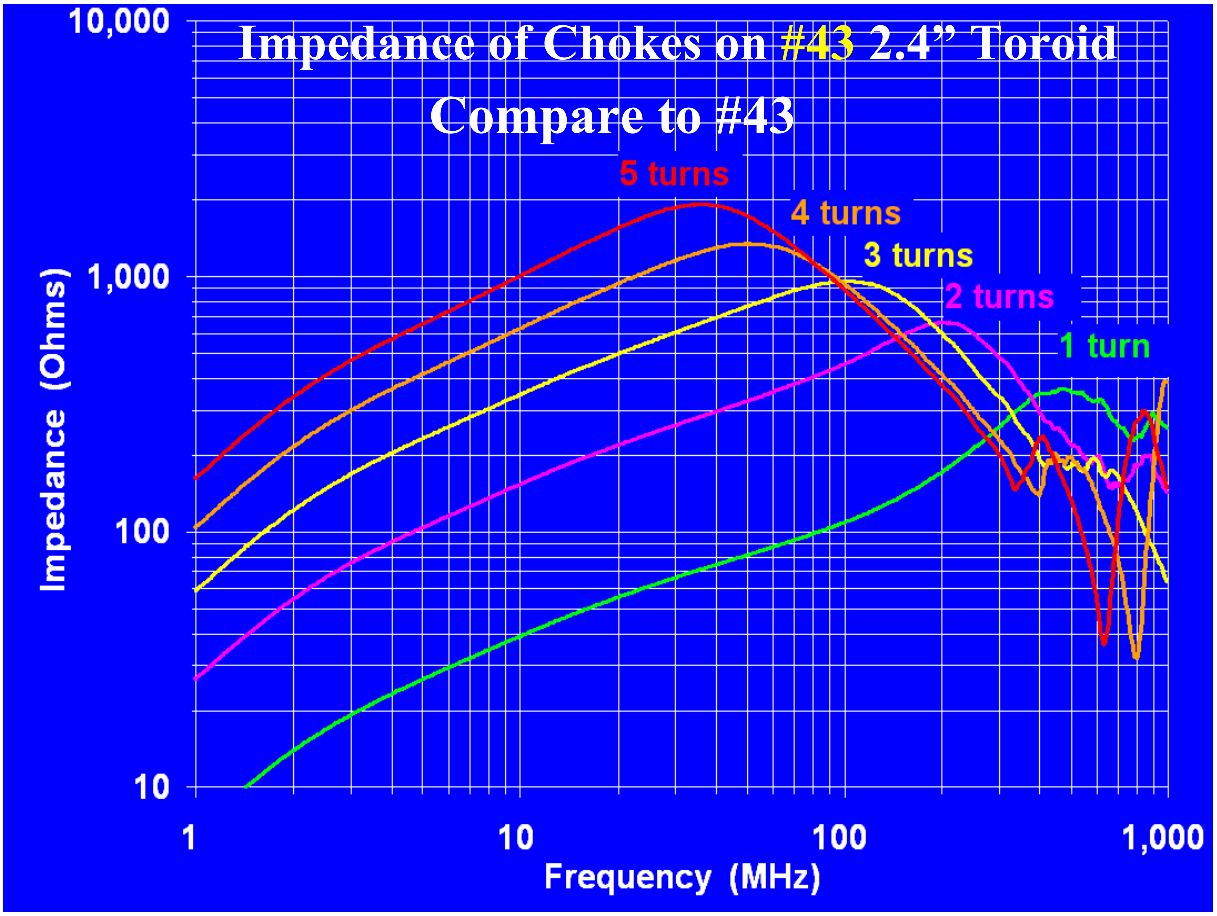
A Multi-turn Choke (#31) is needed for lower frequencies

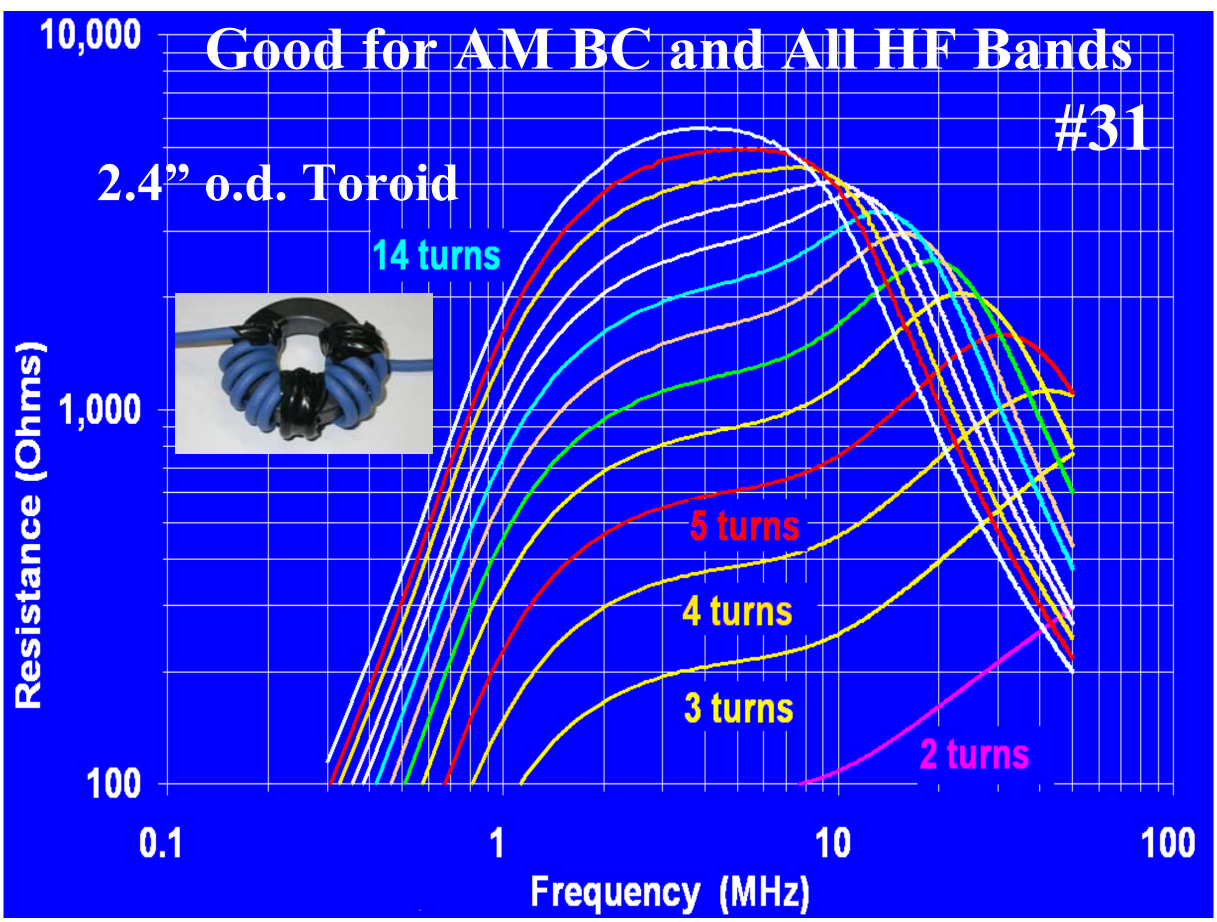
A Really Nice New Mix

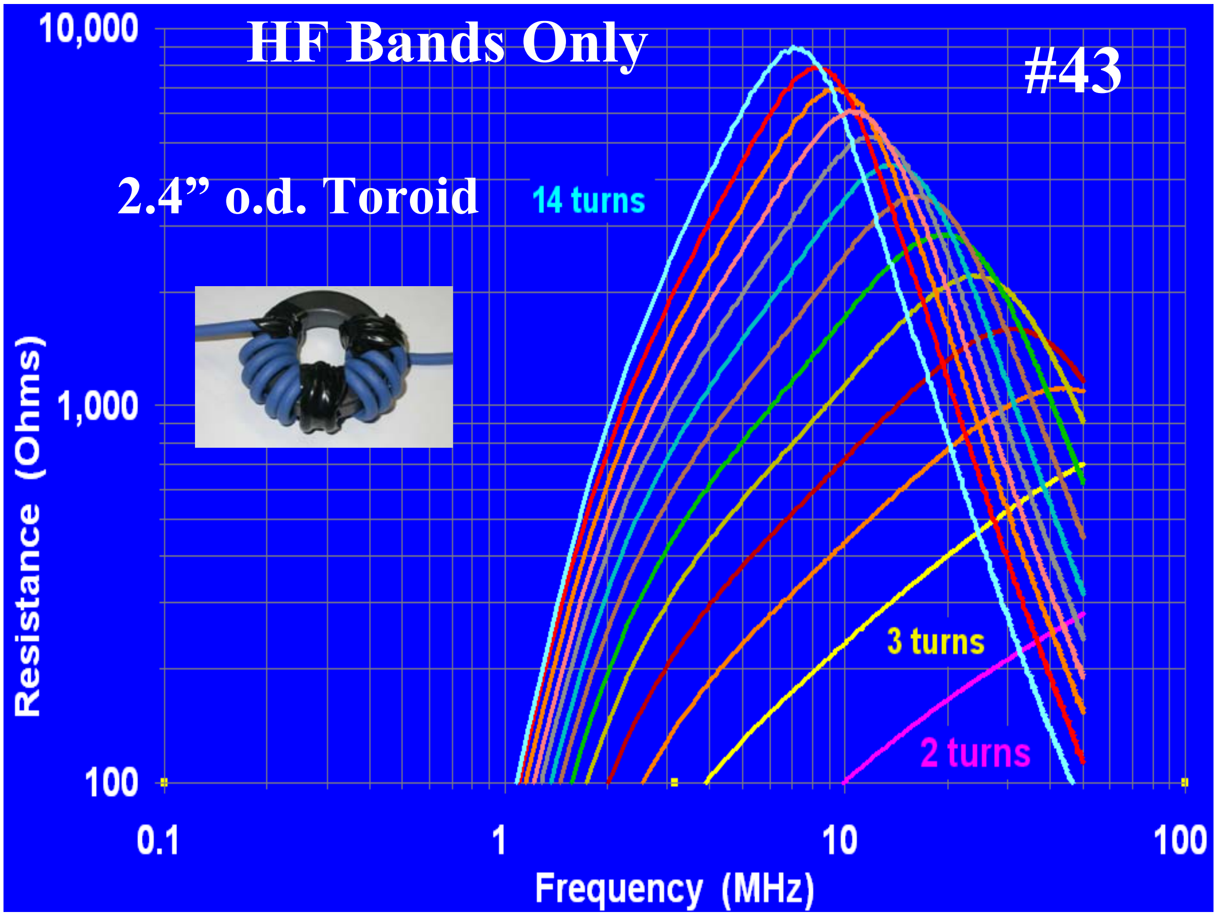
Impedance of Chokes on #31 2.4” Toroid

There’s some dimensional resonance here, but it’s mild, because there’s so much loss



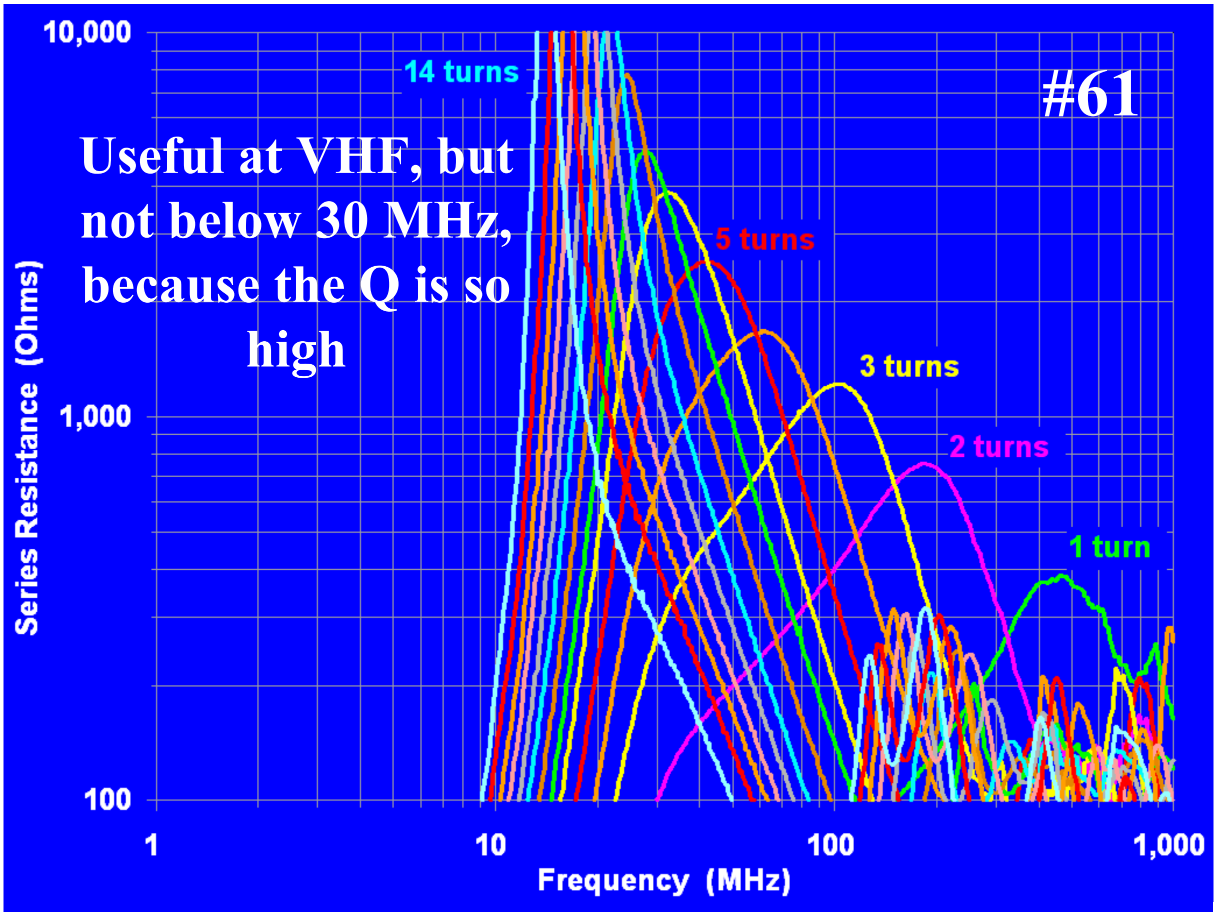

Impedance of Chokes on #43 2.4” Toroid
Compare to #43
5 turns
4 turns
3 turns
2 turns
1 turn
Impedance (Ohms)
10,000
1,000
100
10
1
10
100
1,000
Frequency (MHz)

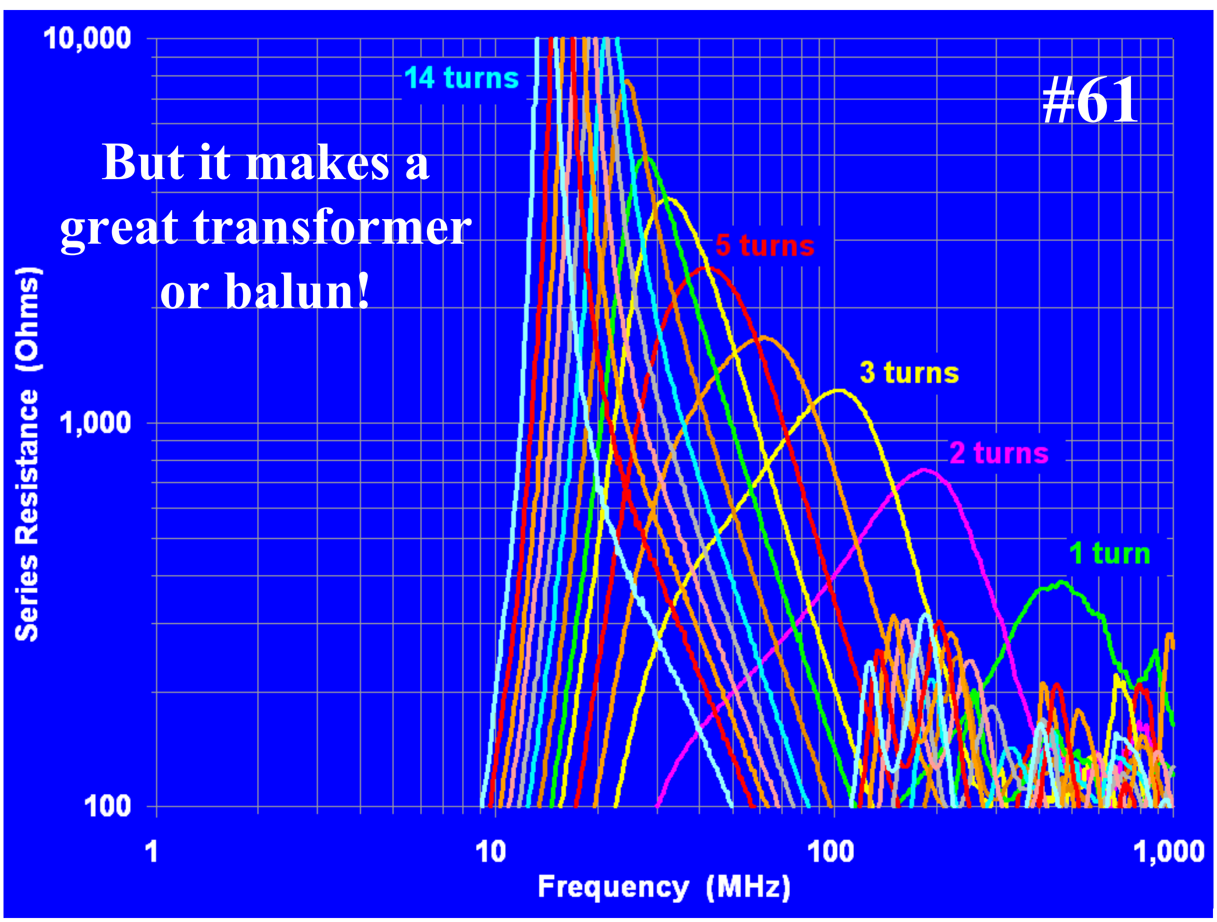

Good for AM BC and All HF Bands
#31
2.4” o.d. Toroid
14 turns
5 turns
4 turns
3 turns
2 turns
Resistance (Ohms)
10,000
1,000
100
0.1
1
10
100
Frequency (MHz)



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

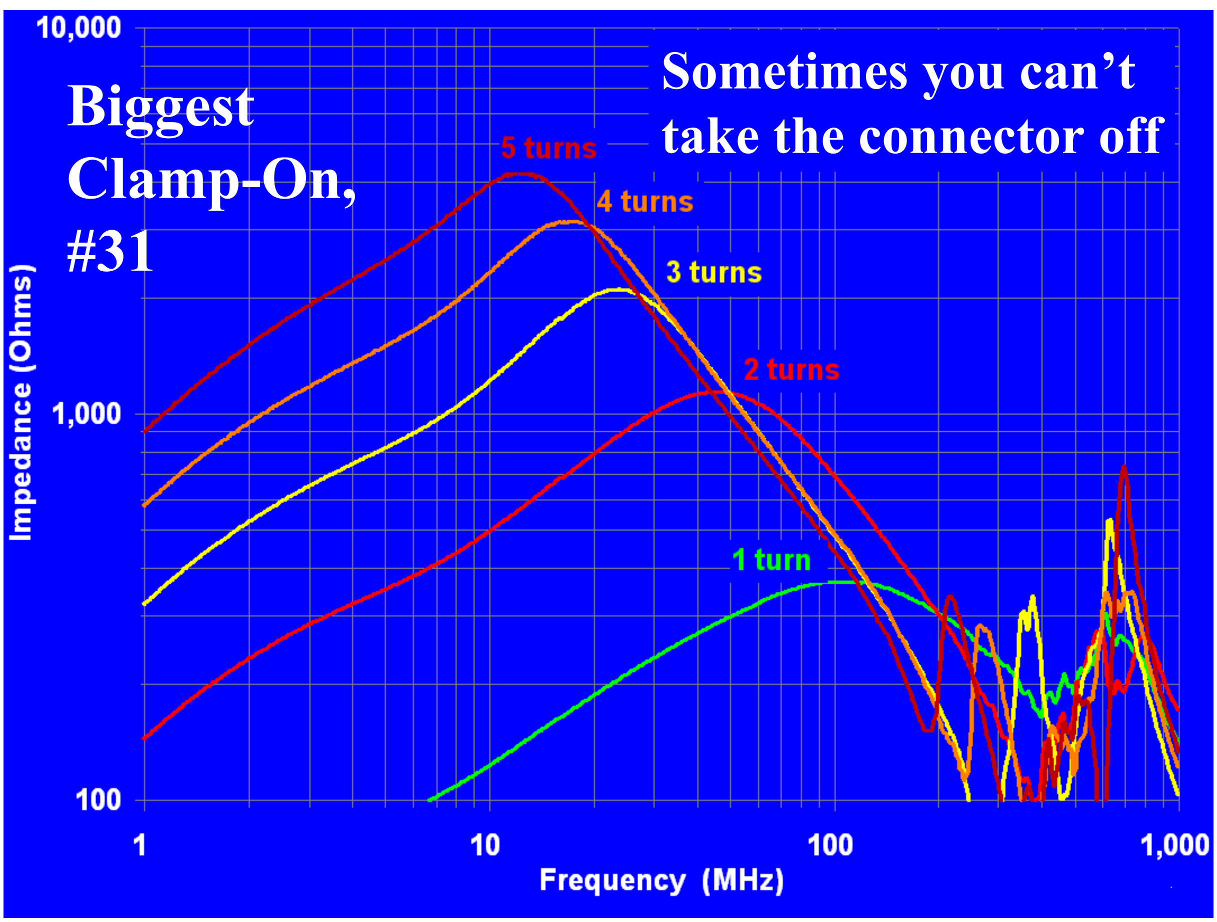

#61
Useful at VHF, but not below 30 MHz, because the Q is so high
14 turns
5 turns
3 turns
2 turns
1 turn
10,000
1,000
100
Series Resistance (Ohms)
1
10
100
1,000
Frequency (MHz)


#61
But it makes a great transformer or balun!
14 turns
5 turns
3 turns
2 turns
1 turn
10,000
1,000
100
Series Resistance (Ohms)
1
10
100
1,000
Frequency (MHz)

#61 is great for HF baluns and transformers

How About Big Cables?

If you can’t easily remove the connector



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
#43
#78
#61
#31


They're brittle!

Three Kinds of Ham RFI

- Interference from ham radio to other non-ham systems
- Interference to 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 ground the 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 <u>to</u> 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

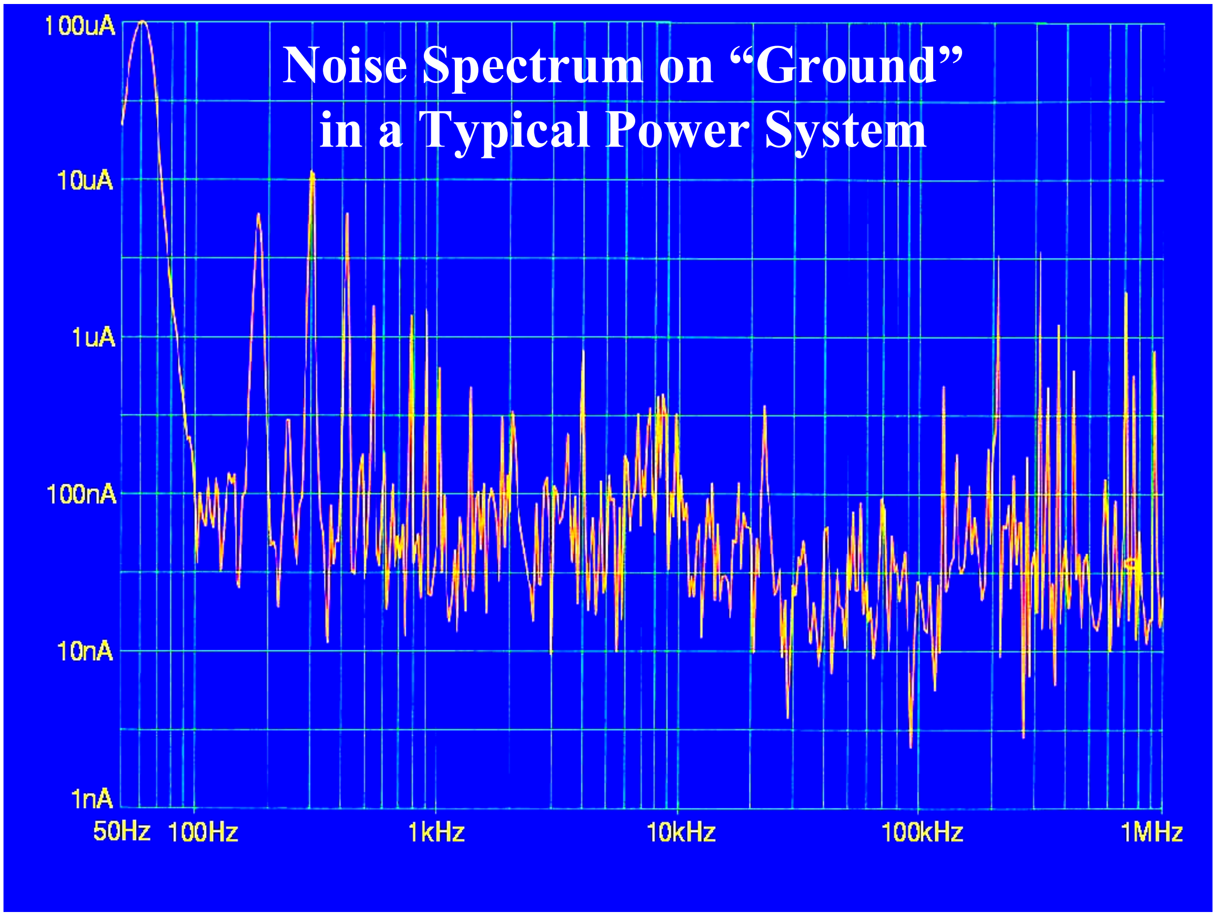
- Identify by killing power to router or hub
- Even when you fix your own, you may hear your neighbors (I did in Chicago)
- Methods of radiation
  – The ethernet cable is a (long wire) antenna
  – Direct radiation from the switch, hub, router, computer, and their power supplies
  – Power supply cables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

Ethernet Birdies

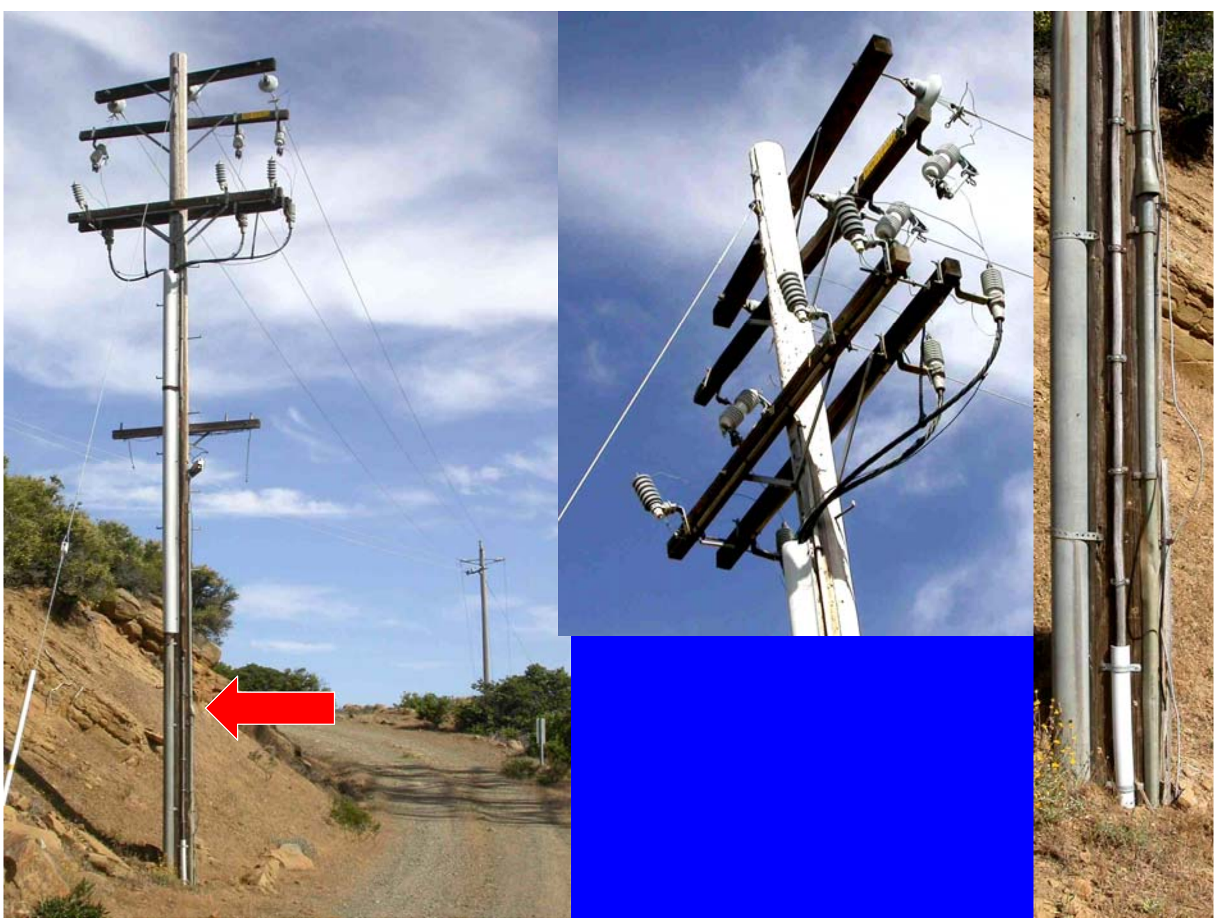
- Chokes will kill the common mode radiation (long wire) from the cable
- Use choke(s) on each cable (and each end of long cables) (Each end talks)
- Use multiple chokes if needed for wide frequency ranges, putting the highest frequency choke nearest to noise source
- Choke the power supply too!

Power Line Filters Can Do More Harm Than Good

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


Noise Spectrum on "Ground"
in a Typical Power System
100uA
10uA
1uA
100nA
10nA
1nA
50Hz
100Hz
1kHz
10kHz
100kHz
1MHz


W6BX



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

Acknowledgements

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

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- **E. C. Snelling and A. D. Giles, *Ferrites for Inductors and Transformers,* Research Study Press, 1983**
- **Henry Ott, *Noise Reduction Techniques in Electronic Systems,* Wiley Interscience, 1988**
- ***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

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- ***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 and Ferrites

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