Understanding and Eliminating RF Interference

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Basic Interference Mechanisms

- Audio cables are antennas
  - Pin 1 problems
  - Shield-current-induced noise (SCIN)
  - Inadequate filtering of equipment ins and outs
  - Audiofool "DC-to-daylight" design philosophy
- Shield current can excite all of these

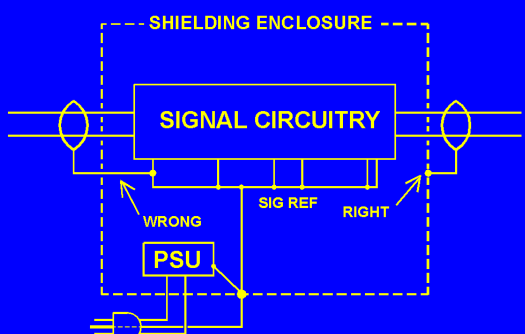
Sources of Shield Current

- Noise voltage on "ground" at ends of cable
  - Filter capacitors on the power line
  - Leakage capacitance in power transformers
  - Current flowing in ground unrelated to audio system (motors, lighting equipment, etc.)
  - Wiring errors
- Induced by magnetic fields
  - Double-bonded neutrals
  - Big transformers and motors
- Radio transmitters (antenna action)

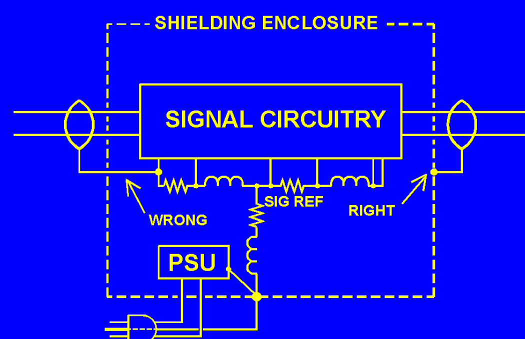
The Pin 1 Problem

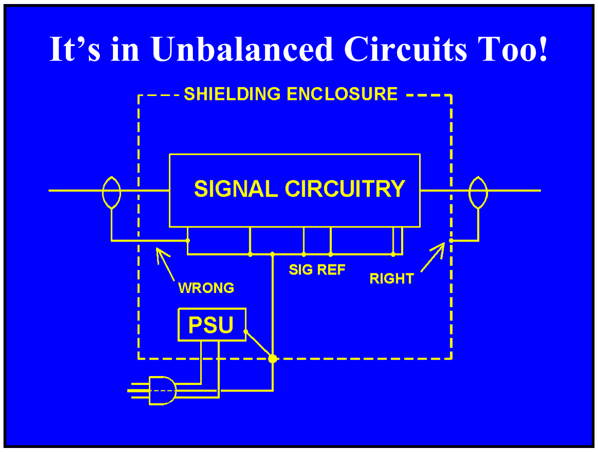
- Current flows on cable shields
  - Hum, buzz, RF
- If shield goes to shielding enclosure, current stays outside the box
- If shield goes to the circuit board, current goes <u>inside</u> the box!

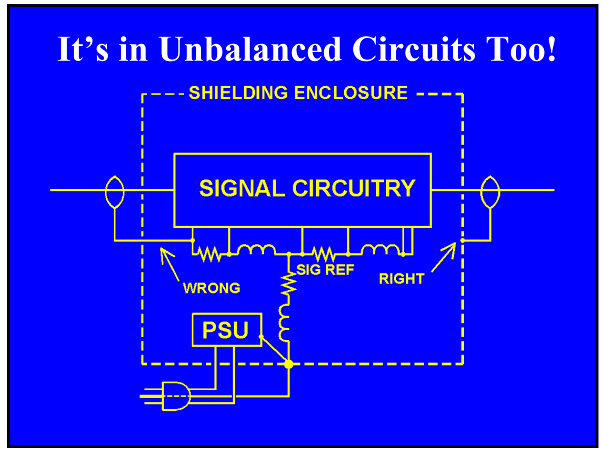
The Pin 1 Problem



The Pin 1 Problem

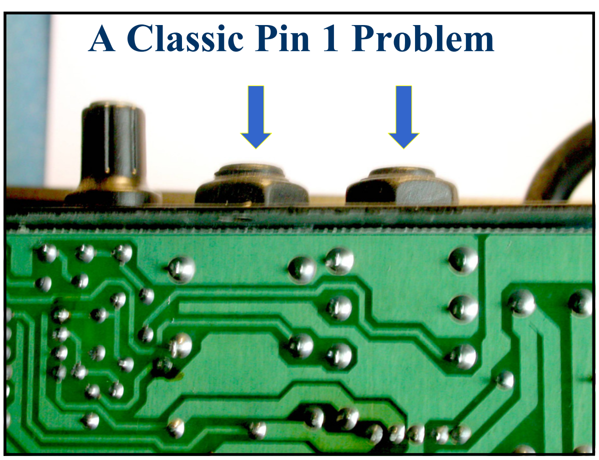


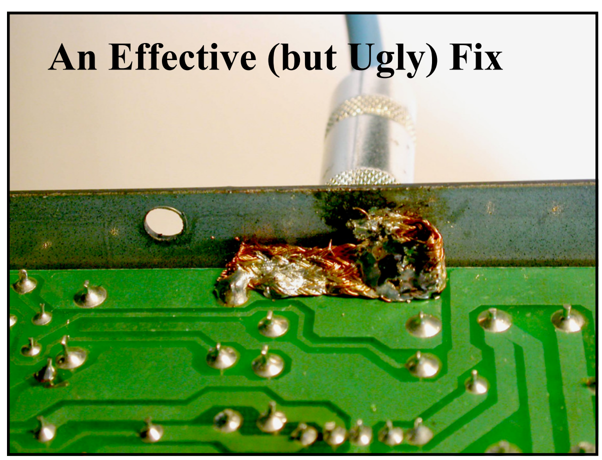

It's in Unbalanced Circuits Too!
SHIELDING ENCLOSURE
SIGNAL CIRCUITRY
WRONG
SIG REF
RIGHT
PSU


It's in Unbalanced Circuits Too!
SHIELDING ENCLOSURE
SIGNAL CIRCUITRY
WRONG
SIG REF
RIGHT
PSU


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


Some Classic Pin 1 Problems
24VAC/500mA
CH 2
OPERATING LEVEL
LIMITER
PHONES

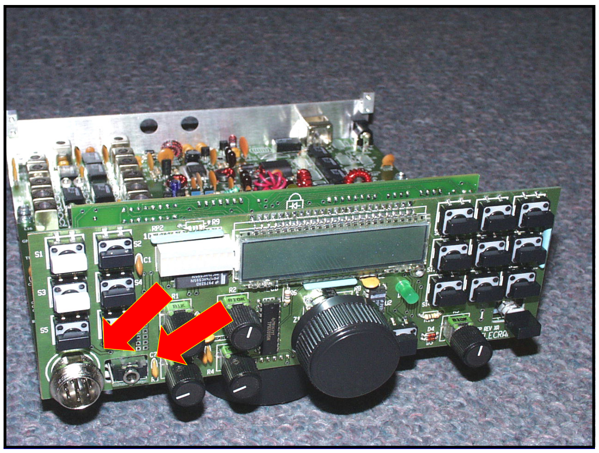

A Classic Pin 1 Problem

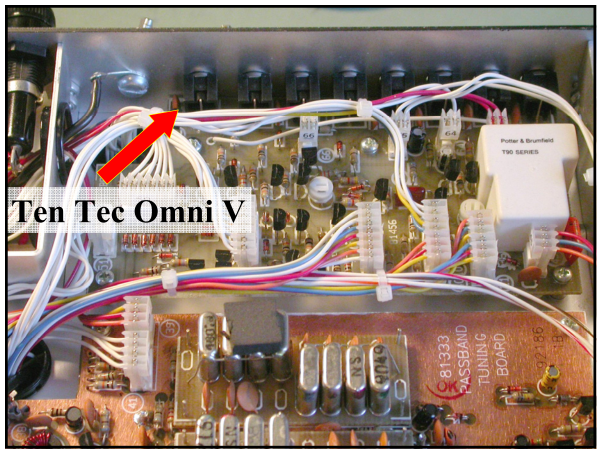

An Effective (but Ugly) Fix

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

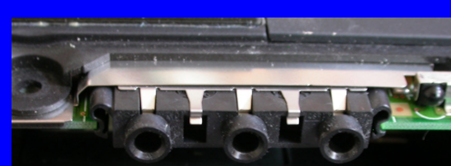




A Pin 1 Problem? Maybe

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!

Too Much Bandwidth

- Wiring often puts RF on equipment inputs (and outputs)
- Equipment must be able to reject it!
- Audio spectrum ends at 20 kHz
  - Filters produce phase shift
  - Phase shift in multiple stages adds up
  - Small rolloffs (0.5 dB) add up
  - So 100 kHz is a reasonable cutoff
  - Going beyond 200 kHz is CRAZY!

The AudioFool Viewpoint

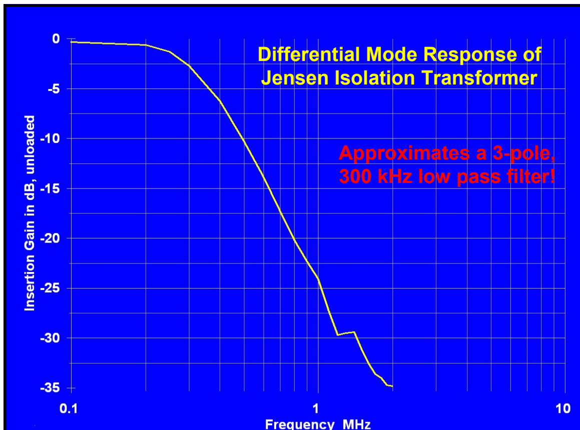
- *The Myth: "We can hear stuff above 20 kHz"*
- Reality: Some distortion mechanisms DO produce audible artifacts from ultrasonic signals, but we hear the <u>problems</u>, not the signals!
- Intermodulation distortion (40 kHz – 30 kHz = 10 kHz)
- Slew rate limiting within electronics of ultrasonic output of a mic (or of square waves from a test generator)

Golden Rules to Avoid RFI

- All wiring can act as an antenna
  - It can <u>receive</u> current if RF is present
  - It can <u>transmit</u> RF if RF current flows on it
- Radio signals cause current to flow
- Don't let that current cause problems

Golden Rules to Avoid RFI

- Fix pin 1 problems
- Fix equipment with excessive bandwidth
  - Add low-pass filters at inputs
  - Input transformers are inherently good low-pass filters (Jensen, Lundahl)
  - Faraday shield blocks common mode



Golden Rules to Avoid RFI

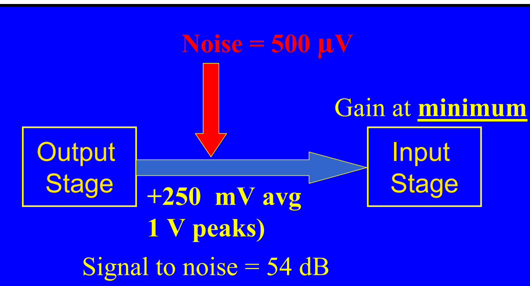
- **Loudspeaker Cables**
  - Always use TWISTED PAIR
  - Shielding is not important
  - Exotic cable is a waste of money
- **Mic and Line level Cables**
  - Avoid drain wires in shields
  - Use braid shielded cable
  - Use twisted pair (tighter twist helps too)

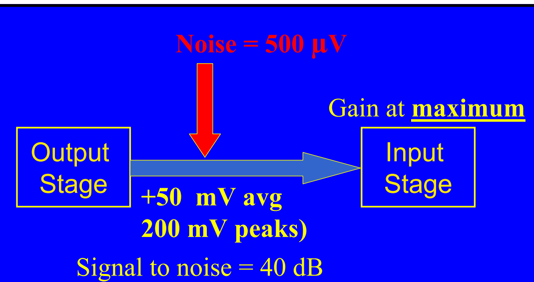
Golden Rules to Avoid RFI

- **Maximize audio levels on cables**
  - Run output stages near their maximum levels
  - Set input gains near their minimum levels

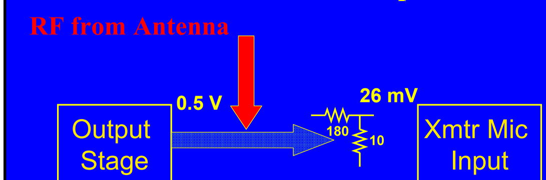
Critical Product Specifications

- **Maximize input level**
  - How much signal does it take to clip the input stage?
- **Maximum output level**
  - How much can the box put out cleanly?





Matching a Computer Output to a Transmitter Input



The pad attenuates the computer output to match the mic input.
It also attenuates any hum, buzz, or RF picked up on the input wiring.

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!

Golden Rules to Avoid RFI

- And when that isn't enough:

Ferrites can block the current!

An AM Broadcast Choke

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

This "Clamp-On" forms a choke that can kill interference from FM and TV

What's a Ferrite?

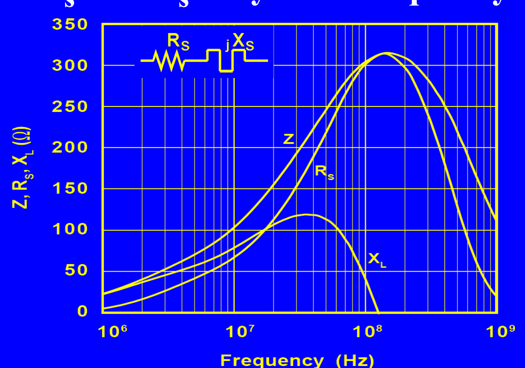
- A ceramic consisting of an iron oxide
  - manganese-zinc – MF, HF (AM broadcast, hams)
  - nickel-zinc – VHF, UHF (FM, TV, cell phones)
- Has permeability much greater than air
  - Better path for magnetic flux than air
  - Multiplies inductance of a wire passed through it
- Is increasingly lossy at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

Permeability

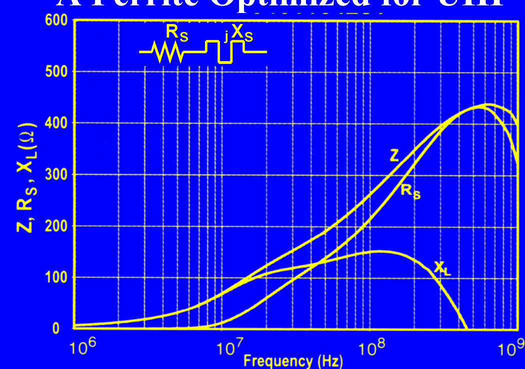
- Symbol is μ
  - μ_0 is permeability of free space (air, aluminum)
  - μ_r on data sheets is usually the <u>relative</u> permeability, referenced to free space
  - Subscript r usually omitted μ
- Typical μ values
  - Steel 1,000
  - Stainless steel 500
  - Mu-metal 20,000
  - Ferrites 100 – 3,000

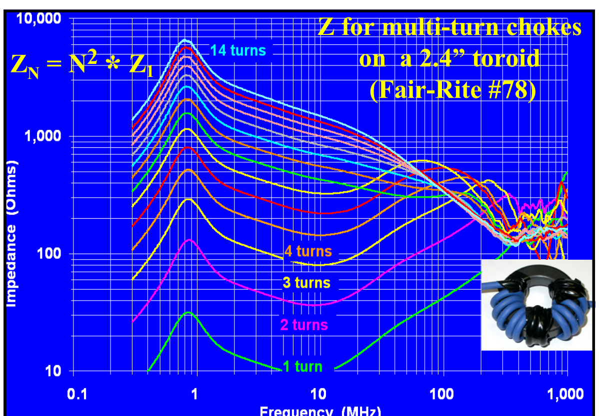
A (too) simple equivalent circuit of a wire passing through a ferrite

R_s and X_s vary with frequency!

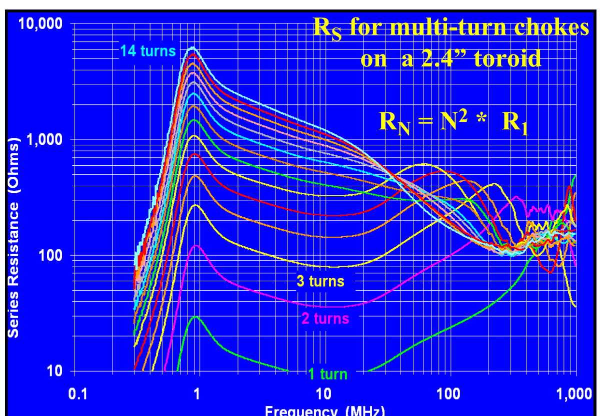


A Ferrite Optimized for UHF

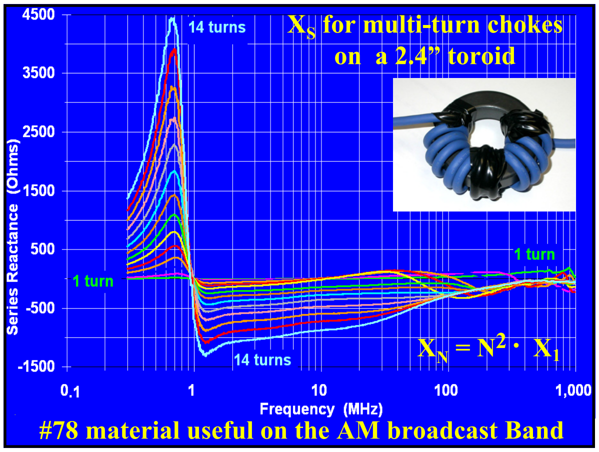


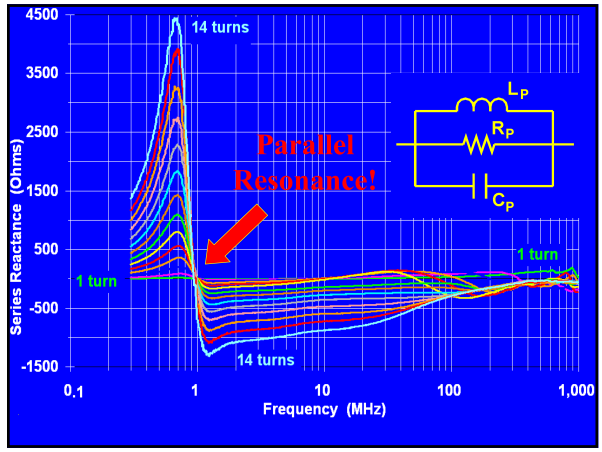


A material useful on the AM broadcast Band



#78 material useful on the AM broadcast Band



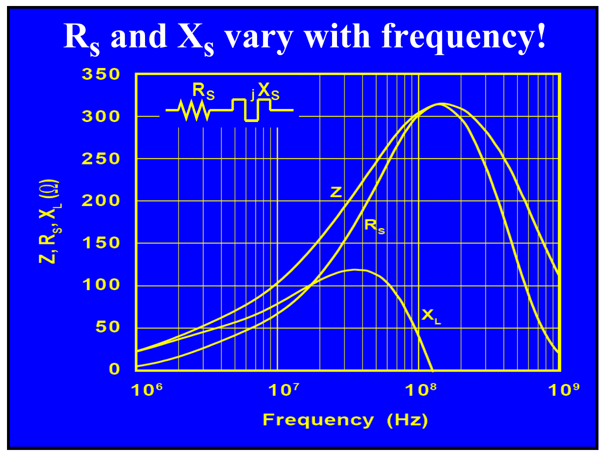


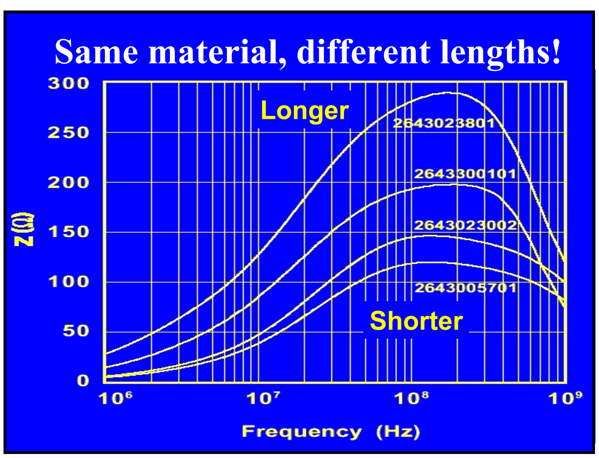
What Causes this Resonance?

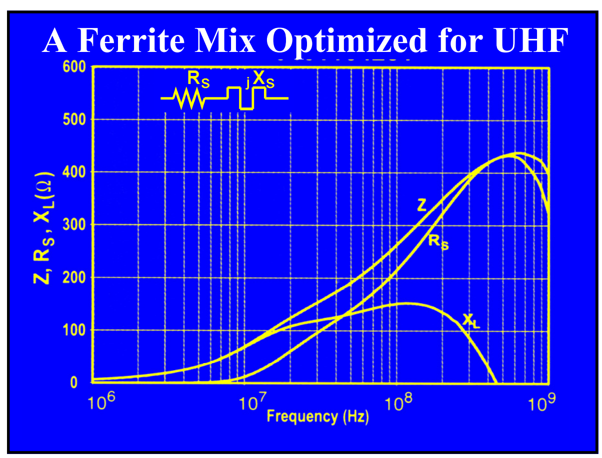
The ferrite material (the *mix*), and

The physical dimensions of the ferrite core.

- There is a finite velocity of propagation within the ferrite
- There are standing waves within the core 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







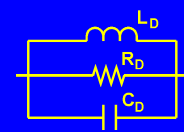
Audio Cable is Lossy at RF

- RF is detected within equipment.
- RF that gets in at a distance will be attenuated by the cable.
- It's RF that gets onto the cable close to the equipment that matters most.
- So put the ferrite choke very close to the equipment that is detecting the RF

Let's Test Our Equivalent Circuit

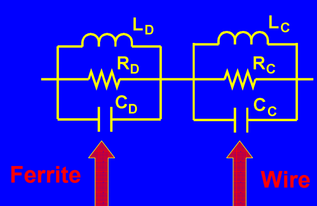
It looks OK for the #78 material at low frequencies, but look at high frequencies – there is another resonance up there!

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.

General Equivalent Circuit

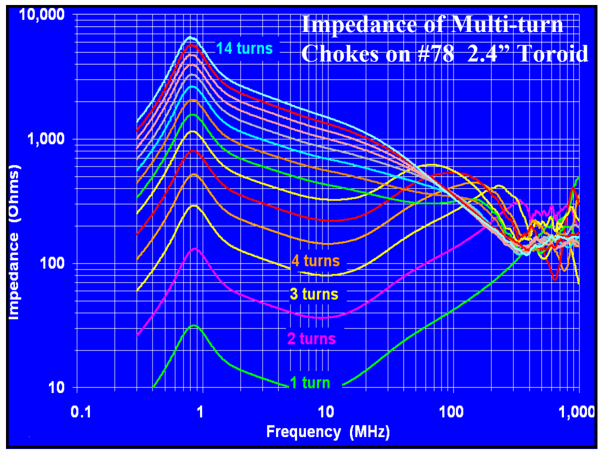


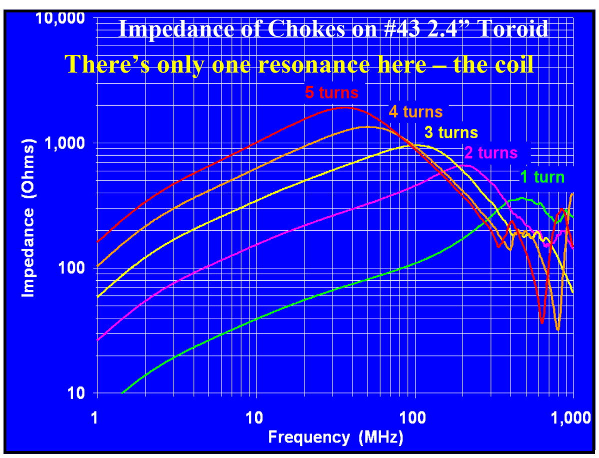
L_C is the inductance of the coil

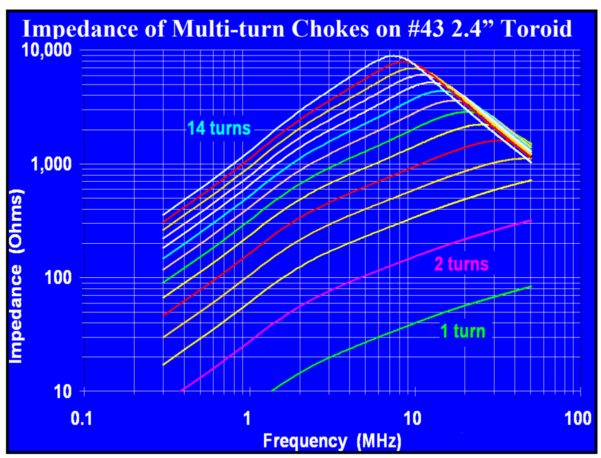
C_C is the stray capacitance of the coil

R_C is the resistance of the wire.

L_C and C_C is the resonance that moves!



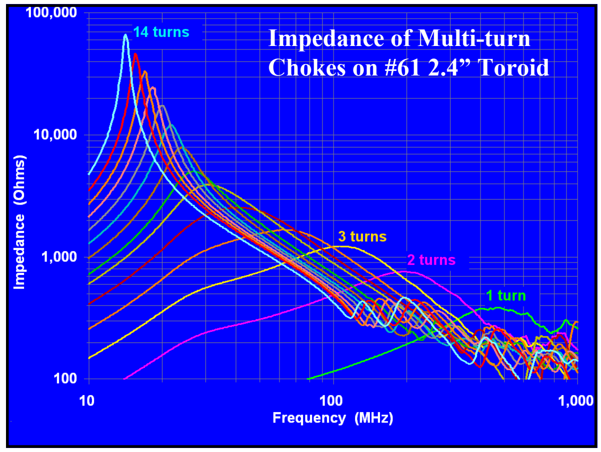




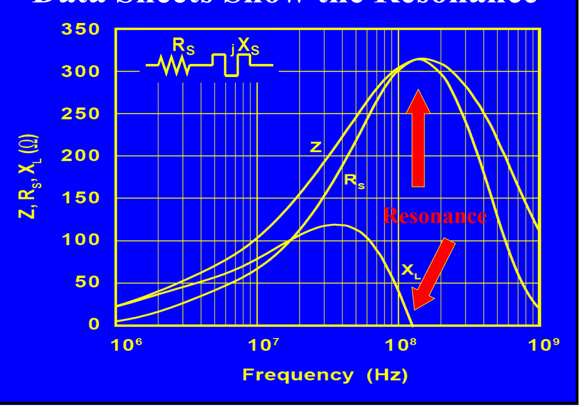
Why no Dimensional Resonance?

The #78 is MnZn, while this one is NiZn

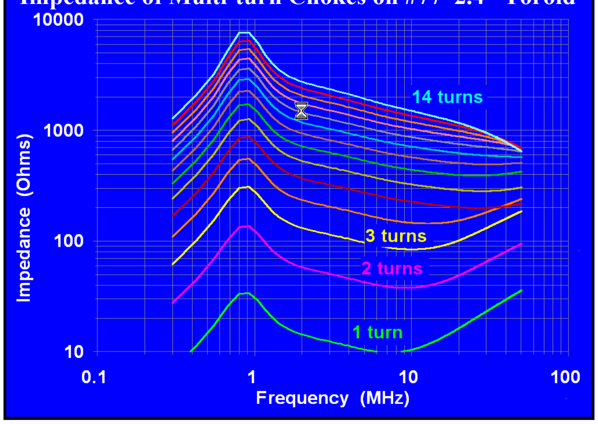
- V_P in #43 is much higher, so dimensional resonance would occur at VHF rather than MF
- At VHF, there is so much loss that it damps the standing waves that would produce dimensional resonance



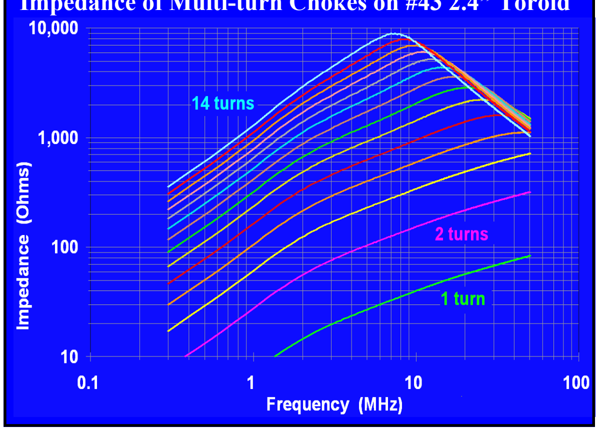
Data Sheets Show the Resonance



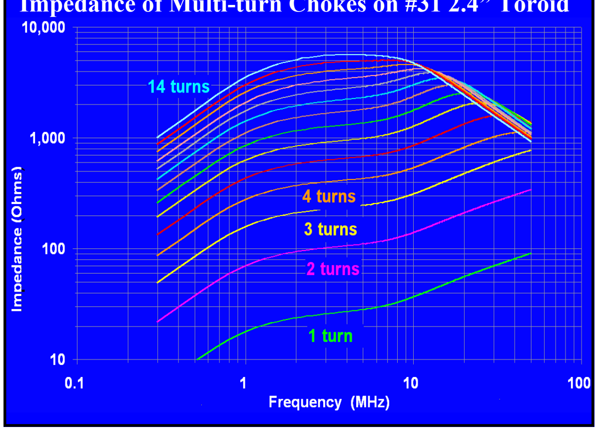
Impedance of Multi-turn Chokes on #77 2.4” Toroid

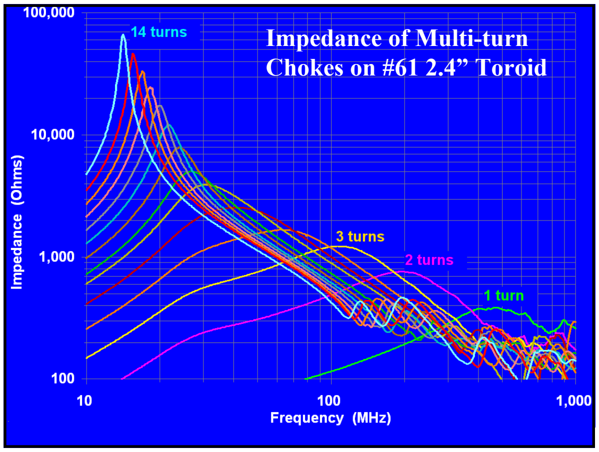


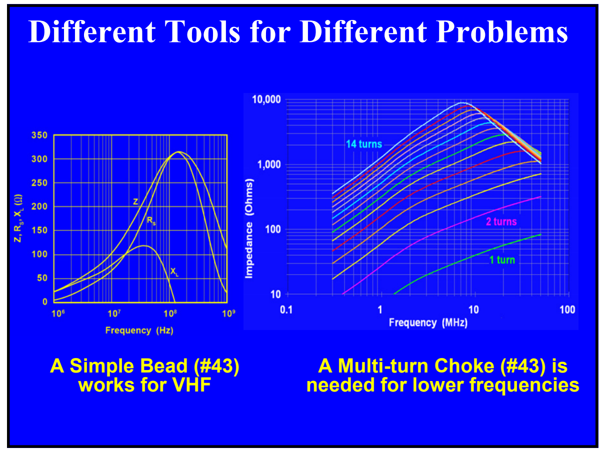
Impedance of Multi-turn Chokes on #43 2.4” Toroid



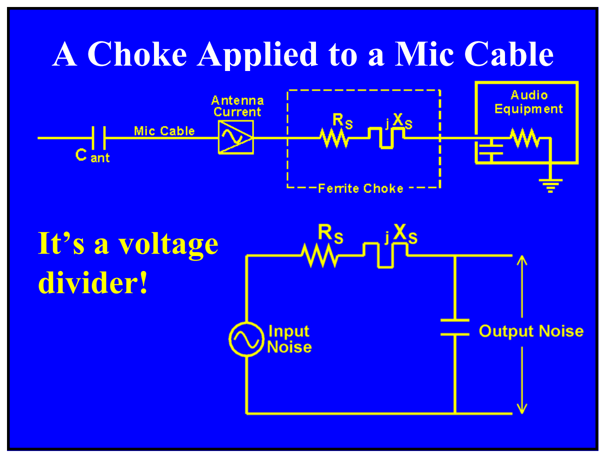
Impedance of Multi-turn Chokes on #31 2.4” Toroid

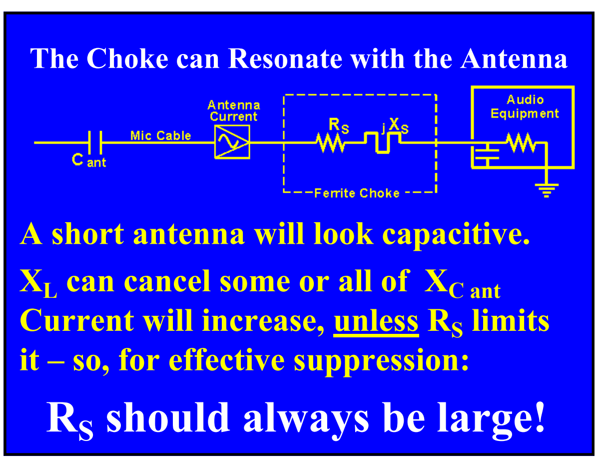


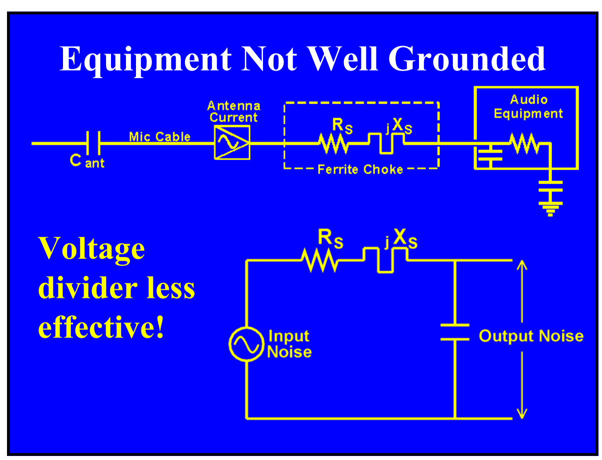

Impedance of Multi-turn
Chokes on #61 2.4" Toroid
14 turns
3 turns
2 turns
1 turn
Impedance (Ohms)
100,000
10,000
1,000
100
10
100
1,000
Frequency (MHz)


Different Tools for Different Problems
A Simple Bead (#43) works for VHF
A Multi-turn Choke (#43) is needed for lower frequencies
14 turns
2 turns
1 turn
Impedance (Ohms)
Frequency (MHz)
Frequency (Hz)


So How do We Use These Tools?


A Choke Applied to a Mic Cable
C ant
Mic Cable
Antenna Current
R_S
jX_S
Ferrite Choke
Audio Equipment
It's a voltage divider!
Input Noise
Output Noise


The Choke can Resonate with the Antenna
C ant
Mic Cable
Antenna Current
R_S
jX_S
Ferrite Choke
Audio Equipment
A short antenna will look 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!

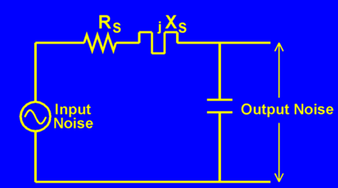

Equipment Not Well Grounded
C ant
Mic Cable
Antenna Current
R_S
jX_S
Ferrite Choke
Audio Equipment
Voltage divider less effective!
Input Noise
Output Noise

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)
  - At least 700 ohms needed, more is better
- 700 – 1,000 ohms R_S should be a "minimum" design goal

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 smaller ferrite part if we provide the capacitor



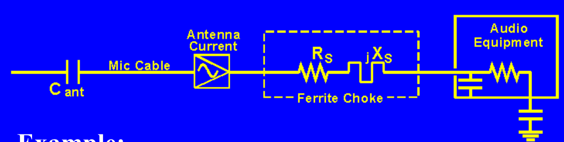
You May Not Need an Elephant Gun

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

Threshold Effect

- For "brute force" suppression, the ferrite choke should <u>add</u> enough series R that the <u>resulting</u> 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.

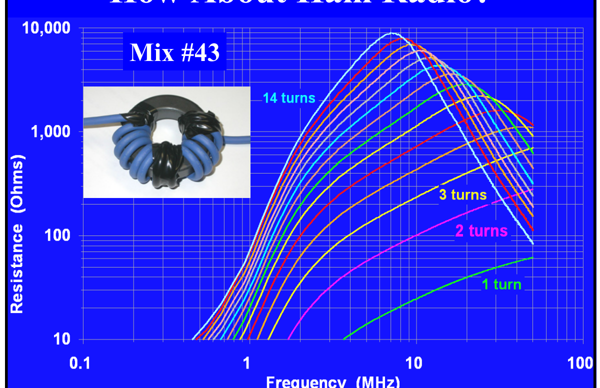
Threshold Effect



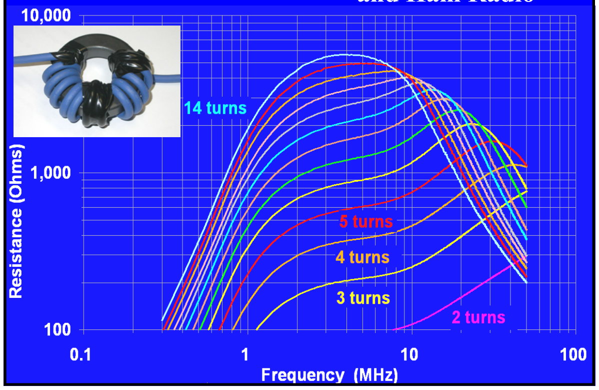
Example:

Without the choke, the total antenna circuit is $300\angle{-60°}$, and we add a choke that is $300\angle{60°}$, bringing the series Z to $300\angle{0°}$. The current doesn't change. Additional R_S will begin to reduce the current, but R_S must increase to 600Ω to reduce detected RF by 12 dB (assuming no change in X_S).

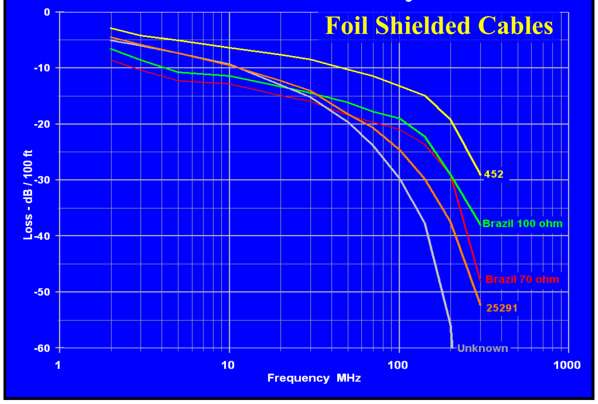
How About Ham Radio?



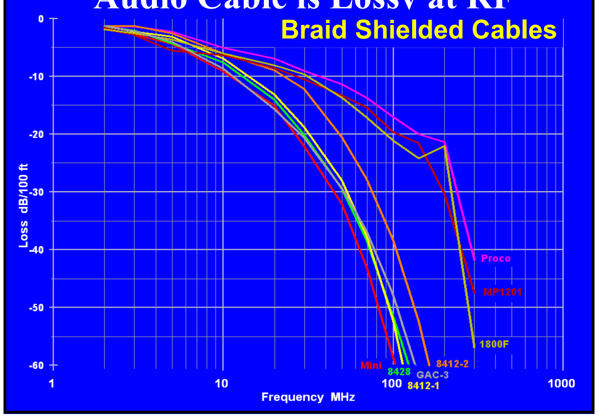
A Useful New Mix for AM Broadcast and Ham Radio



Audio Cable is Lossy at RF



Audio Cable is Lossy at RF



Audio Cable is Lossy at RF

- RF is detected within equipment
- RF that gets in at a distance will be attenuated by the cable
- It's RF that gets onto the cable close to the equipment that matters most
- So put the ferrite choke very close to the equipment that is detecting the RF

Cell Phones

- Use several #61 beads
  - Select for >350 Ω at 800 MHz
  - Use at least three beads
  - Put beads very close to equipment receiving interference

Guidelines for Suppression

- Put choke within λ/20 of equipment
  - Cable between choke and equipment will act as antenna
- If interconnect wiring > λ/10, suppression may be needed at both ends
- When chokes in series to cover multiple frequency ranges, highest frequency choke should be nearest to equipment

Choosing a Ferrite Part

- Below resonance, Z will be approximately proportional to:
  - Length of part that surrounds the wire
  - *ln (D/d)* where *D* is the outer diameter and *d* is the inner diameter
  - N^2
  - μ (varies with frequency)

Choosing a Ferrite Part

- Thus, to maximize suppression use a part that:
  - is longer
  - fits the wire most snugly
  - is thicker
  - is of a material has greater series R

Resonance and Suppression

- Ferrite chokes for suppression generally:
  - provide the greatest suppression at resonance
  - are effective for <1 octave above resonance
  - are effective for 1-3 octaves below resonance

Ferrites and Loss

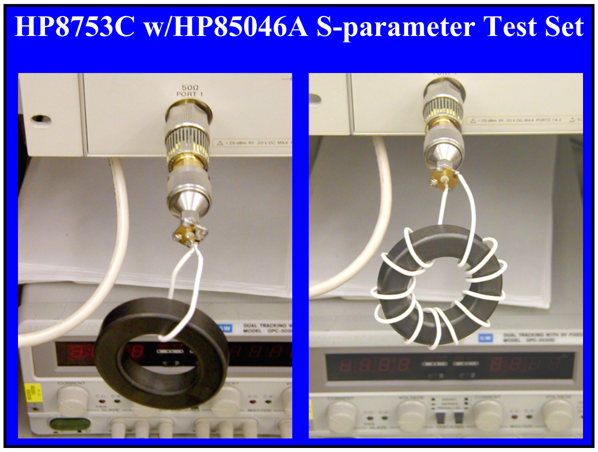
- Ferrites for suppression should be very "lossy" within the spectrum they need to suppress
- Ferrites for transformers and inductors should have as little loss as possible within the spectrum where they are operating

Other Ferrite Characteristics

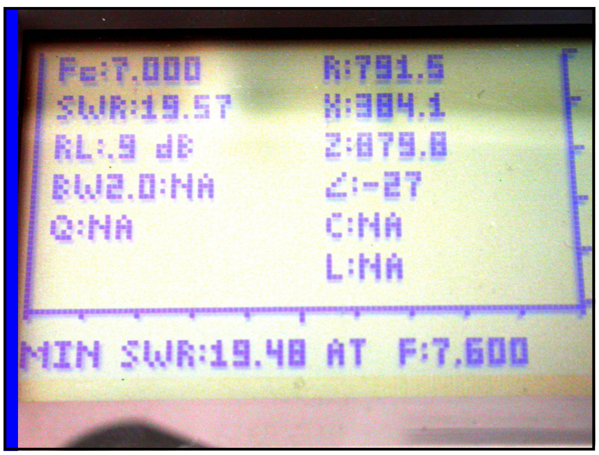
- The resistivity varies over 5 orders of magnitude from one mix to another
  - Some are good insulators
  - Some are rather conductive
- Ferrites saturate at high signal levels, reducing μ
- μ decreases with increasing temperature

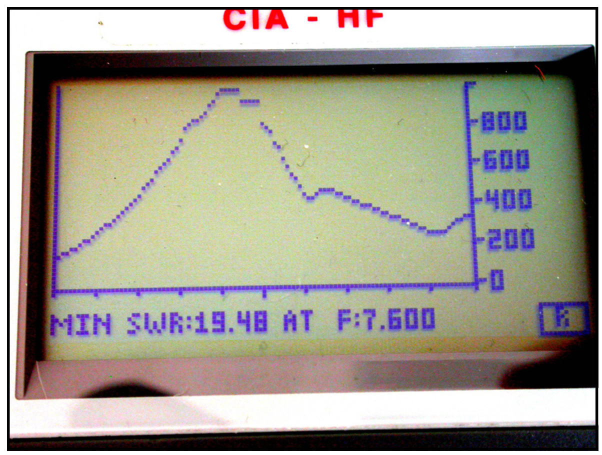
Measuring Ferrite Chokes

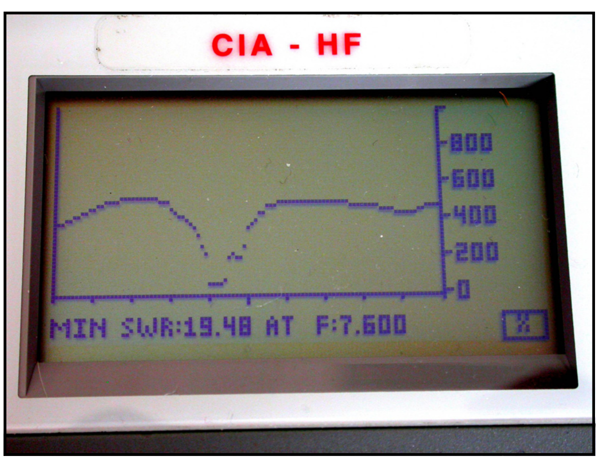
- Antenna Analyzer ($500 - $2,000)
  - AEA CIA-series
- Lab Test Equipment ($10K - $30K)
  - Network Analyzer
  - Impedance Bridge or Analyzer
- RF generator, series resistor, and voltmeter (or scope, or spectrum analyzer)

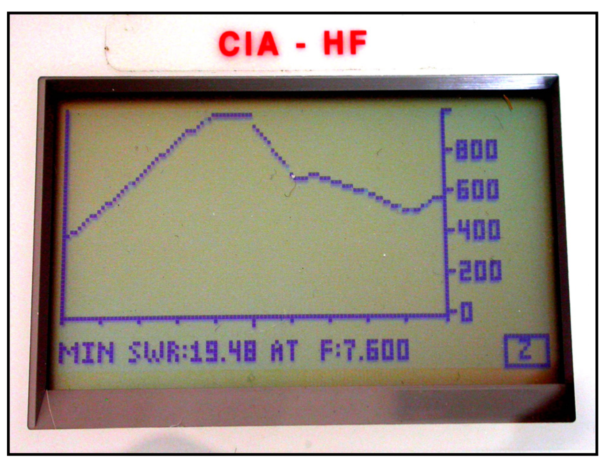

HP8753C w/HP85046A S-parameter Test Set


AEA CIA-HF


Fc:7.000
R:791.5
SWR:19.57
X:384.1
RL:.9 dB
Z:879.8
BW2.0:NA
∠:-27
Q:NA
C:NA
L:NA
MIN SWR:19.48 AT F:7.600


CIA - HF
800
600
400
200
0
MIN SWR:19.48 AT F:7.600
R

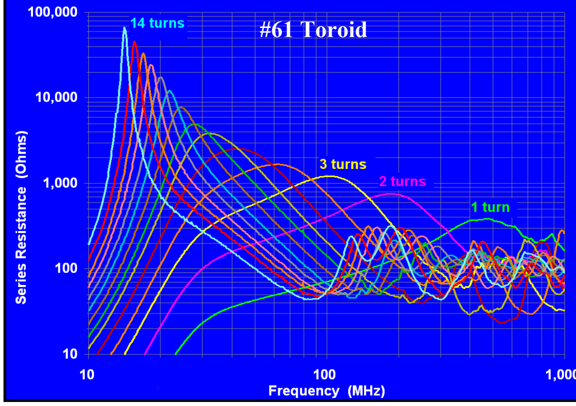

CIA - HF
800
600
400
200
0
MIN SWR:19.48 AT F:7.600
X


CIA - HF
800
600
400
200
0
MIN SWR:19.48 AT F:7.600
Z

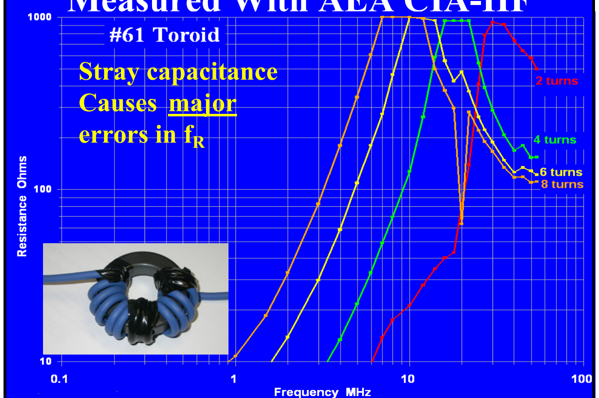
Limitations of CIA and MFJ

- Input capacitance 15 pF detunes the choke
  - Moves resonance down (sometimes a lot!)
- Input resistance of 1.5K ohms limits accuracy at high impedance
- Accuracy degrades for Z_X >> 50 ohms
- Don't trust Z at frequencies > 10 MHz

Measured With Lab-Quality Gear



Measured With AEA CIA-HF



Three Kinds of Ham RFI

- Interference from ham radio to other gear
- 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

The Principle of Reciprocity

- If the mechanism is passive, what helps minimize received interference will generally also help reduce transmitted noise
  - Anything Digital
  - Anything with a microprocessor
  - Anything with a clock (or oscillator)
  - Computers
  - Appliances
  - Home Entertainment
  - Power supplies

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

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

RFI to Doorbells, DC Alarm Circuits

- Simple low-pass filters
  - Series choke, parallel capacitor
  - Series resistor, parallel capacitor
  - K-com filters

RFI to Ground Fault Interrupters (GFCI)

- Detects imbalance between hot (phase) and neutral, interrupts if > 5 mA
- There's active electronics inside
  - Can false trigger on RF (mostly HF)
  - Add 0.1 µF 1 kV capacitor between phase and conduit

Identifying RFI to the Ham Bands

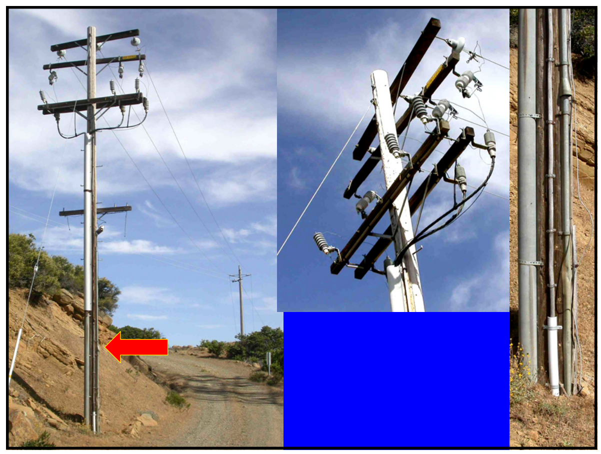
- Check your own house first!
  - Kill power to your house and listen with battery power
- With power restored, listen with a talkie that covers HF
- RF noise from power lines is mostly arcing at insulators, almost never from transformers
- Use a directional antenna to listen at VHF, even when problem is at HF
- At HF, listen to the "grounding" downleads

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

Some 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

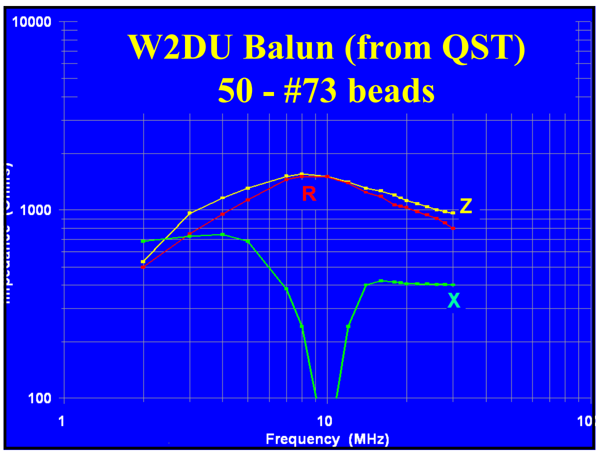
- Identify by killing power to router or hub
- Even when you fix your own, you may hear your neighbors (I do)
- Methods of radiation
  - The ethernet cable is a (long wire) antenna
  - Direct radiation from the switch, hub, router, computer, and their power supplies
  - Power supply cables are antennas

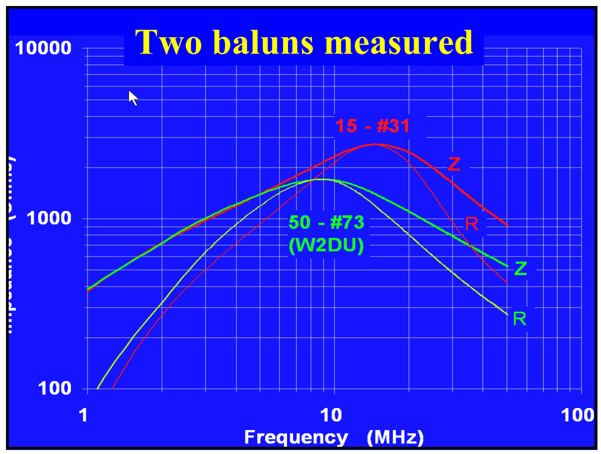
Ethernet Birdies

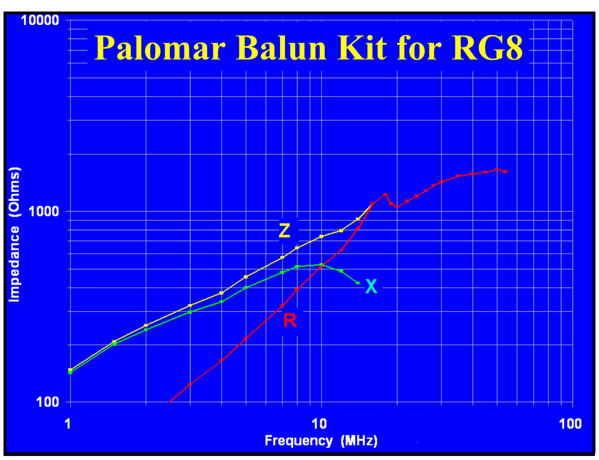
- Chokes will kill the common mode radiation (long wire) from the cable
- Use choke(s) on each cable (and each end of long cables) (Each end talks)
- Use multiple chokes if needed for wide frequency ranges, putting highest frequency choke nearest to noise source
- Choke the power supply too!

A Look at Baluns

- A W2DU balun (called a "current" or "choke" balun) is simply a lot of beads strung onto the end of the coax
- All baluns are not created equal!
- It is possible to overheat and short out a W2DU balun with too much current
  - That resistance is real, and the power it dissipates can "cook" the coax!
  - I've done it with 100 watts!







Acknowledgements

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- Neil Muncy (ex-W3WJE)
- Steve Kusiceil
- Fair-Rite Products

References

- ***Fair-Rite Products Catalog*** This 200-page catalog is a wealth of product data and applications guidance on practical ferrites. This company is a class act. http://www.fair-rite.com The vast majority of ferrite parts available at retail in the US are made by Fair-Rite.
- ***Ferroxcube Catalog and Applications Notes*** More online from another great manufacturer of ferrites. http://www.ferroxcube.com
- E. C. Snelling, ***Soft Ferrites, Properties and Applications,*** CRC Press, 1969 The bible on ferrites, but heavy math and physics.
- Henry Ott, ***Noise Reduction Techniques in Electronic Systems,*** Wiley Interscience, 1988 **The best book there is on EMC.**
- ***ARRL RFI Book***
- Marv Loftness**, *AC Power Interference Handbook* (ARRL)**
- Applications notes on my website – http://audiosystemsgroup.com

Understanding and Eliminating RF Interference

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