Jensen AN-004
HUM & BUZZ IN UNBALANCED INTERCONNECT SYSTEMS
by Bill Whitlock

ORIGINS OF HUM
Often sound systems exhibit strange and perplexing behavior such as hum that appears and disappears when power to other equipment, not even part of the audio system, is switched on or off! Traditional methods to eliminate hum often seem more like voo-doo than engineering and, more often than not, are trial and error exercises that end only when someone says "I can live with that". This author has previously written about *balanced* lines in audio systems, so this paper will be strictly confined to unbalanced systems.[2]

In contrast to a balanced system, an unbalanced system uses only two wires, one for signal and one for ground. Its use still prevails in consumer audio, probably because it is cheap to make and it performs acceptably well in very small systems such as typical home stereo setups. However, any unbalanced scheme has an inherent problem called ***common impedance coupling***. From Ohm's law we know that when current flows in a resistance, a voltage drop appears across that resistance. With the exception of superconductors, any conductor (wire) has resistance. If two different circuits share the same conductor or wire, a current flowing in either circuit will produce a voltage drop across the wire. As shown in Figure 1, a partial schematic of the simplest possible system, ***the shield conductor of the interconnecting cable becomes the offending common impedance***.

Since the cable shield is effectively connecting the grounds of the devices together, it carries a current derived from the power line as well as the audio signal current. Although this fact is often overlooked or ignored, it is fundamental to this discussion. Whatever voltage is present between its inputs, points A and C in Figure 1, will be amplified by Device B. It cannot tell the difference between signal and hum, and will amplify both if they are present. To determine what the input "sees", we must trace the circuit loop from point A to B to C. Since the voltage A to B (shield voltage drop) is in series with the voltage B to C (the signal), the voltages will directly add. Clearly, it would be very desirable for the shield voltage drop to be zero to avoid contaminating the signal. In the real world, regardless of shield construction, material or gauge, *we cannot make the shield conductor resistance zero*. Our only remaining choice is to somehow reduce the interchassis current, ***I*** in Figure 1, to an acceptable level.

INTERCHASSIS CURRENT: THEORY
This current is caused by the charge and discharge of capacitances between power line and chassis. An undesired but unavoidable primary to secondary capacitance exists in the power transformer of every piece of AC operated equipment. Sometimes intentional capacitors and resistors are added from power line to chassis to suppress RFI and/or meet safety regulations. To predict the severity of the hum problem these capacitances create, we can analyze the circuit using the steps of simplification shown in Figure 2.

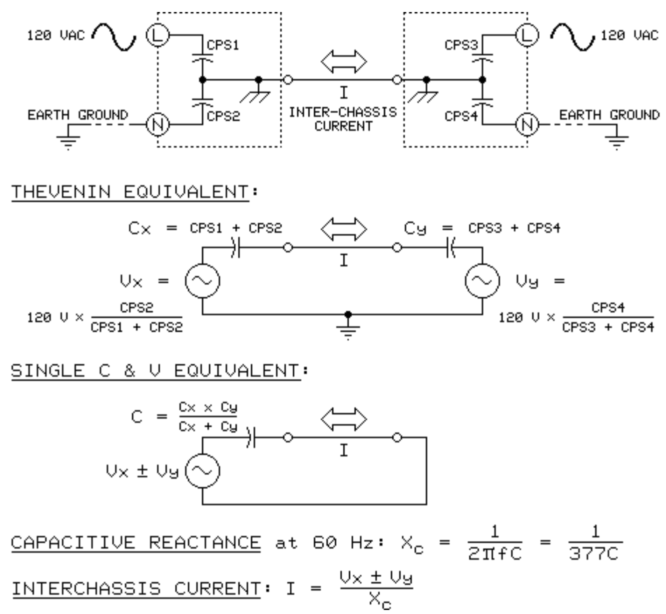

Figure 2 - ANALYZING THE EQUIVALENT CIRCUIT

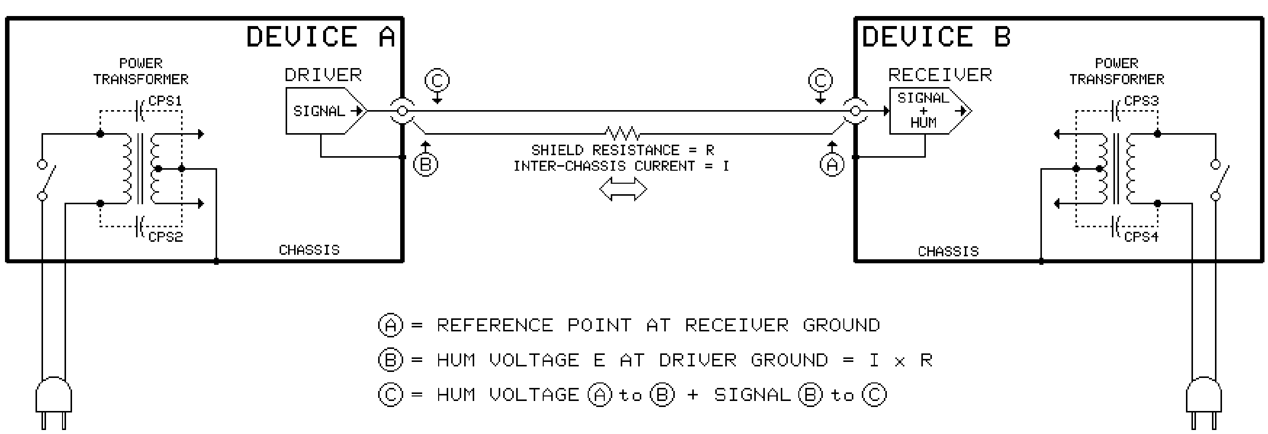

Figure 1 - THE HUM GENERATING MECHANISM
The basic problem is that the shield is a common path for both inter-chassis "ground" and signal currents.

Note the $V_x \pm V_y$ term in the single capacitor equivalent circuit. The ± accounts for the fact that most consumer equipment has a two-prong AC plug which can be inserted into an outlet either of two ways. A special example illustrates how extreme the effects of plug reversal can be. Consider the case where C_{PS1} is ½ the value of C_{PS2} and C_{PS3} is ½ the value of C_{PS4} ***(this condition would be highly unlikely in the real world).*** If the two plugs are connected to the AC line as shown in the diagram, each pair of capacitors forms a voltage divider with a 3:1 division ratio, making chassis voltages Vx and Vy each 40 volts AC with respect to ground. Since no current will flow in a wire connecting two points of equal voltage, current ***I*** will be zero. However, if one of the AC plugs is reversed, the chassis voltages will no longer be equal and current ***I*** will flow. Except for this special case, plug reversals simply cause a change in the interchassis current, rather than the total cancellation seen in this example. For this reason, reversing AC plugs will almost always change the hum level in a system..

It is also very unlikely that the two capacitances, C_{PS1} and C_{PS2} or C_{PS3} and C_{PS4}, would be exactly matched in any piece of equipment. Mismatch ratios of two to one are common. Since all utility 120 VAC power in this country is distributed *asymmetrically* with respect to earth ground, one side called "neutral", is grounded. The other, called "hot" or "line", is at 120 volts with respect to ground.[4] Recently, proponents of a scheme called "Balanced AC Power" have claimed that "[hum reduction] results are often quite dramatic".[3] Balanced power uses a center-tapped transformer to make each side of the line 60 volts with respect to ground. Although intuitively attractive, this approach can completely cancel interchassis currents in a system of three or more devices only in the case where each of the devices had such matched capacitances. This would be an extremely rare occurrence. Although 10 to 15 dB hum reductions, which would be more routinely achieved, might be considered "dramatic" in a video system, this author cannot recommend this or any other "line conditioning" method as a cost effective solution for audio system hum problems.

INTERCHASSIS CURRENT: MEASUREMENT

When designing or troubleshooting a system, a highly recommended first step is to measure actual ground currents of the system devices. This can be done quite simply using an AC voltmeter adapted, as shown in Figure 3, to measure AC current. This same setup can also measure chassis current between devices.

The 1 kΩ resistor converts current to voltage at 1 millivolt per microamp while the capacitor limits the measurement to frequencies under about 1 kHz. One lead of this current meter is connected to the shield of an input or output jack on the device under test. An IHF/RCA plug is handy for this and it generally won't matter which jack you choose, since all shield grounds are usually tied together inside the device. The other lead of the current meter is connected to a ground equivalent to power line neutral. The safety ground of any modern outlet is convenient for this. It is required by safety codes to be tied to earth ground, as is the neutral. The current measurement should be taken under four conditions: device "off", device "on", then repeated with the device's AC plug reversed. Taking the highest reading will give us a "worst case" number which can then be used, along with Table 1, to estimate the system hum levels produced when this device is connected to others via cables.

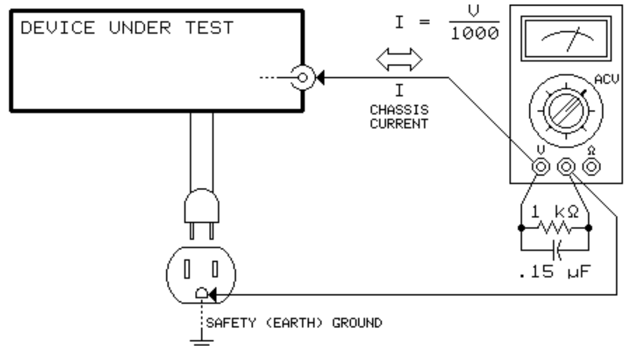

Figure 3 - MEASURING THE CHASSIS CURRENT

The author has tested a variety of consumer devices, including CD players, cassette decks, tuners, receivers, and power amplifiers, for chassis current to ground. The broad categories of typical ground currents developed from the testing were used in Table 1. Ground current is generally related to AC power consumption of the device, since this dictates the size of its power transformer and, to some extent, its interwinding capacitances. Ground current **L**, 5 μA RMS, is typical of "low power" consumer gear drawing under 20 watts. This includes most CD players, cassette decks, and turntables. Current **M**, 100 μA RMS, is typical of "medium power" consumer gear drawing 20 to 100 watts. This includes most tuners, low to medium power receivers or power amplifiers, and some small TV receivers. Current **H**, 1 mA RMS, is typical of "high power" consumer gear drawing, or capable of drawing, well over 100 watts. This includes most high powered amplifiers or powered subwoofers and large screen or projection TV receivers. Table 1 shows the calculated effect of these currents when they flow in interconnect cable shields in an unbalanced audio system. A contact resistance of 50 mΩ per connection was used and the 0 dB reference level is 300 mV RMS or about −10 dBV. All results have been rounded to the nearest dB.

Please note that this characterization of chassis ***current*** *applies only to devices with two-prong AC plugs*. Three-prong plugs effectively connect the device chassis to safety ground, making the chassis a *voltage* source. System effects of this will be discussed later.

Cable Length	3 ft ≈ 1 m			10 ft ≈ 3 m			20 ft ≈ 6 m			50 ft ≈ 15 m			100 ft ≈ 30 m		
Ground Current	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
#26 GA (41 mΩ per ft) Shield Conductor	−109	−83	−63	−101	−75	−55	−96	−70	−50	−89	−63	−43	−83	−57	−37
#24 GA (25 mΩ per ft) Shield Conductor	−111	−85	−65	−105	−79	−59	−100	−74	−54	−93	−67	−47	−87	−61	−41
#22 GA (16 mΩ per ft) Shield Conductor	−112	−86	−66	−107	−81	−61	−103	−77	−57	−96	−70	−50	−91	−65	−45

Table 1 - CALCULATED HUM LEVEL, dB re 300 mV, vs GROUND CURRENT, CABLE LENGTH, and SHIELD GAUGE

AUDIBILITY OF HUM & BUZZ

Just what level of hum or buzz is audible depends on many factors. A recent AES paper indicates that noise artifacts should be under −120 dB to be inaudible for serious listening in residential environments.[5] The experience of this author indicates that levels higher than about −80 dB are annoying to most listeners. The noises originating with the power line are generally described as either "hum", which is predominantly 60 Hz, or "buzz", which consists of a mixture of high-order harmonics of 60 Hz. These harmonics are the result of power line waveform distortion, which commonly reaches 5% THD and is caused by many types of non-linear power line loads. Because the human ear is much more sensitive to frequencies in the 2 kHz to 5 kHz range at these very low levels, buzz is usually more audible than hum, even though the hum level may be electrically larger.

BREAKING THE INTERCHASSIS CURRENT PATH

To eliminate hum, we must effectively eliminate interchassis ground current. We could eliminate it by simply breaking the chassis to chassis shield connection. Of course, this alone would not solve our problem. We must break the signal line as well and insert a device which will sense the voltage at the output of device A and regenerate it into the input of device B, while ignoring the voltage that exists between the now disconnected device grounds. These properties generally describe a differential responding device with high common-mode rejection, usually called a ***ground isolator***. *See reference* [2] *for more information on this subject.*

Two basic types of differential responding devices, active differential amplifiers and audio transformers are available at reasonable cost. We won't consider active optical or carrier modulated isolation amplifiers here because such devices which also have acceptable audio performance are still quite expensive.

Active differential amplifier circuits are used in a number of commercially available devices. To a greater or lesser extent, they all share several disadvantages: they can further complicate the ground system by contributing interchassis currents of their own, since they require AC power; they cannot handle ground voltage differences over about 10 volts RMS; they use semiconductors or integrated circuits which are prone to degradation or failure caused by power line or lightning induction voltage transients; and, worst of all, they are exquisitely sensitive to source impedance. This sensitivity limits hum rejection, even in a *balanced* system (for which they are intended), but it makes them nearly useless in an unbalanced system.[2] A typical example of such devices is the popular Sonance AGI-1 (which uses the Analog Devices SSM2141). Lab measurements on this unit, shown in Figure 4, reveal that over the 200 Ω to 1 kΩ range of source (output) impedances typical in consumer equipment, its hum rejection is only 15 to 30 dB.

High quality audio transformers are, by their nature, relatively insensitive to source impedance and exhibit excellent hum rejection performance in *either* balanced or unbalanced systems. Under the same conditions and same range of source impedances, the passive transformer based ISO-MAX® model CI-2RR measures 90 to 110 dB. As shown in the Figure 4 graph, its measured hum rejection is ***over 70 dB better*** than the active device. It requires no power of any kind and can handle ground voltage differences up to 250 volts RMS without malfunction, degradation, or damage.

There is a widespread belief that *all* audio transformers have inherent limitations such as high distortion, mediocre transient response, and large phase errors. Unfortunately, many such transformers do exist and not all of them are cheap. The vast majority of available audio transformers, even when used as directed, do not achieve professional performance levels. As Cal Perkins wrote "With transformers, you get what you pay for. Cheap transformers create a host of interface problems, most of which are clearly audible."[6] If well designed and properly used, however, audio transformers qualify as true high fidelity devices. They are passive, stable, reliable, and require neither trimming, tweaking, nor excuses.

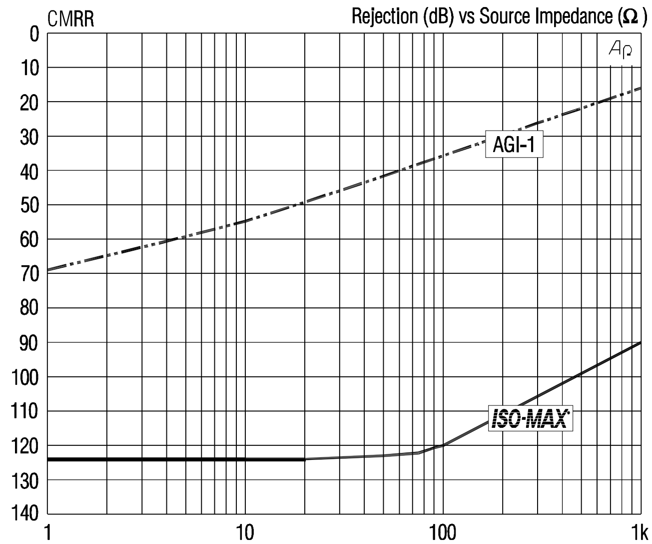

Figure 4 - HUM REJECTION vs SOURCE IMPEDANCE

DIAGNOSIS OF A LARGER SYSTEM

Most systems consist of more than two devices and often consist of a mixture of floating (2-prong AC plug) and safety grounded (3-prong AC plug). In addition, devices may be connected to external sources of ground currents, such as cable TV. Our previous analysis of a generalized two device system allows us to apply the same principles to analyze and treat hum problems in larger systems. Our example system, shown in Figure 5, consists of a large screen TV receiver with audio outputs, a stereo preamp control center, a sub-woofer with internal power amplifiers, and a stereo power amplifier for the satellite speakers. All devices have 2-prong AC plugs, except the sub-woofer, which has a 3-prong plug. Initially, we will not make the cable TV connection shown by the dotted line. The interconnect cable is a foil shielded type with a #24 gauge drain wire having a resistance of 25 mΩ per foot. Now, let's go through the process step-by-step.

Step 1 is to measure or estimate the worst case ground current of each device having a 2-prong AC plug (as described under heading 3). *To keep our analysis process as easy as possible, we will be using some simplifying assumptions and approximations throughout. Therefore measurements need not be made with laboratory precision. Our calculated hum levels will generally be pessimistic by several dB.*

Step 2 is to measure or calculate the interchassis resistance for each cable run. Vendor data usually provides either resistance per unit length or equivalent wire gauge information for the cable's shield. Remember to include some shield contact resistance at each connector (normally one at each end) as part of the total. If the

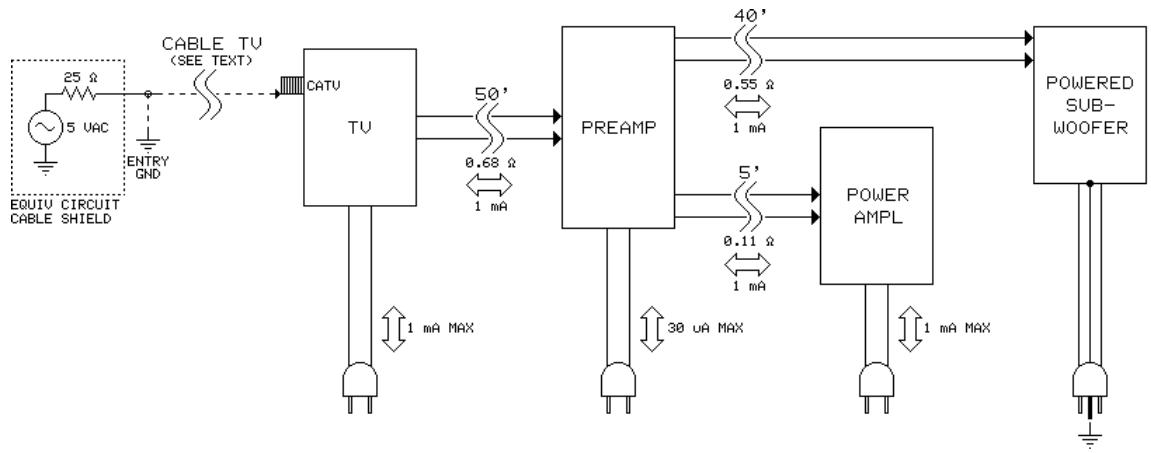

Figure 5 - THE EXAMPLE SYSTEM "BEFORE"

cable run is a stereo pair, remember to divide by two because the two shields are in parallel. The 50 foot run from TV to preamp in Figure 5 was calculated as follows:

50 ft cable shield @ 25 mΩ/ft = 1.25 Ω
2 connector contacts @ 50 mΩ each = 0.1 Ω
Total resistance per cable = 1.25 Ω + 0.1 Ω = 1.35 Ω
Resistance of 2 paralleled cables = 1.35 Ω ÷ 2 = 0.68 Ω

Step 3 is to estimate current flow in each cable (or cable pair, in this case). At this point we will make some simplifying assumptions, but according to the following rules:

A - If two devices with different ground currents are connected, the current flow between them is limited to the <u>lower</u> of the two currents. If the ground currents have equal values, flow between them is that value.

B - Current flow between two high ground current devices can flow <u>through</u> a lower ground current device chassis from connector to connector.

C - A device connected to safety ground or any external path to earth ground or AC neutral can support <u>unlimited</u> current flow.

D - If current into a device may flow out in multiple paths, assume that value will flow in <u>all</u> paths that can support it (according to rule A).

Make a simple diagram of the system, similar to Figure 5, and enter the measured or estimated worst case ground current for each floating (2-prong plug) device near its AC plug symbol. Applying the rules, determine the current flow in each cable (or cable pair) and enter the value on the diagram. In our example, although the preamp can support only 30 μA through its power connection, note that the 1 mA ground current from the TV will flow <u>through</u> it to either the power amplifier *(which can support 1 mA through its power connection)* or the sub-woofer *(which can support unlimited current through its safety ground)*.

Step 4 is to calculate the hum voltage drop for each cable. Knowing the values of interchassis resistance (from step 2) and current flow (from step 3) for each cable, allows us to find the hum voltage. According to Ohm's law, E = I x R where E is the hum voltage, I is the interchassis current, and R is the interchassis resistance. Therefore, in Figure 5, the hum voltages are:

1 mA x 0.68 Ω = 0.68 mV for TV to preamp cable,
1 mA x 0.55 Ω = 0.55 mV for preamp to sub-woofer, and
1 mA x 0.11 Ω = 0.11 mV for preamp to power amplifier.

Step 5 expresses the ratio in dB of each of these hum voltages to the signal voltage, since the hum voltage directly adds to the signal at the receive end of each cable. Because each cable carries a nominal 300 mV (sometimes expressed as −10 dBV) maximum signal level, this will be our reference level. For each voltage calculated in step 4, the hum level, in dB relative to the reference signal, is calculated as dB = 20 x log (E ÷ 300 mV). Expressing our example voltages in dB gives us:

−53 dB at preamp input from TV,
−55 dB at sub-woofer input from preamp, and
−69 dB at power amplifier input from preamp.

These numbers do ***not*** include the additional hum caused by a device which may amplify the hum appearing at its input. In this example, even if the preamp volume control is "off", unacceptably high hum levels exist at the inputs of both the sub-woofer and power amplifiers. If we advance the volume to unity preamp gain (preamp input and output levels the same), the hum level to both power amplifiers will further increase. ***Calculations should assume that all hum voltages are in-phase and additive***. While it is possible for the hum at the preamp input to be anti-phase to the hum at the power amplifiers *(as volume is advanced, hum would <u>decrease</u> to a "null" and then <u>increase</u> beyond the null)*, we won't rely on this possibility.

TREATMENTS TO REDUCE HUM

As a general rule, problem areas involve the longer cables and higher interchassis currents. In our example system of Figure 5, these are the 40 and 50 foot cable runs. Figure 6 shows the same system with transformer isolators added to the long runs. Note how the isolators reduce interchassis currents *(the 1 μA flow through each isolator is due to interchassis <u>voltage</u> now present - more on that later)*. Since the isolators block the high chassis currents from the TV and sub-woofer, the preamp to power amplifier current is now only 30 μA and flows in the shortest, lowest shield resistance cable. Following steps 3, 4, and 5 as before, the new hum estimates calculate as:

- –113 dB at preamp input from TV,
- –115 dB at sub-woofer input from preamp, and
- –99 dB at power amplifier input from preamp.

In reality, we can't achieve the –113 dB and –115 dB levels. Recall that Figure 2 showed a Thevenin equivalent circuit for each device, consisting of voltage source V_X and capacitance C_X. If an isolator effectively disconnects a device from ground, its chassis will "float" above safety ground at its Thevenin voltage. This voltage, which appears as common-mode (on both input lines) to the isolator, could range from 0 to 120 V. A reasonable typical is 60 V which is +46 dB relative to a 300 mV reference signal. Even the best *real* isolator, with a CMRR of 120 dB, will have an output hum level of +46 dB – 120 dB or –74 dB.

If, as shown in Figure 6, we ground each device through a separate wire (<u>not</u> through the audio cable shields), we can essentially remove the common-mode voltage from the isolator. More and more equipment, TV receivers especially, have plastic cabinets and the only exposed metal may be screwheads and connectors, making it unclear how to ground the "chassis". DO NOT make the ground wire connection to anything INSIDE the cabinet — you may severely damage the equipment and/or create a lethal shock hazard. You can confirm that a screwhead, for example, is an effective "chassis" ground by: 1) disconnecting the equipment from everything except AC power, 2) with an AC voltmeter, monitor the voltage between an audio output jack's outer (shield) contact and the AC outlet's safety ground pin, and 3) verify that the voltmeter reading drops to under a volt when the grounding wire connected to the AC outlet's safety ground pin is touched to the screwhead. When grounded this way, the output hum level of our example system will drop from –74 dB to about –110 dB (the thermal noise floor of a Jensen ISO-MAX® CI-2RR isolator). With isolators and added grounds in place, our estimate becomes:

- –110 dB at preamp input from TV,
- –110 dB at sub-woofer input from preamp, and
- –99 dB at power amplifier input from preamp.

The –99 dB figure can be improved further by lowering the shield resistance of the 5 foot cable which uses a foil shielded cable with #24 gauge drain wire (25 mΩ per foot). Cable using a #18 gauge equivalent braided copper shield (6.5 mΩ per foot) will lower hum level by 5 dB from –99 dB to –104 dB.

The ***cable TV*** connection is shown to illustrate the problems it can cause. Most cable systems supply AC power to their trunk mounted repeater amplifiers through the trunk cable itself. This 60 Hz AC current flows through the shield of the coaxial trunk cable and (surprise) causes AC voltage drops. For safety reasons (lightning strikes to the trunk line, for example) the residential "drop" cable is usually "grounded" near its point of entry to the building. This ground may be to a water pipe, a separate earth ground rod, the same ground point used by the main AC power panel, or the ground connection may not even exist. In any case the cable TV shield will typically carry several volts of hum with respect to the building's safety ground wiring. When the dotted cable connection is made in Figure 5, this ground voltage difference can cause very high currents (just under 200 mA in our example) to flow from cable shield to TV, through audio cable to the preamp through more audio cable to the sub-woofer system and its safety ground. The resulting voltage drops in the audio cables produce truly horrible hum levels of about –6 dB. One might be sorely tempted to "lift" the safety ground of the sub-woofer to reduce the hum (which it would).

DO NOT DEFEAT SAFETY GROUNDS!

A "ground adapter" is intended to <u>provide</u> a safety ground for 3-conductor power cords when used with 2-prong outlets, NOT <u>defeat</u> the safety ground provided by a 3-prong outlet. Defeating a safety ground could allow lethal voltages to appear on all equipment in an interconnected system.

In most systems, the best way to deal with the cable TV problem is to stop the current flow with a 75 Ω RF isolator. Most commercial RF isolators are simply high-pass filters which use capacitive coupling, resulting in input to output capacitances up to 4 nF. Although these isolators certainly <u>*reduce*</u> the current injected into the ground system, RF transformer type isolators, with capacitances under 50 pF, work about 40 dB better, to effectively <u>*eliminate*</u> the current. The Jensen ISO-MAX® VR-1FF is such a transformer type isolator. Because our modified system of Figure 6 prevents the TV chassis currents from passing through any audio cables, it does not need an RF isolator. Generally, neither RF isolator type can be used with DSS receivers because they do not pass DC current.

An unbalanced audio system with two or more safety grounded devices (3-prong AC plugs) will virtually <u>always</u> require audio isolators to prevent hum. Without isolation, the voltage drops occurring in the safety ground wiring of the building are forced onto the audio cable shield system through the two or more safety ground connections. This problem will generally be made more severe as the

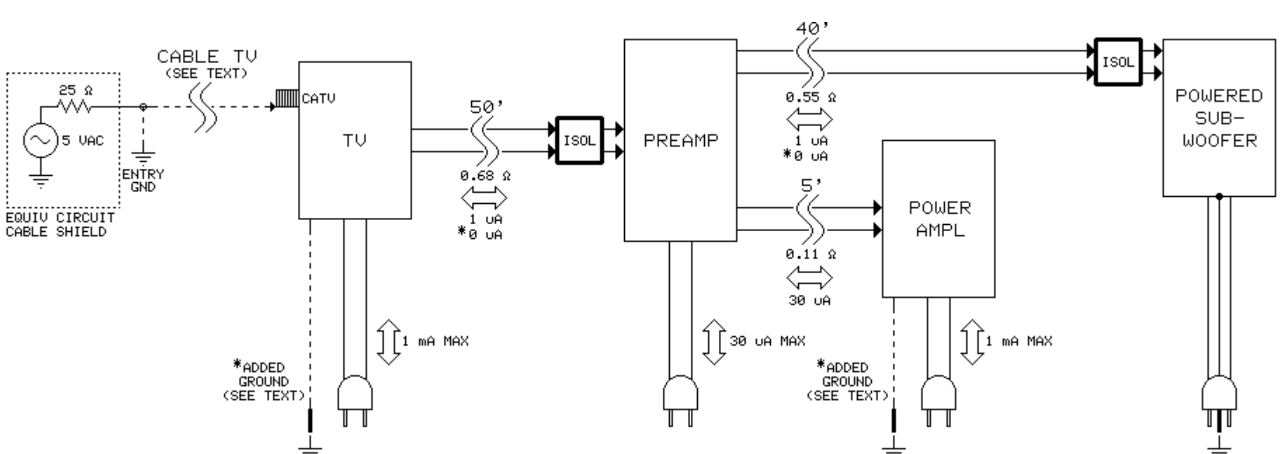

Figure 6 - THE EXAMPLE SYSTEM "AFTER"

distance (and length of intervening building safety ground wiring) increases. The worst case is two safety grounded devices operating from two different branch circuits of the building's AC power. The best case is two safety grounded devices located very near each other and operated from the same AC receptacle.

Magnetic pickup loops can easily be created by improper routing of cables. Any closed loop of wire in the proximity of an AC magnetic field will have a current induced in the loop. When this current flows in the shields, it produces voltage drops which contaminate the audio just as interchassis currents do. Common sources of strong AC magnetic fields are power transformers, motors, fluorescent lights, AC power wiring (even inside walls and conduit), TV sets, and computer CRT displays. A simple stereo pair of interconnect cables between two devices forms a loop because the shields are tied together at both ends. Since loop pickup is directly proportional to the area inside the loop, the cables should be dressed as physically close together as possible. In fact, all cables that connect between the same two devices should be bundled together in order to minimize loop area. The bundles should, of course, be kept as far as possible from magnetic field sources.

CONCLUSIONS AND TIPS

Hum and buzz in unbalanced audio systems is caused by common impedance coupling in the shield resistance of the interconnecting cables. This coupling can be minimized by reducing shield resistance, reducing or eliminating interchassis currents, or both.

✓ Choose shielded cable for low shield resistance. A cable with 6.5 mΩ/ft (6.5 Ω per 1000 ft) shield resistance and 90% shield coverage is much preferred over one with 25 mΩ/ft shield resistance and 100% shield coverage.

✓ Use high quality, transformer based audio ground isolators to eliminate high interchassis currents.

✓ Bundle together all audio cables connecting the same two devices and keep the bundle away from power cabling or other AC magnetic fields.

✓ NEVER, NEVER DEFEAT THE SAFETY GROUNDING of any device having a 3-prong power cord. The results of doing so can be **deadly** to you and/or your customer.

✓ If the system contains more than one safety grounded device, use audio ground isolators to eliminate current flow through audio cables connecting them.

✓ Add external grounding, if possible, to devices without any other system ground path in order to reduce common-mode voltage at the isolators.

✓ Use a transformer type RF isolation device, if necessary, to prevent ground currents that may result from the cable TV connection.

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Jensen Transformers, Inc.
7135 Hayvenhurst Avenue
Van Nuys, California 91406

Tel (818) 374-5857 Fax (818) 374-5856
http://www.jensen-transformers.com