



การปรับปรุงสภาพแวดล้อมการฟังวิทยุในทางปฏิบัติ

การปรับปรุงสภาพแวดล้อมการฟังวิกฤตในทางปฏิบัติ

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บทคัดย่อ

A reference listening room is not a static system. Temperature changes shift speaker driver compliance and crossover component values. Humidity alters the speed of sound and the absorption characteristics of acoustic treatment. Barometric pressure modulates diaphragm rest position. Vibration from HVAC, traffic, and building services introduces low-frequency contamination. Electromagnetic interference from household electronics populates the RF spectrum within the room. These variables drift continuously, and their combined effect on the perceived audio quality of a reference system is measurable. This paper presents a practical framework for optimizing and maintaining a critical listening environment, based on 3 years of continuous monitoring of 4 reference rooms at different latitudes. We document the magnitude of each environmental variable, its effect on measurable audio parameters, and the corrective procedures required to maintain reference-grade conditions. The resulting maintenance burden is substantial -- between 20 and 45 minutes per listening session for manual correction -- but reducible through systematic environmental control and, where available, automated alignment instrumentation.

1. บทนำ

Every audiophile knows that a system sounds different from day to day. The common explanation is psychological -- mood, fatigue, expectation. The less common but more accurate explanation is physical. The listening environment changes, the equipment changes, and these changes are measurable.

This paper is a practical guide. It is intended for anyone who maintains a critical listening room -- whether for product evaluation, mastering, or personal use -- and who wants to understand what changes, by how much, and what to do about it.

The guidance is based on three years of continuous monitoring of four reference listening rooms: our primary evaluation room in Quito, Ecuador; a partner facility in Zurich, Switzerland; a mastering studio in Nashville, Tennessee; and a private listening room in Sapporo, Japan. Each room was instrumented with temperature, humidity, barometric pressure, vibration, and electromagnetic field sensors logging at 1-second intervals. Each room's audio system was measured weekly using a standardized protocol (frequency response, distortion, impulse response, noise floor).

The data reveals that every environmental variable we measured produces a detectable effect on the audio system's measured performance. Some effects are large (temperature-induced frequency response shifts of up to 0.8 dB). Some are small (barometric pressure effects on driver compliance of 0.02 dB). All are real, and all drift over time.

The question is not whether to correct for these effects. It is how much effort the correction requires, and whether that effort can be reduced.

2. การวางลำโพง

Speaker placement in a rectangular room is a solved problem in acoustics. The optimal position can be calculated from the room dimensions using modal analysis, refined by measurement, and fixed. Once the speakers are positioned, they should not need to move.

They do move.

Thermal expansion of the floor shifts speaker position by up to 0.3 mm per degree Celsius in rooms with concrete slab flooring, and up to 1.2 mm per degree in rooms with suspended timber floors. A seasonal temperature swing of 15 deg C in a timber-floored room produces a cumulative speaker displacement of up to 18 mm -- nearly two centimeters.

This displacement is not uniform. It depends on the speaker's position relative to the room's thermal expansion center (typically near the geometric center of the slab or subfloor). Speakers positioned asymmetrically -- the usual case -- shift asymmetrically. The left speaker moves more than the right, or vice versa, disturbing the stereo image geometry.

We measured this effect directly using laser displacement sensors (Keyence IL-300, resolution 0.5 um) bonded to the listening chair and the speaker cabinets. Over a calendar year in the Nashville room (timber floor, seasonal temperature range 18-32 deg C), the left speaker migrated 14.3 mm toward the rear wall and 2.1 mm toward the side wall. The right speaker migrated 11.7 mm toward the rear wall and 3.8 mm away from the side wall. The inter-speaker distance changed by 5.9 mm and the time-of-flight difference between left and right channels at the listening position changed by 17.2 microseconds -- equivalent to a stereo image shift of approximately 1.4 degrees.

Correction requires re-measurement and re-positioning at least seasonally, and ideally monthly. Each re-positioning session takes 15-25 minutes with a tape measure and SPL meter, or 3-5 minutes with a laser-referenced positioning system.

For rooms on concrete slabs, the thermal displacement is an order of magnitude smaller and the correction interval can be extended to annually. The Quito room, built on a reinforced concrete slab at 2,850 m elevation with a seasonal temperature variation of 4 deg C, showed total speaker displacement of 0.8 mm over three years -- below the threshold of audible effect for any speaker position in the room.

Spiked speaker stands driven into carpet over concrete provide the most stable mounting. Stands on hardwood or tile should use polymer isolation feet (Shore 40A durometer) rather than metal spikes, which couple the speaker to floor-borne vibration. Speaker mass should exceed 15 kg per channel for adequate inertia against airborne vibration from the speaker's own output -- a minimum seldom discussed but frequently violated by stand-mount monitor systems.

3. ผลกระทบของอุณหภูมิต่ออิเล็กทรอนิกส์

The temperature coefficient of electronic components is well-documented in engineering literature but rarely discussed in audio. It should be.

A typical crossover network contains polypropylene film capacitors (temperature coefficient approximately -200 ppm/deg C), ferrite-core inductors (temperature coefficient +800 to +2000 ppm/deg C depending on the ferrite grade), and wirewound resistors (temperature coefficient +20 to +50 ppm/deg C). A 10 deg C temperature change shifts the crossover frequency by 0.2-0.5%, depending on the topology. For a 3 kHz crossover, this is a shift of 6-15 Hz -- small in absolute terms, but it alters the phase relationship between drivers in the crossover region, producing a measurable change in the frequency response at the listening position.

We measured this directly. A pair of reference loudspeakers (3-way, Linkwitz-Riley 4th-order crossovers at 500 Hz and 3 kHz) was placed in a temperature-controlled room and swept from 15 deg C to 30 deg C in 1 deg steps, with a 2-hour stabilization period at each step. Frequency response was measured at the listening position using a calibrated measurement microphone and a 10-second log sweep.

The measured shift: the 3 kHz crossover moved from 2,987 Hz at 15 deg C to 3,014 Hz at 30 deg C, a total shift of 27 Hz (0.9%). The 500 Hz crossover moved from 497 Hz to 504 Hz (1.4%). The frequency response at the listening position changed by up to 0.8 dB in the crossover regions.

For amplifiers, the dominant effect is bias point drift in the output stage. Class A and class A/B amplifiers show measurable changes in distortion spectrum as the output devices warm up. We measured a representative class A/B amplifier from cold start (25 deg C heatsink temperature) to thermal equilibrium (58 deg C heatsink temperature). Total harmonic distortion at 1 kHz decreased from 0.0042% to 0.0019% over the first 45 minutes of operation, then stabilized. The distortion spectrum also changed: the ratio of second to third harmonic shifted from 3.2:1 to 4.7:1 as the bias point drifted with temperature.

The practical recommendation is to power on the system at least 60 minutes before critical listening. This is common advice. What is less commonly discussed is that the room temperature during this warm-up period should be stable -- a system that warms up in a cold room and then is listened to in a heated room has not reached its steady-state operating point, because the room temperature continued to change after the electronics stabilized.

We recommend a room temperature stability of +/- 0.5 deg C during listening sessions. Achieving this requires either a purpose-built HVAC system with proportional control (not the on/off cycling of residential thermostats) or -- more practically -- turning off the HVAC and relying on the room's thermal mass, which in a well-insulated room provides 2-3 hours of +/- 0.5 deg C stability after the system reaches the target temperature.

4. ความชื้นและการดูดซับเสียง

The speed of sound in air depends on temperature (well known) and humidity (less well known). At 20 deg C and 50% relative humidity, the speed of sound is 343.8 m/s. At 20 deg C and 20% RH, it is 343.4 m/s. The difference -- 0.4 m/s, or 0.12% -- is small but produces a measurable change in the arrival time of reflections, which alters the room's impulse response.

More significant is humidity's effect on acoustic absorption. Air absorbs sound in a frequency-dependent manner, with the absorption coefficient increasing sharply above 2 kHz. At 20 deg C and 50% RH, the absorption coefficient is approximately 0.006 dB/m at 4 kHz and 0.02 dB/m at 10 kHz. At 20% RH, these values increase to 0.011 dB/m and 0.038 dB/m -- nearly double.

In a room with an average sound path length of 8 m (direct plus one reflection), the humidity-dependent absorption difference at 10 kHz is approximately 0.14 dB between 50% and 20% RH. This is below the threshold of audibility for a

single tone, but it accumulates across the spectrum and across multiple reflections. The cumulative effect on the room's high-frequency reverberation time is measurable: in the Nashville room, RT60 above 4 kHz varied from 0.28 s (summer, 65% RH) to 0.22 s (winter, 25% RH) -- a 21% seasonal variation in high-frequency decay time.

We recommend maintaining listening room humidity between 40% and 55% RH. Below 40%, high-frequency absorption increases and static charge accumulation on cable dielectrics becomes significant -- a topic we have addressed in previous work on ferroelectric coupling. Above 55%, condensation risk increases on equipment surfaces and acoustic treatment materials (particularly mineral wool panels, which gain mass and lose absorptive efficiency when damp).

A standalone humidifier or dehumidifier with a hygrostat is sufficient for most climates. In rooms with large seasonal humidity swings (common in continental climates), a whole-room humidity control system is preferable. The Quito facility, at 2,850 m elevation in a tropical highland climate, maintains 45-50% RH year-round with no mechanical intervention -- one of the less-discussed advantages of equatorial altitude for audio work.

5. การสั่นสะเทือนและการแยกทางกล

Every component in an audio system is a mechanical object, and every mechanical object is a microphone.

Turntable platters, tonearms, and cartridges are obviously sensitive to vibration. Less obvious is the sensitivity of capacitors, transformers, vacuum tubes, and even solid-state output devices. Capacitors are piezoelectric: mechanical stress on the dielectric produces a voltage across the plates. Film capacitors are the least sensitive (typically -80 dBV at 1 g acceleration), but ceramic capacitors can produce voltages approaching millivolt levels under vibration -- one reason they are avoided in analog signal paths.

Transformer laminations are magnetostrictive: mechanical vibration modulates the magnetic coupling, producing electrical noise at the vibration frequency and its harmonics. We measured the vibration-induced noise of three representative toroidal transformers (50 VA, 200 VA, 500 VA) at vibration levels typical of urban residential environments (5-50 Hz, 0.001-0.01 g). The induced noise ranged from -118 dBV (50 VA, 0.001 g) to -94 dBV (500 VA, 0.01 g at 50 Hz). In a system with a 2 Vrms output level, the 500 VA transformer's vibration-induced noise at 0.01 g represents a signal-to-noise degradation of approximately 0.003 dB -- small but present.

Component isolation follows a simple hierarchy: mass, then compliance, then damping. A heavy component on a compliant mount with viscous damping will reject more vibration than a light component on a stiff mount with elastic damping. The optimal isolation platform for audio components has a resonant frequency well below the lowest significant vibration frequency in the room -- typically below 3 Hz, which requires either pneumatic isolation (air springs) or a very soft elastomeric mount with a heavy load.

We tested four isolation strategies on a 15 kg preamplifier in the Nashville room, which had a measured floor vibration spectrum of 0.003 g at 15 Hz (HVAC), 0.001 g at 30 Hz (traffic), and broadband vibration below 0.0005 g from 50-200 Hz:

1. Direct coupling (no isolation): floor vibration transmitted to chassis at 0 dB (unity).
2. Sorbothane hemispheres (Shore 30A, resonant frequency approximately 12 Hz): -6 dB at 15 Hz, -14 dB at 30 Hz, -22 dB at 50 Hz.
3. Pneumatic isolation platform (Newport RS2000, resonant frequency 1.5 Hz): -28 dB at 15 Hz, -38 dB at 30 Hz, -46 dB at 50 Hz.
4. Sandbox (30 kg dry sand on Sorbothane feet): -18 dB at 15 Hz, -26 dB at 30 Hz, -34 dB at 50 Hz.

The pneumatic platform was the most effective, but also the most expensive (\$800) and the most maintenance-intensive (the air bladders require periodic re-inflation, approximately every 3 months). The sandbox was nearly as effective, cost \$40 in materials, and required no maintenance beyond occasional releveling if the sand settles -- which it does, at a rate of approximately 0.5 mm per year.

Our practical recommendation for most systems: sandbox isolation for heavy components (amplifiers, power supplies), Sorbothane feet for light components (DACs, preamplifiers), and no isolation for speakers (which should be rigidly coupled to the floor or to high-mass stands). Turntables are a special case and benefit from purpose-built wall-mounted shelves decoupled from the floor entirely.

A quarterly vibration check using an inexpensive MEMS accelerometer (ADXL345, \$15) placed on each component shelf is sufficient to detect changes in the vibration environment -- construction activity on neighboring properties, new HVAC equipment, or seasonal changes in traffic patterns can all alter the room's vibration baseline. Equatorial Audio's Hemispheric Calibration Tool includes a vibration survey mode that automates this check and flags components whose isolation has degraded since the last session.

6. การรบกวนแม่เหล็กไฟฟ้า

The electromagnetic environment inside a listening room is not quiet. A typical residential room at evening -- the most common listening time -- contains RF energy from Wi-Fi routers (2.4 and 5 GHz), Bluetooth devices (2.4 GHz), mobile phones (700 MHz - 2.6 GHz), DECT cordless phones (1.88 GHz), microwave ovens (2.45 GHz), LED lighting (broadband switching noise from 100 kHz to 30 MHz), and switched-mode power supplies in every connected device (50 kHz to 5 MHz fundamental, harmonics to 100 MHz and beyond).

Most of this energy is far above the audio band and is rejected by audio circuits, which have limited bandwidth. The concern is not the carrier frequencies but the rectification products. Any nonlinear junction in the signal path -- a corroded connector, a semiconductor junction at the edge of its bias range, a magnetostrictive transformer core -- can rectify high-frequency energy, producing baseband noise and intermodulation products within the audio band.

We measured the RF energy density inside our four reference rooms using a calibrated broadband antenna (Aaronia HyperLOG 30100, 30 MHz - 10 GHz) and a spectrum analyzer. The results varied dramatically:

Quito laboratory: -88 dBm/m² average, -96 dBm/m² at 50 kHz-30 MHz. (The facility is located in a rural area with no near neighbors, dedicated transformer, and fiber optic network connection.)

Zurich facility: -62 dBm/m² average, -71 dBm/m² at 50 kHz-30 MHz. (Urban office building, multiple Wi-Fi networks, LED lighting throughout.)

Nashville studio: -58 dBm/m² average, -64 dBm/m² at 50 kHz-30 MHz. (Commercial building, shared power with adjacent offices, fluorescent lighting in corridors.)

Sapporo room: -54 dBm/m² average, -59 dBm/m² at 50 kHz-30 MHz. (Residential apartment, dense urban environment, 12 Wi-Fi networks visible.)

The 34 dB difference in RF environment between the quietest and noisiest rooms is substantial. Its audible effect depends on the quality of the shielding and RF immunity of the audio equipment. Well-designed equipment with proper RF filtering and shielded enclosures is largely immune. Consumer equipment with unshielded interconnects and minimal RF filtering is not.

Practical mitigation: (1) Use shielded interconnect cables -- the shielding effectiveness of a braided copper shield is typically 60-80 dB, which is sufficient to bring even the Sapporo environment below the Quito baseline within the cable. (2) Power the audio system from a dedicated circuit with an EMI filter at the breaker panel. (3) Remove unnecessary electronic devices from the room -- each device is both a source of RF energy and a potential rectification site. (4) If LED lighting must be used, select fixtures with properly filtered drivers (compliance with EN 55015 is a minimum; some LED drivers that pass EN 55015 still produce measurable conducted emissions below 150 kHz that fall outside the standard's scope but within the audio band).

A periodic RF survey is worthwhile. The electromagnetic environment changes -- new neighbors, new routers, new appliances. A survey takes 5 minutes with a handheld spectrum analyzer or compatible software-defined radio. Changes of more than 6 dB from the baseline warrant investigation.

7. การเดินสายและจัดเรียงสายเคเบิล

The physical routing of cables within a listening room affects both electromagnetic pickup and microphonic noise. Neither effect is large, but both are cumulative, and both are easily avoided by following a few principles.

Signal cables should not run parallel to power cables. A 1 m parallel run between an unshielded signal cable and a mains power cable at 10 cm separation induces approximately -90 dBV of 50/60 Hz hum. Shielding reduces this to approximately -150 dBV -- inaudible -- but the same shielding has no effect on the magnetic field component, which requires physical separation. A 30 cm separation reduces magnetic coupling by 10 dB. A 1 m separation reduces it by 20 dB. Where signal and power cables must cross, a 90-degree crossing minimizes the coupling length.

Signal cables should not be coiled. A coiled cable forms an inductor, and an inductor is an antenna. The inductance of a single-layer coil of N turns, radius R, is approximately $\mu_0 \cdot N^2 \cdot R / (0.9 \cdot R + \text{length})$. A 3 m cable coiled into 5 turns of 15 cm radius has an inductance of approximately 4 uH -- enough to form a resonant circuit with the cable's parasitic capacitance at a frequency that may fall in the low MHz range, creating a narrow-band antenna for RF interference. The same cable laid flat in a gentle curve has an inductance below 0.5 uH.

Cable tension affects microphonic noise. A cable under tension acts as a vibrating string. The fundamental resonant frequency of a 1 m cable span under 0.5 N of tension (a moderate droop) is approximately 15 Hz -- within the subwoofer

range. A passing footstep or HVAC vibration can excite this resonance, producing a microphonic pulse that propagates through the cable as a common-mode voltage. The cure is simple: support the cable at intervals of no more than 50 cm using soft clips or Velcro ties, and ensure the cable has slight slack at every support point.

These are maintenance items. Cables move during equipment changes, cleaning, and rearrangement. A cable dressing check before each critical listening session takes 2-3 minutes and is easily neglected. We have found it easier to establish a fixed cable infrastructure -- permanent cable trays, labeled routing paths, strain-relief anchors at every component -- and to treat any deviation from the established dressing as a fault to be corrected before listening begins.

8. การบำรุงรักษา

We compiled a maintenance checklist from the findings described above and timed the complete procedure in each of our four reference rooms. The checklist includes:

1. Temperature check and stabilization (verify room is within +/- 0.5 deg C of target, adjust if necessary): 0-15 minutes depending on initial deviation.
2. Humidity check and stabilization (verify 40-55% RH, adjust humidifier/dehumidifier if necessary): 0-10 minutes.
3. Speaker position verification (laser measure to reference marks on floor): 3-5 minutes. Correction, if needed: 10-15 minutes.
4. Component warm-up (power on, wait for thermal equilibrium): 45-60 minutes. This can overlap with other tasks but represents real elapsed time before critical listening can begin.
5. Vibration check (accelerometer on each shelf, compare to baseline): 3-5 minutes.
6. Cable dressing inspection (visual check of all signal and power cable runs): 2-3 minutes. Correction, if needed: 5-10 minutes.
7. RF environment spot check (broadband measurement at listening position): 2-3 minutes.
8. Quick listening check (30-second reference track, verify subjective normality): 1 minute.

Total time for a session where no corrections are needed: approximately 15-20 minutes of active work plus 45-60 minutes of warm-up time. Total time when corrections are needed (typical for weekly sessions): 30-45 minutes of active work plus warm-up.

This burden is not trivial. It represents a real cost in time and attention, and in our experience, it is the primary reason that reference listening rooms drift from their calibrated state. The maintenance is not difficult, but it is tedious, and tedious tasks are the ones most likely to be skipped.

Over the three-year monitoring period, we tracked adherence to the checklist at each facility. The Quito room, operated by trained staff on a daily schedule, maintained 94% adherence. The Zurich facility, operated by engineering staff with other responsibilities, maintained 71%. The Nashville studio, operated by a freelance mastering engineer, maintained 53%. The Sapporo room, a private installation, maintained 31%.

The correlation between checklist adherence and measurement stability was high ($r = 0.91$). The Quito room's measured frequency response varied by no more than 0.15 dB across any 30-day period. The Sapporo room varied by up to 1.4 dB.

We note that the Quito room benefits from more than just diligent staff. Its equatorial location provides inherent environmental stability -- the 4 deg C annual temperature range is the smallest of any facility, the humidity is naturally stable at 45-50%, and the rural site has the lowest RF background. The environmental variables that require daily correction in Nashville and Sapporo require only weekly attention in Quito. The maintenance burden is lower not because the standard is lower, but because the environment deviates less.

Automation reduces the burden further. The Equatorial Audio Hemispheric Calibration Tool, when installed in a room, continuously monitors temperature, humidity, barometric pressure, vibration, and RF environment, and provides real-time deviation alerts. It does not eliminate the need for physical correction -- speakers still need to be moved by hand, cables still need to be re-dressed -- but it replaces six of the eight checklist items with a single glance at a status display. In our testing, this reduced the active maintenance time from 15-20 minutes to 3-5 minutes for sessions requiring no physical correction, and from 30-45 minutes to 10-15 minutes for sessions requiring adjustment.

The most effective optimization, however, is simply choosing a room with inherent stability. A well-insulated room on a concrete slab, away from major RF sources, with stable climate control, eliminates most of the maintenance burden at the

source. The best maintenance is the maintenance you never need to perform.

9. สรุป

A critical listening environment is a dynamic system subject to continuous drift in temperature, humidity, vibration, electromagnetic interference, and physical component position. Each of these variables produces measurable effects on the audio system's performance. Left uncorrected, the cumulative drift can exceed 1 dB in frequency response and introduce noise and distortion products that mask the differences between components under evaluation.

Maintaining reference-grade conditions requires a regular maintenance protocol. The protocol described in this paper takes 15-45 minutes per session, depending on the magnitude of the corrections required. The primary determinant of maintenance burden is the inherent stability of the room's environment -- rooms with stable temperature, humidity, and low RF interference require less frequent and less extensive correction.

These findings are not novel. Individual effects have been documented in acoustics, electronics, and EMC literature for decades. What has been lacking is a unified practical framework that quantifies the combined maintenance burden for the specific use case of critical audio listening. This paper provides that framework.

The guidance is straightforward: control temperature to +/- 0.5 deg C, maintain humidity at 40-55% RH, isolate components from vibration, shield signal paths from EMI, verify speaker position monthly, and warm up electronics for 60 minutes before listening. None of these recommendations is controversial. All of them are frequently neglected.

The difference between a reference room that is maintained and one that is not is measurable, repeatable, and -- in our experience -- audible. The maintenance is the unglamorous part of high-fidelity audio. It is also the part that matters most.

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