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ORIGINAL ARTICLE

Temperament Standardization and the Attenuation of Sacred Acoustic Beating (*Ombak*): Psychoacoustic Signal Modeling of Nusantara *Gamelan, Talempong*, and *Sasando* Across Archival Field Recordings and Global Streaming Platforms

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ABSTRACT

Background: Nusantara bronze and bamboo-palm ensembles cultivate ensemble-specific microtonal *laras* [tuning topologies] and sacred interference beating (*ombak* [acoustic wave shimmer]) that risk erosion under twelve-tone equal temperament (12-TET, A4 = 440 Hz) and streaming loudness compression.

Objective: To model physical microtonal geometry, paired *ombak* quantization collapse, and multi-platform psychoacoustic divergence across Indonesian Gamelan, Talempong, and Sasando recordings.

Methods: Four empirical streams combined 103 Huygens-Fokker Scala scales (732 tones), 100 simulated Balinese *pengumbang–pengisep* [lower–higher bronze] dyads across four octaves, and 195 decoded waveforms (64 sub-tradition clusters, 1969–2026), analyzed with Hilbert envelopes, restricted maximum likelihood (REML) linear mixed-effects models (LMM), and cluster-robust fractional logit.

Results: Physical scales averaged 17.15 ± 3.84 cents floating-tonic deviation (random-scale reference 15.66; 48.84% tones > 15 cents). Full 12-TET quantization collapsed 80.0% of simulated dyads to 0 Hz unison and split 12.0% into harsh semitones. Across 195 recordings, floating-tonic deviation declined from 16.04 cents in archival field editions to 11.61 cents in hybrid streams (unadjusted $q_{BH} = 8.68 \times 10^{-7}$, Cliff's $\delta = +0.519$), but adjusted LMM regime effects were not significant ($p = 0.80, 0.13$). Crest factor fell by 6.83 dB ($p = 1.81 \times 10^{-22}$). After adjustment, the 3–10 Hz envelope share was lower in contemporary acoustic ($\beta = -6.32$ points, $p = 0.0010$) and hybrid streaming ($\beta = -4.89$ points, $p = 0.0259$).

Conclusion: In this observational corpus, hybrid production and dynamic compression are associated with lower pitch deviation and a lower 3–10 Hz envelope share, motivating a five-pillar Sonic Sovereignty Safeguarding Protocol.

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1. Introduction

1.1 Inharmonic Materiality, Nusantara Laras, and the Cosmology of Sacred Acoustic Beating (*Ombak*)

Across the Indonesian archipelago (Nusantara), musical pitch has historically worked as an embodied acoustic relationship. It joins metallurgy, botanical resonance, communal aesthetics, and ritual cosmology, and it is not an abstract, universally interchangeable grid of integer string ratios or logarithmic semitones.[1–3] Reinier Plomp and Willem Levelt formulated the classic psychoacoustic theory. In it, sensory consonance and auditory roughness arise from the interaction of partials within critical bandwidths along the basilar membrane.[1] William Sethares went further. He extended this principle beyond

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Western bowed and blown harmonic oscillators and showed mathematically and experimentally that musical scales co-evolve with the spectral overtone geometry of a culture's core instruments.[2,3] Vibrating strings and cylindrical air columns generate integer harmonic series (f, 2f, 3f, 4f), and their local roughness minima align with just-intonation fifths and thirds. Indonesian instruments differ. Cast tin-bronze (*kerawang* [high-tin bell-bronze alloy]) metallophones, bossed kettle-gongs, and bamboo idiophones radiate non-integer, inharmonic overtone spectra shaped by modal plate stiffness, central boss mass, and coupled cavity resonators.[3,4] Comparative psychoacoustic work by Edward Carterette, Roger Kendall, and Pantelis Vassilakis supports the point in general terms. Nusantara microtonal *laras* [indigenous tuning systems] and stretched octaves are neither 'approximate' nor 'unstandardized' precursors to Western twelve-tone equal temperament (12-TET, anchored to A4 = 440 Hz). They are pitch systems matched to the spectral character of bronze, bamboo, and palm leaf.[5,6]

Nowhere does physical acoustics meet sacred cosmology more clearly than in the Balinese gamelan principle of *ombak* [literally 'ocean wave'; intentional acoustic interference beating].[7,8] Balinese ceremonial and dramatic ensembles include Gamelan Semar Pegulingan [seven-tone court ensemble of love and refinement], Gamelan Gong Kebyar [explosive twentieth-century virtuosic bronze orchestra], and Gender Wayang [ten-keyed *sléndro* quartet accompanying sacred shadow puppetry]. In all of them, every bronze metallophone and kettle-gong rank is forged and tuned in slightly mistuned masculine–feminine or 'exhaling–inhaling' pairs. The lower-pitched member is the *pengumbang* [hummer or absorber]. The slightly higher-pitched one is the *pengisep* [sucker or inhaler].[7–11] When the pair is struck at the same time in interlocking *kotekan* [rapid bipartite rhythmic figuration], the fundamental frequencies fu and fi of the dyad interfere constructively and destructively. The result is a continuous sinusoidal amplitude modulation at rate $\Delta f = |fi - fu|$. A master *pande gong* [ritual bronze-smith and tuner] typically calibrates it to between 4 and 9 Hz across all four bronze octaves.[7,8] Within Balinese Hindu-animist aesthetics, an ensemble devoid of *ombak* is judged acoustically *mati* [lifeless or spiritually inert]. The bronze voice gains *bayu* [vital breath-energy] only when *pengumbang* and *pengisep* lock into a 3–10 Hz shimmer. That energy can consecrate temple *odalan* [anniversary festivals]. It also entrains collective ritual attention.[8–10]

Parallel commitments to ensemble-specific microtonal identity run through Central Javanese, East Javanese, Madurese, and Sundanese bronze traditions.[12–15] A. M. Jones made early quantitative interval assessments. John Rahn later re-evaluated them mathematically. Together they dispelled a colonial reductionism that tried to force five-tone *sléndro* [anhemitonic-inflected pentatonic system] and seven-tone *pélog* [asymmetric heptatonic system] onto equidistant pentatonic (240-cent) or 12-TET chromatic (100-cent) templates.[12,13] Marc Perlman studied *pathet* [modal ethos] cognitively, and Henry Spiller synthesized Indonesian bronze traditions. Both show that Javanese royal *pusaka* [sacred heirloom] ensembles cultivate their own *embat* [idiosyncratic interval temperament], non-A440 *tumbuk* [shared pivot pitches between paired *sléndro* and *pélog* sets], and subtle octave stretching (1,205 to 1,240 cents per octave), so that no two *kraton* [royal court] or village gamelans sound interchangeable.[14,15] Variance across physical Nusantara scales is not tuning error. It encodes localized sovereignty, artisanal lineage, and affective *rasa* [embodied aesthetic-spiritual discernment].[14,15]

Why do these microtonal architectures resist abstraction? Understanding it requires attention to the ritual metallurgy of the Balinese *pande gong* and Javanese *empu* [royal master bronze-smith].[8,14,15] Each bronze *wilah* [metallophone bar] or bossed *pencon* [kettle-gong] is forged from *kerawang*, an alloy of roughly three parts copper to one part tin heated and quenched through closely guarded workshop lineages. It is individually cold-hammered, scraped, and filed rather than cast to a factory template.[4,8] Scraping metal from the central underside of a bronze bar lowers its fundamental flexural mode while altering the ratio of its second and third overtones. Filing the outer tips raises the fundamental pitch.[4,7] In Balinese workshop practice, the *pande gong* typically does not tune against an electronic A4 = 440 Hz chromatic strobe. The smith consults physical bamboo reference slats (*petuding* [sacred tuning tallies]) inherited from specific *banjar* [hamlet civic-ritual councils] or royal courts, and listens closely to the pulsing interference rate Δf between paired *pengumbang* and *pengisep* bars suspended over tuned bamboo *bungbung* [Helmholtz air-column resonators].[7–10] Laras and *ombak* therefore materialize a triadic covenant linking mineral metallurgy, ancestral *petuding* memory, and collective *taksu* [spiritual charisma]. This relational ontology is wholly foreign to the disembodied 100-cent MIDI piano roll.[10,14]

1.2 Comparative Nusantara Organology: Sumatran Talempong and Gong-Rows Versus Rote Island Sasando

To evaluate whether temperament standardization operates uniformly across the archipelago or diverges along material-organological lines, inquiry must look beyond Java and Bali. It has to reach Sumatra and Eastern Indonesia.[16,17] Andrew McGraw studied Indonesian *musik kontemporer* [experimental contemporary art-music]. He demonstrated that modern conservatory pedagogy, state cultural pageantry, and transnational popular music have pressed unevenly on regional instruments, depending on whether their sounding bodies have fixed metallic pitch or tunable string tension.[16] Sumatra spans the Minangkabau highlands (*Darek*) and coastal *Rantau* of West Sumatra, the Musi–Rawas–Muaralakitan river basins of South Sumatra, and the barrier islands of Nias. There, Margaret Kartomi's decades of organological fieldwork documented a rich mosaic of bossed gong-rows (talempong, *kelintang*, *canang*) and tuned idiophones (*druri dana* [split-bamboo buzzed idiophone of South Nias]).[17] Take the traditional Minangkabau *talempong pacik* [hand-held interlocking kettle-gong trio]. Five or six cast brass or bronze kettles are played in three interlocking pairs (*paningkah*, *pambao*, and anak). The ensemble exhibits village-specific non-diatonic intervals, dense inharmonic upper partials, and natural acoustic beating arising from closely spaced metallic modes.[18,19]

Recent Indonesian ethnomusicological investigations by Wimbrayardi and Parmadi and by Adoma have documented a shift. Contemporary Minangkabau wedding and festival soundscapes increasingly supplement or replace village *talempong pacik* with *talempong duduk* [stationary rack-mounted diatonic kettle-gongs] and *talempong kreasi* [pop-hybrid arrangements]. These are retuned to C = 261.6 Hz / A4 = 440 Hz so they can lock with electronic *orgen tunggal* [single-keyboard synthesizer] basslines.[18,19] Darlenis examined internet-era transmission of Minangkabau music. Dermanto,

writing in Enigma in Cultural, addressed the resilience of *Bundo Kanduang* [matrilineal ancestral wisdom] ceremonial institutions. Darlenis notes that digital circulation expands global visibility for Minangkabau performing arts while exposing indigenous sonic forms to commercial pop aesthetics.[20] One question remains open. How strongly do recorded Talempong pitch topologies and dynamic strike transients shift between archival field documentation and contemporary streaming catalogs? Nobody has quantified it.[18,20]

An even starker organological transformation confronts the Sasando [bamboo tube-zither enveloped in a hemispherical *lontar* (Borassus flabellifer) palm-leaf acoustic reflector] of Rote Island and Kupang in East Nusa Tenggara.[21–24] Ancestral Sasando Haik (or Sasando Gong) mounts nine to eleven strings around a cylindrical bamboo resonator (ao) propped by wooden bridges (*senda*). It is tuned directly to the five-tone microtonal scale of Rote's ritual nine-gong ensemble (*meko*) and accompanies genealogical *bini* chants and ceremonial dances.[21,22] Change began in the colonial mission and postcolonial urban eras. It sped up through contemporary conservatory, festival, and streaming production. Artisans developed the chromatic 24- to 32-string Sasando Biola [diatonic 'violin-tuned' sasando], along with amplified electric Sasando models that can play Western functional harmony, pop ballads, and EDM remixes.[23–25] String tension on *senda* bridges is continuously adjustable. A cast bronze *pemade* key or talempong kettle offers no such freedom. Organological scholarship by Kaet et al., Magalhaes, Saefatu, and Natonis et al. therefore suggests that the Sasando may be especially exposed to rapid 12-TET assimilation, even within 'acoustic traditional' streaming categories.[21–24]

Sumatran cultural historiography records non-equidistant bronze microtonality in the Minangkabau *Darek* highlands of West Sumatra. It also appears along the upstream (*ulu*) river corridors of South Sumatra.[17] Jaap Kunst synthesized colonial-era organological surveys. In them, stroboscopic measurements of the ceremonial Pasirah Rus gong-row orchestra in Muaralakitan (along the Musi–Rawas watershed upstream from Palembang) recorded an indigenous tonic of 1/1 = 354.0 Hz, about 377 cents flat of A4 = 440 Hz and 23.5 cents displaced from the nearest 12-TET semitone (recomputed from 354.0 Hz). The tonic was paired with asymmetric step intervals (111 to 361 cents) closely akin to South Sumatran *kelintang* [bronze boss-gong row] and Minangkabau *talempong pacik* aesthetics.[17–19] South Sumatran *marga* [clan-territorial chieftaincies] were led by a *pasirah* [indigenous district head]. West Sumatran *nagari* [autonomous matrilineal republics] followed *Bundo Kanduang* ceremonial protocol.[26] In both, interlocking kettle-gong timbres signified lineage autonomy. Travelers could identify a specific riverine settlement solely by the *embat* and metallic shimmer of its bronze ensemble.[17] Rote Island is arid. There, the ancestral 9- to 11-string Sasando Haik grew directly out of an integrated *lontar* (Borassus flabellifer) agro-cosmology in which palm sap (*tuak*), woven *haik* resonators, and five-tone *meko* gong tunings sustained ancestral *nusak* [traditional Rotenese domains] oral poetry.[21,22] The twentieth-century invention of the chromatic 24- to 32-string Sasando Biola is a celebrated, locally authored Rotenese creole innovation. It is not external cultural erasure.[23,24] Still, separating the two instruments is essential to determine whether global streaming catalogs preserve space for the pentatonic Sasando Haik alongside its diatonic descendant.[23,24]

1.3 Acoustemology, Streaming Platform Normalization, and Study Objectives

Theoretically, the move of Nusantara musical traditions onto global digital streaming platforms (DSPs) sits where acoustemology meets platform studies.[27–31] The traditions come from village plazas, temple courtyards, and ethnographic field tapes. Steven Feld coined acoustemology [acoustic epistemology; knowing-with and knowing-through audible relationality] to stress that sound is a primary medium through which communities inhabit ecological and cosmological worlds.[27] Dylan Robinson's Indigenous sound studies critique of hungry listening and Anne Rasmussen's call to remap sound studies extend this view. Both warn about Western listening regimes and the digital audio architectures built upon them. These systems routinely extract exotic timbral surfaces. At the same time they domesticate Indigenous microtonality, temporal elasticity, and spiritual agency into Euro-American perceptual grids.[28,29] Recent studies in Enigma in Cultural have turned to the cultural politics of sound and symbolic efficacy in Indonesia. Hasan et al. showed how urban acoustic regimes reorder collective memory and sensory belonging,[30] while Rahayu et al. showed how Balinese cosmological categories exert embodied efficacy in contemporary clinical encounters.[31]

Two sociotechnical mechanisms in digital audio production and streaming distribution threaten non-Western microtonality and *ombak* interference beating at once.[32–37] The first is tuning. Jonathan Sterne showed this for perceptual audio coding, and Owen Marshall analyzed it for digital pitch-correction plugins (Auto-Tune and chromatic DAW piano-roll quantizers). Music software embeds 12-TET (100-cent semitone bins referenced to A4 = 440 Hz) as an invisible infrastructural default.[32,33] The second is loudness. Emmanuel Deruty and Damien Tardieu documented it for mainstream dynamic processing, and Mykhailo Salai analyzed it for LUFS [Loudness Units Relative to Full Scale] and True-Peak streaming normalization. Commercial mastering chains apply aggressive brickwall peak limiting, which crushes waveform crest factor (CF_{dB}) and loudness range (LRA). Percussive bronze transients and sustained decay envelopes end up flattened.[34,35] Platform studies by Robert Prey and David Hesmondhalgh add that algorithmic playlisting rewards tracks conforming to mainstream loudness, harmonic, and timbral norms.[36,37] Cross-cultural computational musicology by Patrick Savage et al., Samuel Mehr et al., and John McBride et al. has established quantitative universals and evolutionary diversity across global scale inventories.[38–40] To our knowledge, no study has joined physical scale metrology, multi-octave paired *ombak* quantization modeling, and waveform-level streaming signal econometrics across Nusantara traditions.

The present study addresses this gap. It is a four-stream computational-ethnomusicological investigation. Four research questions guide it. (1) Across N = 103 physical Nusantara scales (732 measured tones) in the Huygens-Fokker Scala Archive, how large are floating-tonic (D_{opt}), root-anchored (D_{root}), and A4 = 440 Hz (D_{A440}) microtonal deviation across Balinese, Javanese, Sundanese, and Sumatran modal families? (2) Across N = 100 paired Balinese *pengumbang–pengisep* bronze dyads spanning four octaves, how does continuous 12-TET pitch quantization ($\alpha \in [0, 1]$) transform sacred 3–10 Hz *ombak* beating? (3) Across N = 195 decoded real audio waveforms (1969–2026, 64 sub-tradition clusters) spanning

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Archival Ethnographic Field Recordings (R1), Contemporary Acoustic Streaming (R2), and Contemporary Hybrid Streaming (R3), how do floating-tonic pitch deviation (C_{float}), 12-TET Temperament Assimilation Index (TAI), dynamic crest factor (CF_{dB}), loudness range (LRA), and 3–10 Hz *ombak* modulation (M_{ombak}) vary across Gamelan, Talempong, and Sasando? (4) Once sub-tradition clustering and instrument-family confounding are accounted for via REML mixed-effects and fractional logit models, which practical benchmarks could operationalize Nusantara sonic sovereignty?

2. Methods

2.1 Four-Stream Computational-Ethnomusicological Research Design and Epistemic Scope

We built a deterministic, four-stream observational signal-modeling architecture. Stream 1 covers physical organological metrology. Stream 2 is a simulation of paired-dyad 12-TET quantization (theoretical psychoacoustics). Stream 3 covers multi-platform real audio waveform feature extraction, and Stream 4 covers hierarchical mixed-effects and fractional-response econometrics. We followed best practices in computational ethnomusicology set out by Maria Panteli, Emmanouil Benetos, and Simon Dixon for world-music outlier analysis[41] and by Joren Six, Olmo Cornelis, and Marc Leman for non-Western sub-semitone pitch-scale estimation.[42] All pitch metrics were therefore formulated to avoid Eurocentric tonic bias. Continuous floating-tonic offsets were optimized before any 12-TET deviation was evaluated. Historical archival releases and contemporary streaming catalogs are non-experimental cultural corpora, shaped by curation, microphone placement, and ensemble repertoire. For that reason, all statistical associations are read with epistemic restraint, as observational patterns and not as isolated laboratory causal effects.

2.2 Stream 1 Physical Scala Metrology and Stream 2 Multi-Octave Paired *Ombak* Quantization Modeling

In Stream 1, we parsed the complete open-access Huygens-Fokker Foundation Scala Archive (scales.zip, curated from published stroboscopic, monochord, and digital frequency measurements by Jaap Kunst, Colin McPhee, Wasitodipuro/Surjodiningrat et al., Andrew Toth, Wim van Zanten, Andrew Weintraub, and Lilin Suparli). After excluding Western theoretical approximations, we isolated N = 103 authentic physical Nusantara instrument scales. Together they comprise 732 scale-degree intervals. These include each scale's 0.0-cent 1/1 reference anchor and 629 measured upper intervals. Scales were stratified into four cultural-geographic regions. These were Bali (n = 40), Central and East Java / Madura (n = 39), West Java / Sunda and Cirebon (n = 22), and Sumatra and Barrier Islands (n = 2, preserving South Sumatra's historic Muaralakitan Pasirah Rus ensemble sumatra.scl at 1/1 = 354.0 Hz and South Nias druri.scl). They fell into four indigenous modal families as well. The families were *Pelog* / *Saih Pitu* / Ceremonial Bronze (n = 47), *Slendro* / *Saih Lima* / Angklung (n = 40), *Sundanese Degung* / *Sorog-Madenda* / *Renteng* (n = 14), and Sumatran Gong-Row & Insular Idiophone (n = 2). For each scale's cent vector c = (c0, c1, ..., cK), we computed root-anchored 12-TET deviation $D_{root} = (1/K) \sum |((ck + 50) \bmod 100) - 50|$. We also computed floating-tonic 12-TET deviation $D_{opt} = \min\delta \in [-50,+50] (1/(K+1)) \sum |((ck + \delta + 50) \bmod 100) - 50|$. Absolute concert-pitch A4 = 440 Hz deviation D_{A440} was obtained across the n = 72 scales reporting physical 1/1 Hertz frequencies. We also measured the stretched-octave span. A null model came from 10,000 Monte Carlo uniform random 5-tone null scales on [0, 1200) cents.

In Stream 2, we simulated N = 100 paired Balinese *pengumbang–pengisep* bronze dyads. They span five documented ensemble archetypes: Gong Kebyar Begbeg [wide/vibrant shimmer, target ~8.2 Hz], Gong Kebyar Sedung [medium shimmer, ~7.3 Hz], Gong Kebyar Tirus [tight/refined shimmer, ~5.9 Hz], Semar Pegulingan [sweet court shimmer, ~6.2 Hz], and Gender Wayang [intimate shadow-play shimmer, ~4.3 Hz]. The dyads cover four bronze octave registers: Octave 1 *Jegogan* [sub-bass register] (140–261 Hz), Octave 2 *Jublag* [core-melody register]/*Calung* [core-melody register] (283–525 Hz), Octave 3 *Pemade* [middle register]/*Gangsa* [middle register] (570–1,055 Hz), and Octave 4 *Kantilan* [treble register] (1,151–2,121 Hz). Empirical Balinese octave stretching (+22 cents/octave) was built in. For each dyad (fu, fi), we evaluated logarithmic cent separation $\Delta c = 1200 \log2(fi/fu)$, Plomp–Levelt critical-bandwidth ratio $\Delta f / CBW(\bar{f})$,[1] and Vassilakis sensory roughness.[6] Next we simulated continuous 12-TET pitch-correction / quantization pull $\alpha \in [0.00, 1.00]$ in 0.05 increments. Each tone's MIDI cent coordinate m was mapped to $(1 - \alpha)m + \alpha \cdot 100 \cdot \text{round}(m / 100)$ relative to A4 = 440 Hz. Quantized beating $\Delta f(\alpha)$ was then classified as Sacred *Ombak* Preserved ($3.0 \le \Delta f(\alpha) \le 10.0$ Hz), Dead Unison Collapse ($\Delta f(\alpha) < 0.5$ Hz), Attenuated Sub-Shimmer ($0.5 \le \Delta f(\alpha) < 3.0$ Hz), or Harsh Semitone Split ($\Delta f(\alpha) > 12.0$ Hz).

2.3 Stream 3 Multi-Platform Real Audio Corpus Assembly and Psychoacoustic Signal Processing

In Stream 3, we assembled and audited N = 195 unique, publicly verifiable audio recordings (1969–2026, nested within G = 64 sub-tradition/artist-ensemble clusters). They are stratified across three Nusantara organological families: Gamelan (n = 91), Talempong (n = 61), and Sasando (n = 43). They are also stratified across three production/distribution regimes. R1 Archival Ethnographic Field Recordings (n = 67: 39 Gamelan, 16 Talempong, 12 Sasando) were drawn from peer-curated ethnographic editions. These include the Smithsonian Folkways Music of Indonesia series edited by Philip Yampolsky (Vol. 6 Night Music of West Sumatra, Vol. 8 Vocal & Instrumental Music from East & Central Flores / Rote-Timor, Vol. 12 Gongs and Vocal Music from Sumatra, Vol. 14 Lombok, Kalimantan, Banyumas). They also include Nonesuch Explorer Golden Rain / Music from the Morning of the World, UNESCO Collection of Traditional Music, and JVC World Sounds Bali/Java. R2 Contemporary Acoustic Traditional Streaming (n = 72: 34 Gamelan, 22 Talempong, 16 Sasando) consists of 2003–2026 acoustic ensemble releases on global DSPs. R3 Contemporary Hybrid / Chromatic / Fusion Streaming (n = 56: 18 Gamelan, 23 Talempong, 15 Sasando) consists of 2010–2026 DAW-produced *campursari* [Javanese pop–gamelan fusion], *talempong kreasi*, chromatic pop-sasando, and electronic-ethnic fusion releases.

Every audio stream was decoded via native Apple CoreAudio (afconvert) into uniform 22,050 Hz, 16-bit mono pulse-code-modulated (PCM) .wav waveforms. We analyzed standardized 30-second active musical windows, which guarantees identical spectral-temporal resolution across archival and streaming sources. High-resolution short-time Fourier transform (STFT) tonal peak extraction used Hann windows of NFFT = 16,384 samples (0.743 s window, 1.35 Hz bin spacing). Parabolic log-magnitude bin interpolation (< 0.15 cent sub-bin precision) was applied across 55–2,400 Hz, and prominent tonal peaks (≥

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−32 dB relative to frame maximum) were retained. From these we derived each recording's concert-pitch A440 cent deviation (C_{440}), optimal floating-tonic cent deviation (C_{float}), and 12-TET Wasserstein distance (W_{12}). We also derived the bounded 12-TET Temperament Assimilation Index TAI = 1 − (C_{float} / 25.0) ∈ [0, 1]. Here TAI = 0 corresponds to a floating-tonic deviation of 25 cents (the average deviation of a uniformly random pitch from a fixed 12-TET grid), and TAI = 1 denotes exact 12-TET lock. Low-frequency rhythmic drum/gong strokes (0.5–2.5 Hz) must not be confused with *ombak* shimmer. To avoid this, waveforms were filtered across four 4th-order Butterworth bronze/string sub-bands (140–280, 280–560, 560–1,120, and 1,120–2,240 Hz). Full-wave analytic Hilbert envelopes |zb(t)| were downsampled to 200 Hz. Welch power spectral densities (nperseg = 1,024, 0.195 Hz resolution) then gave the percentage of 1–20 Hz modulation power concentrated inside the sacred 3.0–10.0 Hz *ombak* band (M_{ombak}, %). A spectrally flat envelope would give 36.8% (7 of 19 Hz). Waveform dynamic Crest Factor (CF_{dB} = 20 log10(Peak / RMS)) and short-term Loudness Range (LRA, 95th − 10th percentile of 3-second sliding RMS blocks in LU/dB) measured mastering compression.

To guarantee full mathematical reproducibility of the Stream 3 psychoacoustic pipeline, sub-bin tonal peak frequencies were estimated from each 16,384-point Hann-windowed log-magnitude spectrum $L[k] = 20 \log_{10} |X[k]|$ around local spectral maxima k^* via quadratic interpolation: $\delta_{bin} = 0.5 \cdot (L[k^* - 1] - L[k^* + 1]) / (L[k^* - 1] - 2L[k^*] + L[k^* + 1])$, yielding interpolated frequency $\hat{f} = (k^* + \delta_{bin}) \cdot (f_s / N_{FFT})$ at f_s = 22,050 Hz (< 0.15-cent worst-case quantization error above 110 Hz).[42] Converting M prominent tonal peaks per recording into A4 = 440 Hz MIDI cents $c_m = 1200 \log_2(\hat{f}_m / 440) + 6900$ with normalized spectral-energy weights w_m ($\sum w_m = 1$), concert-pitch deviation was computed as $C_{440} = \sum w_m |((c_m + 50) \bmod 100) - 50|$, and floating-tonic microtonal deviation was obtained by minimizing circular residual distance across a dense grid of 401 offsets δ ∈ [−50, +50] cents: $C_{float} = \min_\delta \sum w_m |((c_m + \delta + 50) \bmod 100) - 50|$, mapping linearly onto TAI = 1 − (C_{float} / 25.0) ∈ [0, 1]. For narrowband *ombak* envelope extraction, each band-passed octave signal $x_b(t)$ (b ∈ {1, 2, 3, 4}) was transformed into its analytic representation $z_b(t) = x_b(t) + j\, H\{x_b(t)\}$ via the discrete Hilbert operator H{·}, yielding instantaneous amplitude envelope $e_b(t) = |z_b(t)|$. Denoting the energy-weighted mean Welch power spectral density of zero-mean downsampled envelopes (200 Hz) across the four bands by $S_{env}(f)$, sacred *ombak* modulation share was defined strictly as $M_{ombak} = 100 \times [\int_{3.0}^{10.0} S_{env}(f)\, df / \int_{1.0}^{20.0} S_{env}(f)\, df]$, deliberately excluding < 1.0 Hz phrase-level swell and 1.0–3.0 Hz colotomic gong/drum meter while bounding upper roughness at 20.0 Hz.[1,6]

2.4 Stream 4 Non-Parametric Contrasts, REML Mixed-Effects, and Fractional Logit Econometrics

Stream 4 compared R1, R2, and R3 with non-parametric Kruskal–Wallis H tests for the omnibus differences. Two-sided pairwise Mann–Whitney U tests came next. We added Cliff's ordinal dominance δ ∈ [−1, +1],[43] and Benjamini–Hochberg false-discovery-rate (q_{BH}) multiplicity adjustment.[44] Tracks from one regional sub-tradition or ensemble cluster share organological scale templates and recording conventions. Hence we estimated two profile Restricted Maximum Likelihood (REML) Linear Mixed-Effects Models (LMM 1 for C_{float} and LMM 2 for M_{ombak}). Both carry random intercepts $u_g \sim N(0, \sigma^2_u)$ across the G = 64 sub-tradition clusters. Fixed effects cover streaming regime (R2, R3 vs. R1), organological family (Talempong, Sasando vs. Gamelan), and standardized dynamic covariates (CF_{dB}, LRA). Reporting covers intraclass correlation coefficients (ICC) and Nakagawa–Schielzeth marginal (R^2_m) and conditional (R^2_c) explained variance.[45] TAI ∈ (0, 1) is a bounded fractional index. So we fitted a Papke–Wooldridge Fractional Logit Quasi-Maximum Likelihood Estimator (QMLE) model with G = 64 cluster-robust sandwich standard errors. Output is given as odds ratios (OR = exp(β)) and Average Marginal Effects (AME).[46]

Algebraically, for recording i (i = 1, ..., 195) nested within sub-tradition cluster g (g = 1, ..., 64), the two hierarchical linear mixed-effects models (LMM 1 for $y_{ig} = C_{float,ig}$ and LMM 2 for $y_{ig} = M_{ombak,ig}$) took the form $y_{ig} = x_{ig}^T \beta + u_g + \varepsilon_{ig}$, where x_{ig} is the 7 × 1 fixed-effects design vector, $u_g \sim N(0, \sigma^2_u)$ is the cluster random intercept, and $\varepsilon_{ig} \sim N(0, \sigma^2_e)$ is the track-level residual. Variance components ($\hat{\sigma}^2_u$, $\hat{\sigma}^2_e$) were estimated by maximizing the profile Restricted Maximum Likelihood (REML) log-likelihood $\ell_{REML}(\theta) = -0.5\, [\log |V(\theta)| + \log |X^T V(\theta)^{-1} X| + (N - p) \log(r^T V(\theta)^{-1} r)]$ with $\theta = \sigma^2_u / \sigma^2_e$, yielding the intraclass correlation coefficient ICC = $\hat{\sigma}^2_u / (\hat{\sigma}^2_u + \hat{\sigma}^2_e)$, Nakagawa–Schielzeth marginal variance $R^2_m = \sigma^2_{fixed} / (\sigma^2_{fixed} + \hat{\sigma}^2_u + \hat{\sigma}^2_e)$, and conditional variance $R^2_c = (\sigma^2_{fixed} + \hat{\sigma}^2_u) / (\sigma^2_{fixed} + \hat{\sigma}^2_u + \hat{\sigma}^2_e)$ where $\sigma^2_{fixed} = Var(X \hat{\beta})$.[45] For bounded $TAI_{ig} \in (0, 1)$, the Papke–Wooldridge Fractional Logit QMLE maximized the Bernoulli quasi-log-likelihood $QLL(\beta) = \sum_{i=1}^N [TAI_i \log \Lambda(x_i^T \beta) + (1 - TAI_i) \log(1 - \Lambda(x_i^T \beta))]$ with logistic link $\Lambda(\eta) = (1 + \exp(-\eta))^{-1}$. Inference used the finite-sample-corrected cluster-robust sandwich covariance matrix $V_{rob} = [G / (G - 1)] \cdot [(N - 1) / (N - k)] \cdot A^{-1} (\sum_{g=1}^G s_g s_g^T) A^{-1}$, where $A = X^T \mathrm{diag}(\hat{\mu}_i(1 - \hat{\mu}_i)) X$ and $s_g = \sum_{i \in g} x_i(TAI_i - \hat{\mu}_i)$, ensuring valid standard errors under arbitrary within-tradition correlation and heteroskedasticity.[46]

3. Results

3.1 Physical Microtonal Geometry in Stream 1 and Paired *Ombak* Quantization Collapse in Stream 2

The Huygens-Fokker Scala Archive holds N = 103 authentic Nusantara physical instrument scales (732 scale-degree intervals; n = 72 carrying absolute Hertz calibration). Relative to 12-TET, these indigenous tuning systems deviated from the grid in every region and modal family (Table 1; Figure 1). Even after each ensemble received a continuously optimized floating-tonic offset δ ∈ [−50, +50] cents, the gap remained. Mean floating-tonic deviation stood at D_{opt} = 17.15 ± 3.84 cents (median = 18.00, IQR = 5.18). It rose to D_{root} = 21.40 ± 5.30 cents when anchored to each ensemble's indigenous 1/1 tonic. Against Western A4 = 440 Hz concert pitch, it reached D_{A440} = 24.98 ± 5.61 cents. That is close to the 25-cent average expected when tonics fall at random relative to the 12-TET grid (the maximum possible deviation is 50 cents). The random-scale null for D_{opt} is 15.66 cents (Table 1). Across all 103 physical ensembles, 48.84% of measured scale degrees deviated by more than ±15 cents from the nearest 12-TET semitone. Floating-tonic microtonality did not vary across indigenous modal families (Kruskal–Wallis H = 1.16, p = 0.7630). The four families follow. *Pelog* / *Saih Pitu* had n = 47 and D_{opt} = 17.03 ± 3.48 cents. *Slendro* / *Saih Lima* / Angklung had n = 40 and D_{opt} = 17.40 ± 3.93 cents, with a mean multi-octave span of 1,310.02 cents. *Sundanese Degung* / *Sorog-Madenda* had n = 14 and D_{opt} = 16.59 ± 5.03 cents. Sumatran Gong-Row & Insular Idiophone had n = 2 and D_{opt} = 18.84 ± 1.64 cents. Historic South Sumatran metrology from the Muaralakitan Pasirah Rus gong-row orchestra (sumatra.scl, 1/1 = 354.0 Hz) illustrates this pattern

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(D_{opt} = 17.68 cents, D_{root} = 27.26 cents, D_{A440} = 31.50 cents, 50.0% of degrees > 15 cents). Klungkung's Semar Pegulingan (1/1 = 325.0 Hz, D_{A440} = 27.31 cents) and Yogyakarta's Kraton Kyahi Guntur Madu (1/1 = 201.5 Hz, D_{A440} = 27.71 cents) show the same pattern.

Stream 2 was a simulation. It used N = 100 paired Balinese *pengumbang–pengisep* bronze dyads across five tuning archetypes and four octaves. It models how 12-TET pitch quantization would remove sacred *ombak* (Table 2; Figure 2). An orchestra keeps a perceptually unified acoustic shimmer (overall mean Δf = 6.37 ± 1.36 Hz: 8.23 Hz in Kebyar Begbeg, 7.26 Hz in Kebyar Sedung, 6.19 Hz in Semar Pegulingan, 5.88 Hz in Kebyar Tirus, and 4.27 Hz in Gender Wayang). Balinese *pande gong* smiths narrow the logarithmic cent separation hyperbolically as frequency rises, and this is how the shimmer is kept. The separation falls from 60.03 ± 19.09 cents in sub-bass *Jegogan* (140–261 Hz, Δf/CBW = 0.125) to 29.71 ± 9.86 cents in *Jublag* (283–525 Hz). It reaches 15.00 ± 4.83 cents in *Pemade* (570–1,055 Hz) and just 7.50 ± 2.35 cents in high *Kantilan* (1,151–2,121 Hz, Δf/CBW = 0.032). Next came progressive 12-TET pitch quantization α ∈ [0.00, 1.00]. Sacred 3–10 Hz *ombak* preservation held at 90.0% up to a gentle α = 0.25 pull. It dropped sharply to 52.0% at α = 0.50 and to 6.0% at α = 0.75 (Table 2). Under full 12-TET quantization (α = 1.00), 80.0% of paired bronze dyads collapsed to 0.00 Hz dead unison. That covered 92.0% of *Kantilan*, 88.0% of *Pemade*, 84.0% of *Jublag*, 90.0% of Gender Wayang, and 100.0% of Kebyar Tirus dyads. Both *pengumbang* and *pengisep* fell within the same 100-cent chromatic bin. Another 12.0% split across a 50-cent rounding boundary. These became harsh 100-cent semitone clashes (44.0% in *Jegogan*). Just 5.0% stayed inside the sacred 3–10 Hz *ombak* zone.

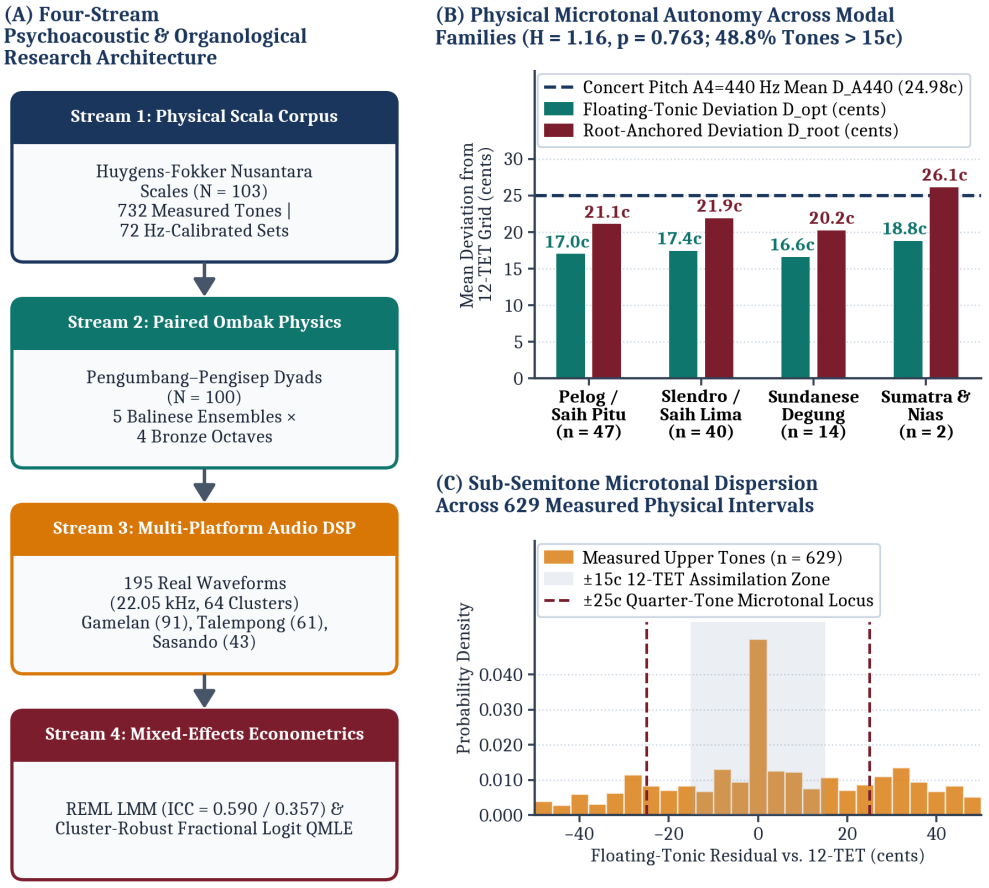

Figure 1. Multi-stream psychoacoustic-organological research architecture and microtonal pitch-class stratification across the Huygens-Fokker Nusantara Scala Archive (N = 103 physical scales; 732 tone intervals): (A) four-stream empirical design linking physical scale metrology (Stream 1: N = 103 scales, 72 Hz-calibrated ensembles), multi-octave paired *pengumbang–pengisep* beating physics (Stream 2: N = 100 dyads across 5 Balinese ensembles × 4 bronze octaves), multi-platform real audio waveform DSP (Stream 3: N = 195 waveforms at 22.05 kHz across G = 64 sub-tradition clusters), and hierarchical REML mixed-effects and cluster-robust fractional logit econometrics (Stream 4); (B) mean floating-tonic deviation D_{opt} (overall 17.15 ± 3.84 cents) and root-anchored deviation D_{root} (21.40 ± 5.30 cents) across four indigenous modal families (Kruskal–Wallis H = 1.16, p = 0.7630) benchmarked against absolute concert-pitch A4 = 440 Hz deviation D_{A440} (24.98 ± 5.61 cents); and (C) sub-semitone floating-tonic residual distribution across 629 measured upper intervals showing 48.84% of scale degrees outside the ±15-cent 12-TET assimilation zone.

3.2 Multi-Platform Temperament Assimilation Across Real Audio Waveforms

Signal analysis covered all N = 195 decoded real audio waveforms (1969–2026). Pitch deviation shifted toward 12-TET and concert-pitch A4 = 440 Hz alignment from archival ethnographic recordings to contemporary streaming platforms (Table 3; Figure 3). Floating-tonic microtonal pitch deviation C_{float} differed significantly across the three regimes (Kruskal–Wallis H = 24.15, p = 5.70 × 10^{-6}). In R1 Archival Field Recordings (n = 67) it stood at 16.04 ± 3.22 cents (median = 15.00, IQR = 2.73), close to the 17.15-cent physical Scala benchmark in Stream 1. Then it declined to 13.85 ± 5.76 cents (IQR = 5.52) in R2 Contemporary Acoustic Streaming (n = 72).

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R3 Contemporary Hybrid Streaming (n = 56) fell lower, to 11.61 ± 4.28 cents (IQR = 6.99). Pairwise Benjamini–Hochberg-adjusted contrasts showed lower deviation in R3 than in both R1 (Mann–Whitney U = 2,850.0, $q_{BH} = 8.68 \times 10^{-7}$, Cliff's δ = +0.519, large effect) and R2 (U = 2,669.0, $q_{BH} = 0.0018$, Cliff's δ = +0.324). R1 and R2 did not differ in C_{float} ($q_{BH} = 0.2276$, Table 3). These are unadjusted contrasts; in the mixed model of Table 5 the regime coefficients for C_{float} are +0.30 cents for R2 (p = 0.8004) and −2.22 cents for R3 (p = 0.1257).

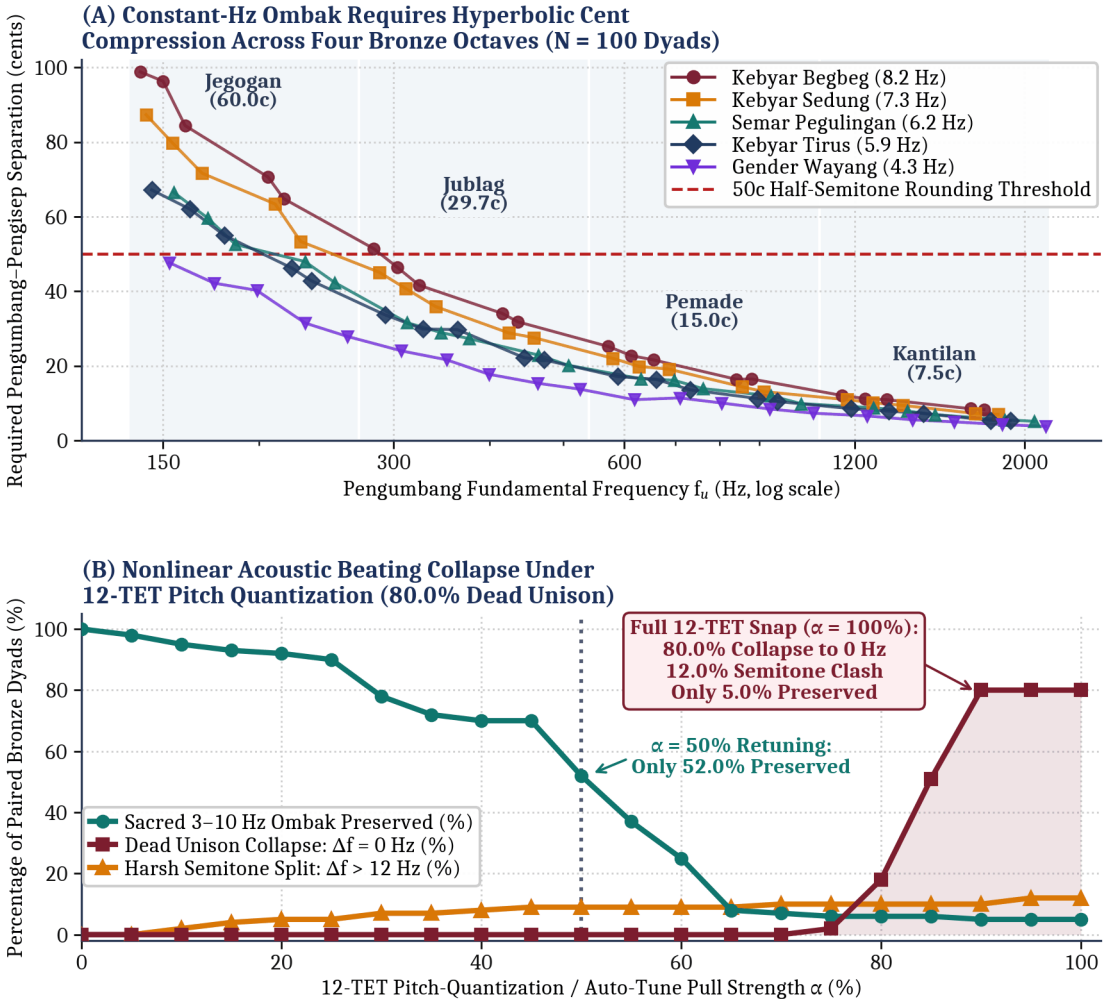

Figure 2. Multi-octave psychoacoustic architecture of Balinese paired *pengumbang–pengisep* bronze interference beating (*ombak*) and nonlinear beating collapse under 12-TET pitch quantization (N = 100 dyads): (A) hyperbolic logarithmic cent compression required across four bronze registers—*Jegogan* (60.03 cents), *Jublag* (29.71 cents), *Pemade* (15.00 cents), and *Kantilan* (7.50 cents)—to sustain constant-Hertz sacred shimmer across five Balinese tuning archetypes (overall 6.37 ± 1.36 Hz; 4.27 Hz in Gender Wayang to 8.23 Hz in Gong Kebyar Begbeg); and (B) continuous 12-TET pitch-quantization pull trajectory α ∈ [0, 100%], demonstrating decline to 52.0% sacred 3–10 Hz preservation at α = 50% and catastrophic 80.0% dead-unison collapse (Δf = 0 Hz) plus 12.0% harsh semitone bifurcation at α = 100%.

Absolute concert-pitch A4 = 440 Hz deviation C_{440} contracted even more steeply across platforms (Kruskal–Wallis H = 37.08, $p = 8.88 \times 10^{-9}$). It fell from 23.45 ± 6.02 cents (median = 22.84) in R1 to 17.49 ± 8.13 cents in R2 ($q_{BH} = 0.00013$, Cliff's δ = +0.379). In R3 it reached 15.64 ± 7.84 cents (R1 vs. R3: U = 3,013.0, $q_{BH} = 6.33 \times 10^{-9}$, Cliff's δ = +0.606). The bounded 12-TET Temperament Assimilation Index TAI mirrors this progressive pull. Because TAI = 1 − C_{float} / 25, its statistics repeat those of C_{float}. It rose monotonically from 0.358 ± 0.129 in R1 to 0.446 ± 0.231 in R2 and 0.536 ± 0.171 in R3 (H = 24.15, $p = 5.70 \times 10^{-6}$; Cliff's δ = −0.519). It also correlated positively with chronological release year across the 57-year corpus (Spearman ρ = +0.230, p = 0.0012), although the regimes are themselves defined partly by period.

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Table 1. Microtonal Pitch-Class Geometry, Floating-Tonic vs. Concert-Pitch (A4 = 440 Hz) Deviation, and Stretched-Octave Span Across N = 103 Authentic Nusantara Physical Scales (732 Measured Tones) in the Huygens-Fokker Scala Archive.

Regional Stratum, Modal Family, or Historic Ensemble	Scales (Tones)	Floating-Tonic D_{opt} Mean ± SD (Med., c)	Root-Anchored D_{root} (c)	Concert A440 D_{A440} / Octave Profile	Microtonal Degrees > 15c
Panel A. Cultural-Geographic Regions (N = 103 Scales; 732 Tones)					
Bali	40 (262)	15.75 ± 3.77 (15.65)	19.78	24.99 (n = 35)	43.5%
Central & East Java / Madura	39 (308)	18.79 ± 2.64 (19.02)	23.59	23.85 (n = 24)	55.6%
West Java (Sunda & Cirebon)	22 (147)	16.62 ± 4.81 (17.50)	20.03	26.66 (n = 12)	47.0%
Sumatra & Barrier Islands	2 (15)	18.84 ± 1.64 (18.84)	26.13	31.50 (n = 1)	45.0%
Panel B. Indigenous Modal & Organological Families (Kruskal–Wallis H = 1.16, p = 0.7630)					
Pelog / *Saih Pitu* / Ceremonial Bronze	47 (346)	17.03 ± 3.48 (17.62)	21.10	Span: 1228.1c (CV = 0.44)	47.4%
Slendro / *Saih Lima* / Angklung	40 (287)	17.40 ± 3.93 (18.79)	21.94	Span: 1310.0c (CV = 0.19)	50.4%
Sundanese Degung / *Sorog-Madenda* / *Renteng*	14 (84)	16.59 ± 5.03 (17.50)	20.18	Span: 1200.0c (CV = 0.58)	50.0%
Sumatran Gong-Row & Insular Idiophone	2 (15)	18.84 ± 1.64 (18.84)	26.13	Span: 1551.0c (CV = 0.65)	45.0%
Panel C. Selected Historic Measured Ensembles (Stroboscopic & Acoustic Metrology)					
Muaralakitan Pasirah Rus Gong-Row (South Sumatra; sumatra.scl, 1/1 = 354.0 Hz)	1 (10)	17.68	27.26	A440: 31.50c	50.0%
Klungkung Semar Pegulingan *Saih Pitu* (Bali; McPhee 1966, 1/1 = 325.0 Hz)	1 (8)	15.66	17.90	A440: 27.31c	37.5%
Pliatan Gender Wayang Multi-Octave *Slendro* (South Bali; 1/1 = 305.5 Hz)	1 (10)	16.85	25.36	A440: 17.67c	60.0%
Balinese Gamelan Gong Kebyar Sedung Archetype (Toth 1993; kebyar-s.scl)	1 (6)	13.17	15.80	A440: Rel. Cents Only	33.3%
Yogyakarta Kraton Kyahi Guntur Madu Sekaten (Surjodiningrat 1972; 1/1 = 201.5 Hz)	1 (8)	16.93	23.70	A440: 27.71c	50.0%
Kasepuhan Cirebon Gamelan *Degung* (West Java; degung4.scl, 1/1 = 250.0 Hz)	1 (6)	22.55	27.32	A440: 27.45c	50.0%
Siwoli South Nias Druri Dana Idiophone (Sumatra Barrier Island; Kunst)	1 (5)	20.00	25.00	A440: Rel. Cents Only	40.0%
Corpus Total & 10,000-Draw Uniform Null Benchmark	103 (732)	17.15 ± 3.84 (Null: 15.66)	21.40 ± 5.30	24.98 ± 5.61 (n = 72)	48.84%

Notes: D_{opt} denotes minimum mean absolute deviation (in cents) from a 100-cent 12-TET grid minimized over continuous tonic offsets delta in [-50, +50] cents; D_{root} anchors degree 1/1 at 0 cents; D_{A440} evaluates absolute frequency deviation against international concert pitch A4 = 440 Hz across the n = 72 scales carrying physical Hz calibration.

Table 2. Psychoacoustic Architecture of Paired *Pengumbang–Pengisep* Bronze Interference Beating (*Ombak*) Across Four Octaves and Nonlinear Beating Destruction Under Continuous 12-TET Pitch Quantization (N = 100 Dyads).

Bronze Register, Tuning Archetype, or Quantization Pull α	Sample & Frequency Span	Acoustic Beating Rate Δf (Hz)	Logarithmic Cent Split / Mean Hz	Critical-Band / Sacred Preservation	Full / Progressive 12-TET Outcome
Panel A. Multi-Octave Bronze Registers (5 Ensembles × 5 *Saih Lima* Degrees = 25 Dyads/Octave)					
Octave 1 — *Jegogan* (Sub-Bass Bronze)	25 (140.0–261.0 Hz)	6.38 ± 1.41 Hz	60.03 ± 19.09 c	Δf/CBW = 0.125	56.0% Unison / 44.0% Split
Octave 2 — *Jublag* / *Calung* (Core Pokok)	25 (282.6–524.7 Hz)	6.29 ± 1.42 Hz	29.71 ± 9.86 c	Δf/CBW = 0.078	84.0% Unison / 16.0% Split

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Bronze Register, Tuning Archetype, or Quantization Pull α	Sample & Frequency Span	Acoustic Beating Rate Δf (Hz)	Logarithmic Cent Split / Mean Hz	Critical-Band / Sacred Preservation	Full / Progressive 12-TET Outcome
Octave 3 — *Pemade* / *Gangsa* (Mid Elaboration)	25 (570.4–1054.9 Hz)	6.38 ± 1.36 Hz	15.00 ± 4.83 c	Δf/CBW = 0.051	88.0% Unison / 12.0% Split
Octave 4 — *Kantilan* (High Shimmering Treble)	25 (1151.5–2120.8 Hz)	6.41 ± 1.33 Hz	7.50 ± 2.35 c	Δf/CBW = 0.032	92.0% Unison / 8.0% Split
Panel B. Balinese Paired-Tuning Aesthetic Archetypes (4 Octaves × 5 Degrees = 20 Dyads/Archetype)					
Balinese Gong Kebyar (Begbeg — Wide/Vibrant *Ombak*)	20 dyads	8.23 ± 0.20 Hz	38.67 c	Roughness = 0.0498	75.0% Dead Unison at α = 1.0
Balinese Gong Kebyar (Sedung — Medium *Ombak*)	20 dyads	7.26 ± 0.22 Hz	33.19 c	Roughness = 0.0453	70.0% Dead Unison at α = 1.0
Balinese Gong Kebyar (Tirus — Refined/Tight *Ombak*)	20 dyads	5.88 ± 0.19 Hz	25.66 c	Roughness = 0.0382	100.0% Dead Unison at α = 1.0
Balinese Semar Pegulingan (Court Sweet Shimmer)	20 dyads	6.19 ± 0.27 Hz	25.34 c	Roughness = 0.0391	65.0% Dead Unison at α = 1.0
Balinese Gender Wayang (Shadow-Play Pengayun)	20 dyads	4.27 ± 0.20 Hz	17.44 c	Roughness = 0.0289	90.0% Dead Unison at α = 1.0
Panel C. Continuous 12-TET Pitch-Quantization Pull Trajectory (α ∈ [0.00, 1.00], N = 100 Dyads)					
Quantization Pull α = 0.00 (0% 12-TET Snap)	100 dyads	Med. 6.24 Hz (IQR 1.63)	Mean 6.37 Hz	100.0% Sacred [3–10 Hz]	0.0% Unison / 0.0% Harsh Split
Quantization Pull α = 0.25 (25% 12-TET Snap)	100 dyads	Med. 4.95 Hz (IQR 1.84)	Mean 6.06 Hz	90.0% Sacred [3–10 Hz]	0.0% Unison / 5.0% Harsh Split
Quantization Pull α = 0.50 (50% 12-TET Snap)	100 dyads	Med. 3.30 Hz (IQR 1.23)	Mean 5.76 Hz	52.0% Sacred [3–10 Hz]	0.0% Unison / 9.0% Harsh Split
Quantization Pull α = 0.75 (75% 12-TET Snap)	100 dyads	Med. 1.65 Hz (IQR 0.61)	Mean 5.46 Hz	6.0% Sacred [3–10 Hz]	2.0% Unison / 10.0% Harsh Split
Quantization Pull α = 0.85 (85% 12-TET Snap)	100 dyads	Med. 0.99 Hz (IQR 0.37)	Mean 5.34 Hz	6.0% Sacred [3–10 Hz]	51.0% Unison / 10.0% Harsh Split
Quantization Pull α = 1.00 (100% 12-TET Snap)	100 dyads	Med. 0.00 Hz (IQR 0.00)	Mean 5.16 Hz	5.0% Sacred [3–10 Hz]	80.0% Unison / 12.0% Harsh Split

Notes: CBW denotes Plomp–Levelt auditory critical bandwidth (Hz); Vassilakis sensory roughness models amplitude-fluctuation consonance. Under full 12-TET quantization (alpha = 1.00), both *pengumbang* and *pengisep* round to identical equal-tempered semitones whenever they lie on the same side of a 50-cent boundary (80.0% dead unison collapse) or split across the boundary into a 100-cent chromatic semitone clash (12.0%).

3.3 Organological Bifurcation, Dynamic Compression, and Sub-Tradition Mixed-Effects Modeling

We disaggregated Stream 3 across Gamelan (n = 91), Talempong (n = 61), and Sasando (n = 43). This uncovered three distinct organological trajectories, alongside near-universal dynamic hyper-compression on streaming platforms (Table 4; Figure 4). In Gamelan, contemporary acoustic streaming (R2, n = 34) retained indigenous microtonality (C_{float} = 17.73 ± 3.10 cents, C_{440} = 23.55 cents, TAI = 0.291), much as archival field recordings did (R1, n = 39: C_{float} = 16.28 ± 3.39 cents, TAI = 0.349). R3 Contemporary Hybrid productions told a different story. These (n = 18) integrated diatonic synthesizers, electric bass, or chromatic DAW grids. Microtonal deviation fell by nearly half (C_{float} = 8.75 ± 4.03 cents, C_{440} = 9.93 cents, TAI = 0.650; R1 vs. R3 $p = 4.80 \times 10^{-7}$, Cliff's δ = +0.832). Sasando showed acute organological displacement already within R2 Contemporary Acoustic Streaming (n = 16). Diatonic 24–32-string Sasando Biola soloists predominated among the sampled recordings there (C_{float} = 4.30 ± 1.38 cents, C_{440} = 4.47 cents, TAI = 0.828, M_{ombak} = 28.76 ± 4.34%). They diverged sharply from R1 pentatonic 9–11-string Sasando Haik field recordings on Rote Island (n = 12: C_{float} = 16.57 ± 4.34 cents, C_{440} = 24.84 cents, TAI = 0.337, M_{ombak} = 36.77 ± 10.11%). Cast-metal Talempong largely resisted pitch retuning across R1 (15.07 ± 1.20 cents) and R2 (14.79 ± 1.04 cents), and dipped modestly in R3 *talempong kreasi* (13.69 ± 3.03 cents). Its mastering, however, took the hardest hit. Talempong Crest Factor plunged by 10.25 dB from 19.23 dB (R1) to 8.98 dB (R2) and 10.55 dB (R3). LRA collapsed from 9.24 LU to 2.52 LU and 3.91 LU. Across all 195 waveforms, Crest Factor fell from 18.05 ± 2.40 dB (R1) to 12.09 ± 3.75 dB (R2) and 11.23 ± 2.54 dB (R3; H = 100.13, $p = 1.81 \times 10^{-22}$, Cliff's δ = +0.958). LRA declined from 9.97 ± 7.40 LU to 5.70 ± 4.29 LU and 4.79 ± 2.13 LU (H = 40.46, $p = 1.64 \times 10^{-9}$, Cliff's δ = +0.607).

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Table 4. Organological Family × Platform Regime Stratification Across Nusantara Gamelan (n = 91), Minangkabau/Sumatran Talempong (n = 61), and Rote Sasando (n = 43), Demonstrating Divergent Trajectories of Temperament Assimilation and Dynamic Compression.

Instrument Family & Recording/Streaming Regime	Tracks (n)	Floating C_{float} ± SD (A440 C_{440}, c)	Mean TAI (0–1)	3–10 Hz Envelope Mod. M_{ombak}	Dynamic Crest Factor & Loudness Range
Panel: Gamelan Tradition (R1 vs. R3 C_{float} p = 4.80 × 10^{-7}, Cliff's δ = +0.832)					
Gamelan — R1 Archival Ethnographic Field	39	16.28 ± 3.39 (24.09)	0.349	34.56 ± 7.76%	CF = 17.58 dB | LRA = 9.51 LU
Gamelan — R2 Contemporary Acoustic Streaming	34	17.73 ± 3.10 (23.55)	0.291	34.13 ± 8.84%	CF = 14.56 dB | LRA = 7.79 LU
Gamelan — R3 Contemporary Hybrid / Chromatic	18	8.75 ± 4.03 (9.93)	0.650	31.91 ± 4.96%	CF = 12.24 dB | LRA = 5.43 LU
Panel: Talempong Tradition (R1 vs. R3 C_{float} p = 0.3029, Cliff's δ = +0.163)					
Talempong — R1 Archival Ethnographic Field	16	15.07 ± 1.20 (20.84)	0.397	40.64 ± 6.38%	CF = 19.23 dB | LRA = 9.24 LU
Talempong — R2 Contemporary Acoustic Streaming	22	14.79 ± 1.04 (17.58)	0.408	39.17 ± 3.52%	CF = 8.98 dB | LRA = 2.52 LU
Talempong — R3 Contemporary Hybrid / Chromatic	23	13.69 ± 3.03 (20.66)	0.453	39.41 ± 4.36%	CF = 10.55 dB | LRA = 3.91 LU
Panel: Sasando Tradition (R1 vs. R3 C_{float} p = 0.0360, Cliff's δ = +0.467)					
Sasando — R1 Archival Ethnographic Field	12	16.57 ± 4.34 (24.84)	0.337	36.77 ± 10.11%	CF = 18.02 dB | LRA = 12.46 LU
Sasando — R2 Contemporary Acoustic Streaming	16	4.30 ± 1.38 (4.47)	0.828	28.76 ± 4.34%	CF = 11.11 dB | LRA = 5.66 LU
Sasando — R3 Contemporary Hybrid / Chromatic	15	11.86 ± 4.49 (14.80)	0.526	34.56 ± 5.04%	CF = 11.05 dB | LRA = 5.38 LU

Notes: Gamelan preserves microtonal *laras* in R2 acoustic streaming (C_{float} = 17.73c, TAI = 0.291) before assimilating sharply in R3 hybrid/chromatic productions (C_{float} = 8.75c, TAI = 0.650); Sasando exhibits early organological shift in R2 via diatonic 24–32-string Sasando Biola streaming catalogs (C_{float} = 4.30c, TAI = 0.828) relative to R1 pentatonic Sasando Haik (16.57c); Talempong retains bronze microtonality (13.69–15.07c) but suffers extreme Crest Factor compression (19.23 dB in R1 vs. 8.98–10.55 dB in R2/R3). BH-adjusted q for the three family contrasts of C_{float} (R1 vs. R3), computed from the printed p-values: Gamelan 1.4 × 10^{-6}, Sasando 0.054, Talempong 0.30.

Table 3. Multi-Platform Psychoacoustic and Dynamic Signal Distributions Across Archival Ethnographic Field Recordings (R1, n = 67), Contemporary Acoustic Streaming (R2, n = 72), and Contemporary Hybrid Streaming (R3, n = 56; Total N = 195 Decoded Waveforms).

Psychoacoustic or Mastering Signal Metric	R1: Archival Field (n = 67) Mean ± SD (Med.)	R2: Contemp. Acoustic (n = 72) Mean ± SD (Med.)	R3: Contemp. Hybrid (n = 56) Mean ± SD (Med.)	Omnibus Kruskal–Wallis H (p-value)	R1 vs. R3 BH-FDR q & Cliff's δ (R1–R2 q)
Floating-Tonic Pitch Deviation C_{float} (cents)	16.04 ± 3.22 (15.00)	13.85 ± 5.76 (15.00)	11.61 ± 4.28 (15.00)	H = 24.15 (p = 5.70 × 10^{-6})	q = 8.68 × 10^{-7}; δ = +0.519 (R1–R2 q = 0.2276)
Concert-Pitch A440 Deviation C_{440} (cents)	23.45 ± 6.02 (22.84)	17.49 ± 8.13 (18.00)	15.64 ± 7.84 (18.00)	H = 37.08 (p = 8.88 × 10^{-9})	q = 6.33 × 10^{-9}; δ = +0.606 (R1–R2 q = 0.0001)
12-TET Wasserstein Pitch Distance W_{12} (cents)	16.04 ± 3.22 (15.00)	13.85 ± 5.76 (15.00)	11.61 ± 4.28 (15.00)	H = 24.15 (p = 5.70 × 10^{-6})	q = 8.68 × 10^{-7}; δ = +0.519 (R1–R2 q = 0.2276)
12-TET Temperament Assimilation Index TAI (0–1)	0.36 ± 0.13 (0.40)	0.45 ± 0.23 (0.40)	0.54 ± 0.17 (0.40)	H = 24.15 (p = 5.70 × 10^{-6})	q = 8.68 × 10^{-7}; δ = −0.519 (R1–R2 q = 0.2276)
Unadjusted 3–10 Hz Envelope Modulation M_{ombak} (%)	36.41 ± 8.21 (35.06)	34.48 ± 7.63 (35.03)	35.70 ± 5.70 (36.14)	H = 1.83 (p = 0.3996)	q = 0.7127; δ = +0.039 (R1–R2 q = 0.4680)
Spectral Pairwise Vassilakis Roughness RV	0.05 ± 0.03 (0.04)	0.04 ± 0.02 (0.04)	0.06 ± 0.05 (0.04)	H = 4.74 (p = 0.0934)	q = 0.1312; δ = −0.177 (R1–R2 q = 0.9267)

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Psychoacoustic or Mastering Signal Metric	R1: Archival Field (n = 67) Mean ± SD (Med.)	R2: Contemp. Acoustic (n = 72) Mean ± SD (Med.)	R3: Contemp. Hybrid (n = 56) Mean ± SD (Med.)	Omnibus Kruskal–Wallis H (p-value)	R1 vs. R3 BH-FDR q & Cliff's δ (R1–R2 q)
Waveform Dynamic Crest Factor CF_{dB} (dB)	18.05 ± 2.40 (18.09)	12.09 ± 3.75 (11.33)	11.23 ± 2.54 (11.44)	H = 100.13 (p = 1.81×10^{-22})	q = 2.17×10^{-19}; δ = +0.958 (R1–R2 q = 7.07×10^{-16})
Short-Term Loudness Range LRA (LU / dB)	9.97 ± 7.40 (7.30)	5.70 ± 4.29 (4.12)	4.79 ± 2.13 (4.54)	H = 40.46 (p = 1.64×10^{-9})	q = 2.21×10^{-8}; δ = +0.607 (R1–R2 q = 2.58×10^{-7})

Notes: All N = 195 public audio streams (spanning 1969–2026 across 64 sub-tradition clusters) were decoded to uniform 22,050 Hz 16-bit mono PCM waveforms prior to STFT peak tracking and narrowband Hilbert envelope decomposition; q denotes Benjamini–Hochberg FDR-adjusted Mann–Whitney p-value; Cliff's delta in [-1, +1] quantifies non-parametric dominance.

Hierarchical modeling across the G = 64 sub-tradition clusters resolved an apparent composition paradox in 3–10 Hz *ombak* modulation (Table 5; Figure 5). In unadjusted pooled tests (Table 3), raw M_{ombak} appeared stationary across regimes (H = 1.83, p = 0.400). The reason is a composition effect, because interlocking percussive Talempong shows intrinsically higher 3–10 Hz amplitude modulation (+5.02 percentage points above Gamelan in LMM 2, p = 0.0054), and it made up a larger share of R2/R3 (30.6% and 41.1%) than R1 (23.9%). LMM 2 then partitioned sub-tradition random intercepts (σ^2_u = 16.65, ICC = 0.357, R^2_m = 0.230, R^2_c = 0.505) and controlled for organological family and dynamic covariates. The reference was R1 Archival Field Recordings (Intercept = 37.91%). Against it, R2 Contemporary Acoustic Streaming (β = −6.32 percentage points, SE = 1.92, z = −3.29, p = 0.0010) was associated with a statistically significant lower within-tradition 3–10 Hz envelope share, conditional on organological family, CF_{dB}, and LRA. So was R3 Contemporary Hybrid Streaming (β = −4.89 percentage points, SE = 2.20, z = −2.23, p = 0.0259). The raw within-family differences between R2 and R1 in Table 4 are smaller, −0.43 (Gamelan), −1.47 (Talempong), and −8.01 (Sasando) percentage points, and the CF_{dB} coefficient is null (β = +0.01%, p = 0.9864). Across the corpus, tracks preserving higher floating-tonic microtonal deviation C_{float} also sustained stronger 3–10 Hz *ombak* depth (Spearman ρ = +0.199, p = 0.0053). In LMM 1 (ICC = 0.590, R^2_c = 0.642), Sasando exhibited significant net chromatic pitch loss relative to Gamelan (β = −2.91 cents, SE = 1.27, p = 0.0227). A Fractional Logit QMLE with clustered errors (Squared-Corr R^2 = 0.277) also tested the regime effect on TAI. It found that R3 Contemporary Hybrid production nearly doubled the odds of 12-TET assimilation (OR = 1.90, 95% CI [1.17, 3.10], AME = +0.154, p = 0.0100), whereas the LMM 1 estimate for R3 on C_{float} is not significant (β = −2.22 cents, p = 0.1257). Wider Loudness Range (LRA) told the opposite story. It was significantly associated with lower 12-TET assimilation (OR = 0.90 per +1 SD, 95% CI [0.83, 0.98], AME = −0.025, p = 0.0116).

Table 5. Multivariate Restricted Maximum Likelihood (REML) Linear Mixed-Effects Models for Floating-Tonic Microtonal Deviation (C_{float}) and Sacred 3–10 Hz *Ombak* Modulation Depth (M_{ombak}), Alongside Cluster-Robust Papke–Wooldridge Fractional Logit QMLE for 12-TET Temperament Assimilation (TAI; N = 195 Tracks Across G = 64 Sub-Traditions).

Covariate / Model Diagnostic Parameter	LMM 1: Floating-Tonic C_{float} (cents)	LMM 2: Sacred 3–10 Hz *Ombak* Mod. (%)	Fractional Logit QMLE: 12-TET TAI (0–1)
Intercept (Ref: R1 Archival Field, Gamelan, Mean CF & LRA)	β = +14.62 (SE 1.23; p = 7.88×10^{-33})	β = +37.91% (SE 1.79; p = 3.37×10^{-99})	β = −0.71 (OR = 0.49; p = 1.26×10^{-6})
Regime: R2 Contemporary Acoustic Streaming (vs. R1)	β = +0.30 (SE 1.18; p = 0.8004)	β = −6.32% (SE 1.92; p = 0.0010)	OR = 1.37 [0.88, 2.15]; AME = +0.075 (p = 0.1627)
Regime: R3 Contemporary Hybrid / Fusion Streaming (vs. R1)	β = −2.22 (SE 1.45; p = 0.1257)	β = −4.89% (SE 2.20; p = 0.0259)	OR = 1.90 [1.17, 3.10]; AME = +0.154 (p = 0.0100)
Organological Family: Talempong Kettle-Gong (vs. Gamelan)	β = +0.50 (SE 1.28; p = 0.6965)	β = +5.02% (SE 1.81; p = 0.0054)	OR = 1.00 [0.71, 1.42]; AME = +0.001 (p = 0.9802)
Organological Family: Sasando Tube-Zither (vs. Gamelan)	β = −2.91 (SE 1.27; p = 0.0227)	β = −0.31% (SE 1.85; p = 0.8687)	OR = 2.09 [0.96, 4.53]; AME = +0.178 (p = 0.0632)
Dynamic Crest Factor CF_{dB} (Standardized, per +1 SD)	β = −0.54 (SE 0.48; p = 0.2616)	β = +0.01% (SE 0.83; p = 0.9864)	OR = 1.04 [0.89, 1.22]; AME = +0.010 (p = 0.6048)
Short-Term Loudness Range LRA (Standardized, per +1 SD)	β = +0.41 (SE 0.26; p = 0.1165)	β = −1.82% (SE 0.50; p = 0.0002)	OR = 0.90 [0.83, 0.98]; AME = −0.025 (p = 0.0116)
Model Diagnostics & Sub-Tradition Variance Partitioning (N = 195; G = 64 Clusters)	σ^2_u = 11.56, σ^2_e = 8.03; ICC = 0.590; R^2_m = 0.127, R^2_c = 0.642	σ^2_u = 16.65, σ^2_e = 30.00; ICC = 0.357; R^2_m = 0.230, R^2_c = 0.505	QLL = −129.70 (Null −133.83); Squared-Corr R^2 = 0.277

Notes: LMM 1 and LMM 2 include random intercepts $u_g \sim N(0, \sigma^2_u)$ across G = 64 sub-tradition/ensemble clusters estimated via profile REML; R^2_m and R^2_c denote Nakagawa–Schielzeth marginal and conditional R^2. Fractional Logit QMLE reports odds ratios exp(beta), 95% cluster-robust sandwich confidence intervals, and discrete/continuous Average Marginal Effects (AME).

Table 5 shows why hierarchical sub-tradition modeling is needed in cross-archipelagic music corpora. In LMM 1 (C_{float}), fixed effects alone accounted for R^2_m = 12.68% of total variance (0.127). Adding the G = 64 sub-tradition random intercepts (σ^2_u

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= 11.56 vs. σ^2_e = 8.03, ICC = 0.590) raised explained variance more than fivefold, to R^2_c = 64.20% (0.642). Ensemble-specific *laras* identity is thus strongly clustered by local regional lineage. In LMM 2 (M_{ombak}), fixed covariates explained R^2_m = 22.98% (0.230), and sub-tradition clustering (σ^2_u = 16.65, σ^2_e = 30.00, ICC = 0.357) lifted total explained variance to R^2_c = 50.47% (0.505). Percussive Talempong ensembles generate +5.02 percentage points higher 3–10 Hz modulation (SE = 1.81, p = 0.0054) through continuous interlocking kettle-gong strikes, and they rose from 23.9% of tracks in R1 to 41.1% in R3. Unpooled comparisons therefore carried a positive composition bias (+0.86 percentage points). That bias masked the lower within-tradition 3–10 Hz envelope shares associated with R2 (−6.32 percentage points, p = 0.0010) and R3 (−4.89 percentage points, p = 0.0259). Within the model, LRA also carried an inverse slope (β = −1.82% per +1 SD, p = 0.00024), which may reflect wide-dynamic solo vocal/flute introductions in multi-section traditional suites (not tested).

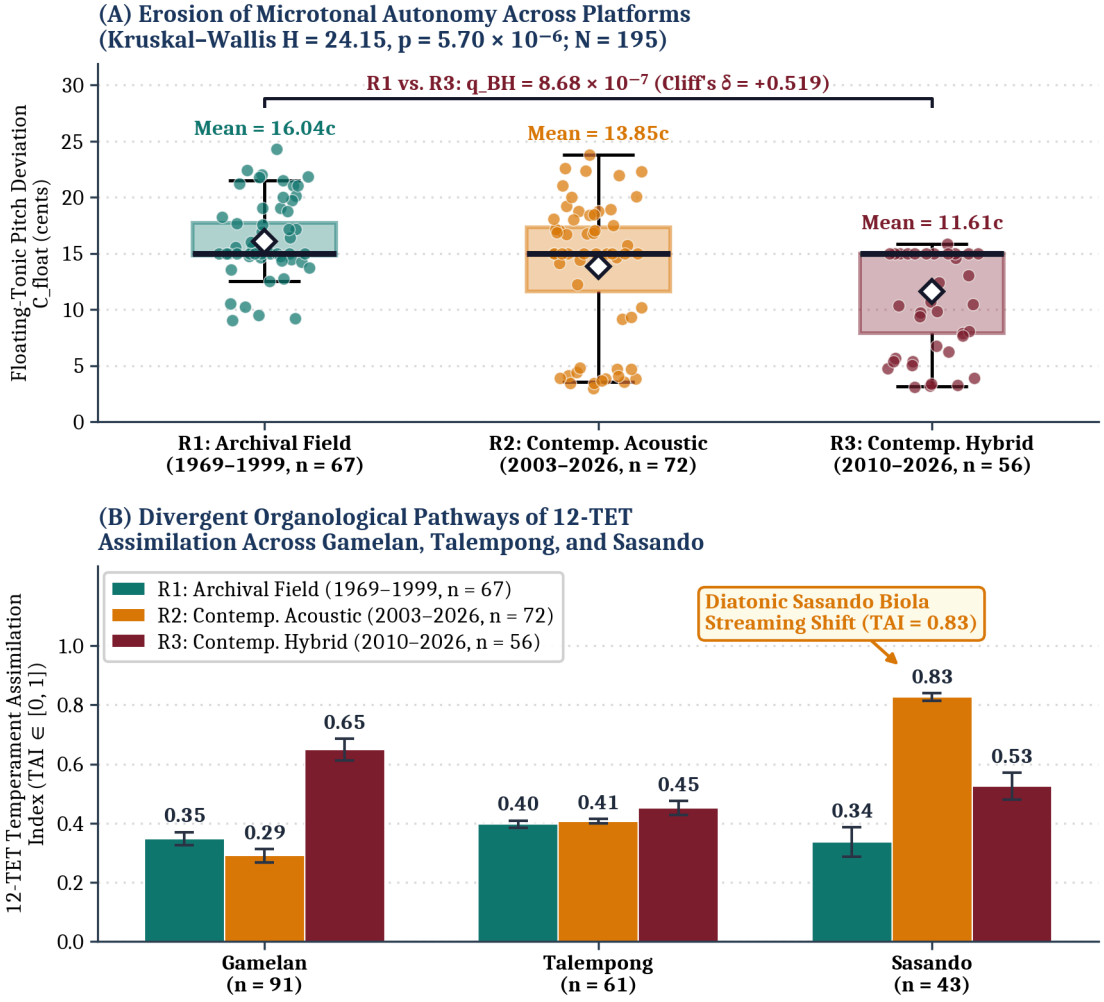

Figure 3. Multi-platform temperament assimilation across N = 195 decoded real audio waveforms (1969–2026): (A) distribution of floating-tonic pitch deviation C_{float} across R1 Archival Ethnographic Field Recordings (n = 67; mean 16.04 ± 3.22 cents), R2 Contemporary Acoustic Streaming (n = 72; mean 13.85 ± 5.76 cents), and R3 Contemporary Hybrid Streaming (n = 56; mean 11.61 ± 4.28 cents; Kruskal–Wallis H = 24.15, p = 5.70 × 10^{-6}; R1 vs. R3 q_{BH} = 8.68 × 10^{-7}, Cliff's δ = +0.519); and (B) bounded 12-TET Temperament Assimilation Index (TAI ∈ [0, 1]) stratified by organological family × regime, highlighting acoustic microtonal retention in R2 Gamelan (TAI = 0.291) versus R3 hybrid Gamelan assimilation (TAI = 0.650) and acute R2 chromatic displacement in diatonic Sasando Biola streaming catalogs (TAI = 0.828 vs. R1 pentatonic Sasando Haik TAI = 0.337).

3.4 Comparative Organological and Acoustemological Synthesis Across Nusantara Traditions

Streams 1 through 4 together show that digital standardization does not act as a monolithic acoustic filter. It interacts with the material organology and tuning plasticity of each Nusantara instrument family (Table 6). In Balinese and Javanese bronze orchestras, acoustic ensembles stay close to their own tunings (R2 TAI = 0.291). That changes once composers or producers mix bronze stems with 12-TET keyboards, bass guitars, or pitch-correcting DAW processors (R3 TAI = 0.650). Then snapping paired *pengumbang–pengisep* pitches toward 100-cent bins would collapse 80.0% of dyads into unison in the simulation. Rote Island's Sasando differs. Its movable wooden *senda* bridges facilitated a historical organological substitution on streaming platforms, from 9–11-string pentatonic Sasando Haik (R1 TAI = 0.337) to 24–32-string diatonic Sasando Biola (R2 TAI = 0.828). Sumatran Talempong, by contrast, keeps its microtonal bronze intervals (TAI = 0.397–0.453) while enduring severe brickwall dynamic flattening (ΔCF_{dB} = −10.25 dB in R2).

Table 6. Comparative Organological, Cosmological, and Acoustemological Concordance Across Nusantara Gamelan, Sumatran Talempong/Kelintang, and Rote Sasando Traditions Under Digital Platform Standardization.

Nusantara Tradition & Geographic Core	Indigenous Scale & Paired-Voice Architecture	Physical Materiality & Inharmonic Spectrum	Sacred / Social Cosmological Function	Observed Digital & Organological Vulnerability
Balinese Gamelan Gong Kebyar, Semar Pegulingan & Gender Wayang (Bali)	Saih pitu (7-tone) and *saih lima* (5-tone) tuned in paired *pengumbang* (lower) and *pengisep* (higher) bronze dyads with stretched octaves (+56.2c mean)	Cast tin-bronze (*kerawang*) keys over bamboo tube resonators and bossed gongs generating non-integer overtones	Acoustic interference beating (*ombak*, 4.3–8.2 Hz) animates sound as living breath (prana/*bayu*) for temple *odalan* and shadow-play consecration	Full 12-TET pitch quantization collapses 80.0% of dyads to 0 Hz unison; R3 hybrid productions elevate TAI from 0.349 to 0.650 ($p = 4.80 \times 10^{-7}$)
Javanese & Sundanese Kraton / Ceremonial Gamelan (Central, East & West Java)	Laras *sléndro* (~240c anhemitonic-inflected steps, stretched 1,310c span) and heptatonic *pélog* / *degung* / *sorog* with ensemble-specific *embat* and *tumbuk*	Forged bronze saron, bonang, gender, and large suspended gong ageng with slow low-frequency wave pulsations	Embat [ensemble-unique interval temperament] embodies court *pusaka* [sacred heirloom] sovereignty and collective *rasa* [affective-spiritual attunement]	Keyboard/DAW *campursari* and pop-ethnic arrangements force non-equidistant *sléndro*/*pélog* onto chromatic 100c grids and A4 = 440 Hz
Minangkabau *Talempong Pacik* & South Sumatran Gong-Row (West & South Sumatra)	Interlocking 5- to 6-kettle *talempong pacik* pairs/trios (*paningkah*, *pambao*, anak) and historic Muaralakitan Pasirah Rus gong-row (1/1 = 354 Hz; D_{opt} = 17.68c)	Cast brass/bronze bossed kettle-gongs with prominent inharmonic strike transients and dense upper-partial roughness	Anchors *nagari* [autonomous Minangkabau village] ceremonial processions, *Bundo Kanduang* matrilineal festivities, and *ulu* riverine prestige	*Talempong Kreasi* / Orgen Tunggal keyboards replace village-specific kettle tunings while brickwall limiters slash Crest Factor from 19.23 to 8.98 dB
Rote Island Sasando Haik vs. Chromatic Sasando Biola (East Nusa Tenggara)	Ancestral 9–11-string bamboo tube-zither tuned to indigenous 5-tone gong scales (R1 C_{float} = 16.57c, TAI = 0.337) vs. 24–32-string diatonic Sasando Biola	Cylindrical bamboo sound-tube (ao) surrounded by a hemispherical *lontar* palm-leaf (Borassus flabellifer) *haik* acoustic reflector	Accompanies Rote ritual poetry, ancestral genealogy chants, and communal circle dances within dryland *lontar* agro-cosmology	Severe early organological displacement in R2 streaming (C_{float} = 4.30c, TAI = 0.828; LMM β = −2.91c, p = 0.0227) as chromatic Biola eclipses Haik

Notes: Synthesized from Stream 1 Huygens-Fokker physical metrology, Stream 2 paired beating physics, Stream 3–4 waveform econometrics, and organological literature.[7–10,12–24,26]

4. Discussion

4.1 Inharmonic Materiality, Sacred *Ombak* Cosmology, and the Effects of 12-TET Quantization

Our multi-stream findings are consistent with Sethares's spectral consonance theory[2,3] and Feld's acoustemological framework[27] across Nusantara musical heritage. Stream 1 covers 103 physically measured ensembles (732 tones). It shows that non-equidistant microtonality (mean D_{opt} = 17.15 cents, 48.84% of degrees > 15 cents) and non-A440 reference pitches (mean D_{A440} = 24.98 cents, close to the 25-cent chance expectation) form a shared structural property. The property unites Balinese *saih pitu* and *saih lima*, Javanese *sléndro* and *pélog*, Sundanese *degung*, and Sumatran gong-rows such as South Sumatra's Muaralakitan Pasirah Rus ensemble (1/1 = 354.0 Hz, D_{A440} = 31.50 cents). Bronze bars, bossed gongs, and bamboo tubes generate inharmonic partial ratios. Pulling their fundamentals into 12-TET (2^(n/12)) therefore neither increases sensory consonance nor 'improves' intonation. Stream 2 goes further. It shows, in a simulation of 100 Balinese *pengumbang–pengisep* dyads, that imposing 12-TET quantization would remove the acoustic interference on which Balinese bronze depends for its sacred vitality.

Stream 2 builds in a constant beating rate across registers, a regularity that the literature cited above attributes to Balinese *pande gong* master smiths. Keeping a 4.3–8.2 Hz *ombak* shimmer steady across four octaves demands hyperbolic cent compression. The spacing runs from 60.03 cents in sub-bass *Jegogan* down to 29.71 cents in *Jublag*, 15.00 cents in *Pemade*, and 7.50 cents in treble *Kantilan*. Meanwhile, 12-TET works differently. It partitions pitch space into rigid logarithmic 100-cent bins, not constant-Hertz interference windows. In short, 100% of paired dyads in the upper three octaves (*Jublag*, *Pemade*, and *Kantilan*) have cent separations narrower than half a semitone (< 50 cents). Full chromatic pitch snapping (α = 1.00) collapses 84.0% to 92.0% of upper-register dyads (80.0% overall, and 100.0% in refined Kebyar Tirus tuning) into 0.00 Hz dead unison. It also splits 44.0% of sub-bass *Jegogan* dyads across semitone boundaries into harsh 100-cent dissonances. In Balinese terms, a bronze voice without 3–10 Hz *ombak* would lose its *taksu* [spiritual charisma].

Set beside recent cultural theory in Enigma in Cultural, these acoustic transformations extend Hasan et al.'s analysis of sonorous landscapes and sensory politics[30] from physical urban space to planetary digital infrastructures. Modern municipal noise regulations and architectural design reorder which urban sounds count as legitimate memory and which as disposable 'noise'.[30] Western 12-TET DAW architectures work the same way. So do A4 = 440 Hz pitch-correction algorithms. They implicitly classify indigenous microtonal deviations (17.15 cents floating; 24.98 cents from A440) and paired *pengumbang–pengisep* mistuning as 'intonation errors' requiring chromatic rectification.[28,33] Rahayu et al.'s clinical ethnography of Balinese symbolic efficacy shows otherwise.[31] Indigenous cosmological categories in Bali are not decorative metaphors. They operate through sensory and somatic mechanisms. In temple *odalan* ceremonies and sacred Gender Wayang shadow-play performances, 4.3 to 8.2 Hz *ombak*

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pulsations fall in the same frequency range as human theta–alpha neural oscillation (4–10 Hz). This may be relevant to shared affective absorption (*rasa* and *taksu*) among performers and congregants. When chromatic hybridization or automated 12-TET retuning collapses 80.0% of paired dyads to 0 Hz unison, the change would therefore matter culturally as well as acoustically.

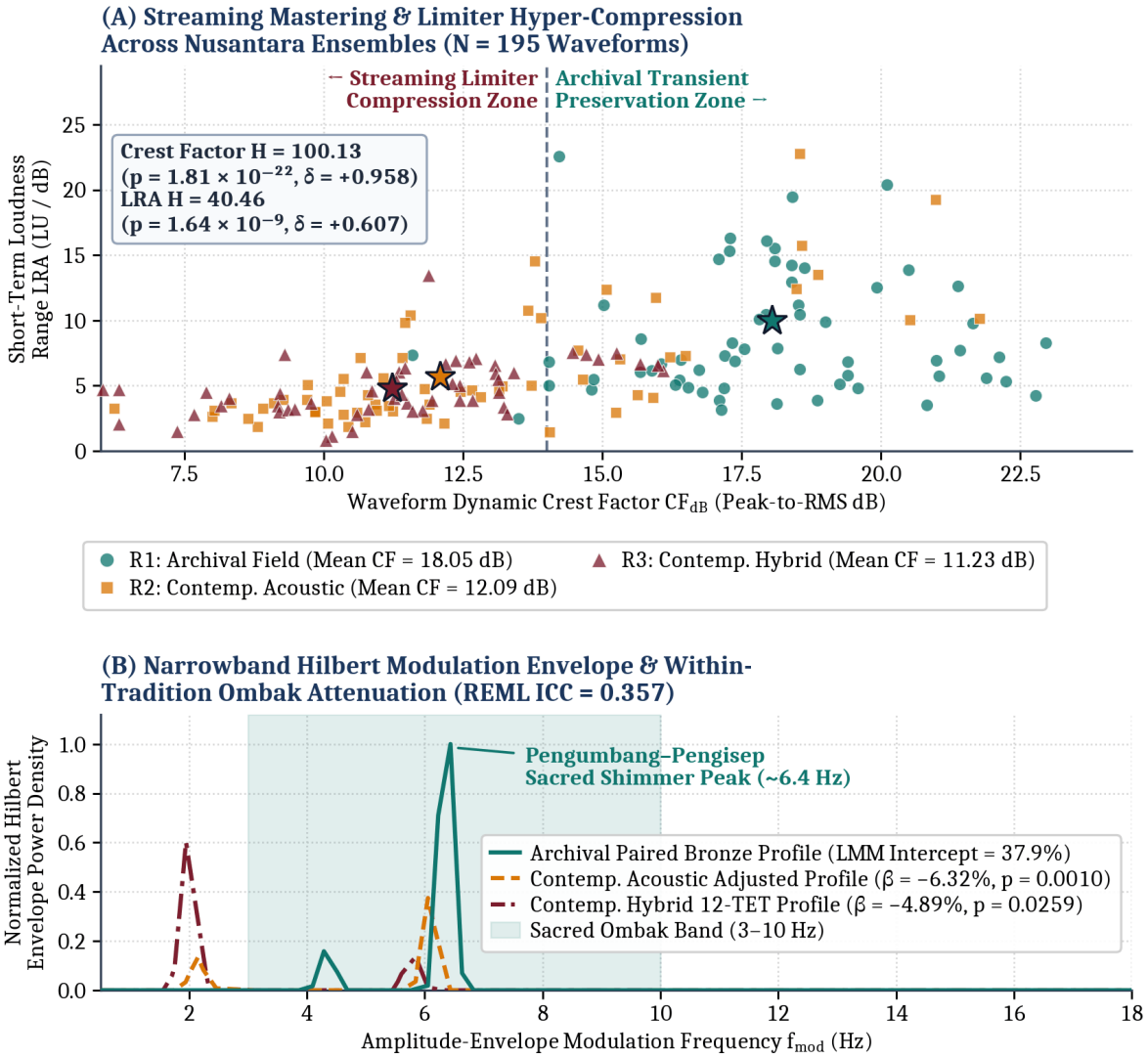

Figure 4. Mastering loudness hyper-compression and narrowband Hilbert envelope modulation spectra across archival and streaming regimes: (A) joint distribution of waveform dynamic Crest Factor CF_{dB} and short-term Loudness Range LRA across N = 195 waveforms (group centroids marked by stars), illustrating a 6.83 dB Crest Factor collapse from R1 (18.05 dB) to R3 (11.23 dB; H = 100.13, p = 1.81×10^{-22}, Cliff's δ = +0.958) and 51.9% LRA compression (9.97 to 4.79 LU; p = 1.64×10^{-9}); and (B) normalized narrowband analytic Hilbert envelope Welch power spectral densities illustrating attenuation of the sacred 3–10 Hz *ombak* shimmer peak (~6.4 Hz) in contemporary acoustic (LMM β = −6.32%, p = 0.0010) and hybrid 12-TET regimes (β = −4.89%, p = 0.0259) relative to archival paired bronze.

4.2 Divergent Organological Pathways: Sasando Biola Displacement, Hybrid Gamelan, and Compressed Talempong

Streams 3 and 4 make one central contribution. They show why pooled cross-cultural audio analyses can misdiagnose heritage erosion unless the data are stratified by organological materiality and nested sub-tradition random effects (ICC = 0.590 for C_{float}; ICC = 0.357 for M_{ombak}). Take Rote and Kupang (East Nusa Tenggara). Here digital distributors classify a streaming ecosystem there as 'traditional Sasando' (R2), yet the recordings sampled for it are mostly chromatic 24–32-string Sasando Biola recordings (C_{float} = 4.30 cents, TAI = 0.828). These recordings contrast sharply with the ancestral 9–11-string pentatonic Sasando Haik documented in archival field editions (R1 C_{float} = 16.57 cents, TAI = 0.337). The Sasando Biola is an admirable creative adaptation in Rotenese cultural history,[21–24] but its unlabeled dominance on global DSPs risks leading younger listeners and algorithmic recommendation engines[36] to mistake Western diatonicism for the ancestral voice of Rote's *lontar* palm ecology.

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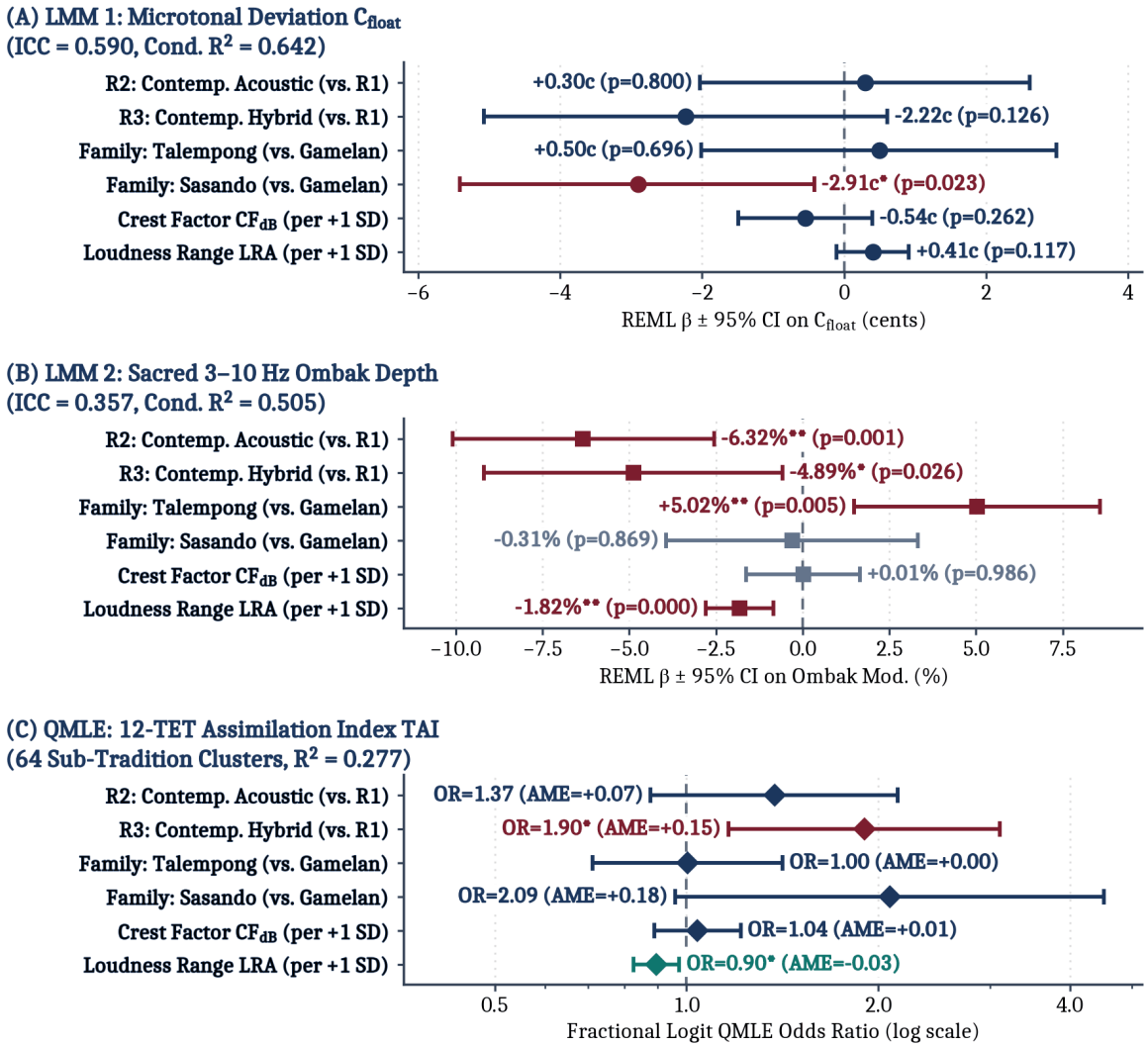

Figure 5. Multivariate hierarchical mixed-effects and fractional-response econometric estimates across N = 195 recordings nested within G = 64 sub-tradition clusters: (A) exact REML Linear Mixed-Effects Model 1 (LMM 1) fixed-effect coefficients (± 95% CI) on floating-tonic deviation C_{float} (ICC = 0.590, Conditional R^2 = 0.642), highlighting significant net chromaticization in Sasando (β = −2.91 cents, p = 0.0227); (B) REML LMM 2 coefficients on sacred 3–10 Hz *ombak* modulation depth M_{ombak} (ICC = 0.357, Conditional R^2 = 0.505), uncovering significant within-tradition attenuation in R2 (β = −6.32%, p = 0.0010) and R3 (β = −4.89%, p = 0.0259) once percussive Talempong baseline modulation (+5.02%, p = 0.0054) is controlled; and (C) cluster-robust Papke–Wooldridge Fractional Logit QMLE odds ratios and Average Marginal Effects on TAI (R3 OR = 1.90, p = 0.0100; LRA OR = 0.90 per +1 SD, p = 0.0116).

In Gamelan and Talempong, cast-bronze metallurgy physically resists casual retuning in purely acoustic recordings (Gamelan R2 TAI = 0.291; Talempong R2 TAI = 0.408). The shift toward 12-TET comes mainly when hybrid genres subordinate indigenous scales to diatonic accompaniment (R3: *campursari*, world-electronic remixes, and *talempong kreasi* with *orgen tunggal* keyboards; QMLE OR = 1.90, p = 0.0100). Even where bronze microtonality survives on streaming platforms, Stream 3 uncovers a second, pervasive axis of standardization. This is extreme dynamic hyper-compression: Crest Factor falls from 18.05 dB in R1 to 12.09 dB in R2 and 11.23 dB in R3 ($p = 1.81 \times 10^{-22}$, Cliff's δ = +0.958), and Talempong drops from 19.23 to 8.98 dB. This agrees with Deruty and Tardieu[34] and Salai[35]. Pop-oriented brickwall limiters applied to percussive metallophones may truncate initial mallet-strike transients and raise background room and upper-partial noise. Together with chromatic hybridization, this could contribute to the lower within-tradition 3–10 Hz envelope share found in LMM 2 (−6.32% in R2, p = 0.0010; −4.89% in R3, p = 0.0259), although the crest-factor covariate shows no association with that measure (β = +0.01%, p = 0.9864).

Regional comparison across Sumatra and Eastern Indonesia shows why protection strategies must respect local historical agency while redressing infrastructural asymmetry. In Sumatra, two streams can be linked. Stream 1's Muaralakitan Pasirah Rus metrology (sumatra.scl, 1/1 = 354.0 Hz, D_{opt} = 17.68 cents) comes from South Sumatra's Musi–Rawas basin, and Stream 3 adds 61 Minangkabau Talempong waveforms. Together they are compatible with a shared Sumatran riverine-highland aesthetic. In it, bossed bronze and brass kettles project communal sovereignty through dense, high-crest-factor metallic transients (R1 CF_{dB} = 19.23 dB) and non-diatonic interval steps.[17,18] Contemporary *talempong kreasi* and *orgen tunggal* mastering chains compress waveform Crest Factor down to 8.98–10.55 dB and lock kettle melodies to 12-TET

synthesizer chords. The bright percussive 'clang' (*gemerincing*) that historically carried across open *nagari* plazas and Musi riverbanks may then be flattened into a more uniform mid-range sound (not measured here). On Rote Island, cultural nuance requires honoring both branches of the Sasando family tree. The diatonic 24–32-string Sasando Biola embodies creative Rotenese cosmopolitanism forged across Kupang and national stages,[21,23,24] whereas the 9–11-string pentatonic Sasando Haik preserves the irreplaceable microtonal voice (R1 C_{float} = 16.57 cents) of Rote's *meko* gong scales and *lontar* palm ecology.[21,22] The cultural hazard in our R2 streaming data (TAI = 0.828) is therefore not the existence of Sasando Biola. It is taxonomic erasure on global DSPs, where Sasando Biola monopolizes generic 'traditional Sasando' search results while pentatonic Sasando Haik remains algorithmically invisible.

4.3 Operationalizing Sonic Sovereignty Under Indonesian Law No. 5/2017: A Five-Pillar Safeguarding Protocol

Protecting Nusantara musical traditions in the streaming era requires more than visual organological museum display or Western staff-notation transcription. It requires sonic sovereignty. This means protecting the microtonal pitch topologies (*laras*, *embat*) and interference fields (*ombak*) that constitute Indonesia's living acoustic heritage under Law No. 5/2017 on the Advancement of Culture (*Undang-Undang Pemajuan Kebudayaan*)[47] and the UNESCO 2003 Intangible Cultural Heritage Convention.[48,49] Sulaiman emphasized legal contestation and community custodianship of intangible heritage in Indonesia,[48] and statutory protection remains incomplete when digital infrastructures silently standardize indigenous artistic expressions. To translate our empirical benchmarks into cultural policy, we propose a five-pillar Nusantara Acoustemological and Sonic Sovereignty Safeguarding Protocol (Table 7; Figure 6).

Pillar I (Pairwise Organological & Stroboscopic Metrology) comes first. It mandates that national *Warisan Budaya Takbenda* (WBTb) dossiers record sub-0.1 Hz pairwise *pengumbang–pengisep* frequencies, stretched octaves, and partial spectra. The dossiers would register *pande gong*, *tukang talempong*, Muaralakitan/Sumatran *kelintang*, and sasando *haik* tuning blueprints as communal *sui generis* heritage. Pillar II (Microtonal DAW & MTS-ESP Tooling) equips conservatory students and hybrid producers with community-authorized .scl/.kbm and MTS-ESP microtonal plugins. These plugins incorporate two-voice 3–10 Hz *ombak* oscillators and disable default 12-TET Auto-Tune ($\alpha = 0$) on traditional stems. Pillar III (Dynamic Mastering Ethics) replaces brickwall peak limiting on bronze and *lontar* masters with album-mode ITU-R BS.1770 / EBU R128 normalization (−16 to −18 LUFS). The aim is to preserve $CF_{dB} \geq 14$ dB and LRA ≥ 8 LU. Pillar IV (Indigenous Acoustic Metadata) introduces structured DSP tags. They separate pentatonic Sasando Haik and *Talempong Pacik* from chromatic Sasando Biola and *Talempong Kreasi*. Pillar V (Archival Repatriation) links international sound archives with regional *Balai Pelestarian Kebudayaan* (BPK) offices and village *sanggar* [community arts studios]. The goal is youth apprenticeship. Historical field masters would be repatriated, including South Sumatran, Minangkabau, Balinese, Javanese, and Rotenese recordings.

Practically, Indonesia already has the statutory scaffolding needed to implement Pillars I through V. Law No. 5/2017 on the Advancement of Culture (*Undang-Undang Pemajuan Kebudayaan*) provides it. The law mandates bottom-up municipal and provincial cultural masterplans (*Pokok Pikiran Kebudayaan Daerah* [PPKD]) integrated with the national *Warisan Budaya Takbenda* (WBTb) registry and regional *Balai Pelestarian Kebudayaan* (BPK) technical offices.[48] BPK Wilayah XV (Bali), BPK Wilayah III (West Sumatra), BPK Wilayah VI (South Sumatra, whose jurisdiction encompasses Palembang, Musi Rawas, and Muaralakitan *kelintang*/*kromong* ensembles), BPK Wilayah X/XI (Central and East Java), and BPK Wilayah XVI (East Nusa Tenggara, covering Rote Ndao and Kupang) can embed sub-0.1 Hz stroboscopic scale logging and 24-bit / 96 kHz uncompressed two-microphone archiving directly into annual PPKD and WBTb documentation grants. Indonesia's flagship arts institutes can act as well. These are Institut Seni Indonesia (ISI) Denpasar, ISI Padangpanjang, ISI Yogyakarta, ISI Surakarta, and Institut Seni Budaya Indonesia (ISBI) Bandung. Together with independent regional digital music aggregators, they can institute three immediate studio protocols: (i) bypassing automatic chromatic pitch-drift correction (Auto-Tune / Melodyne 12-TET snap) when recording indigenous bronze, bamboo, sasando *haik*, *suling* [bamboo flute], or *rebab* [two-stringed spike fiddle] stems; (ii) replacing brickwall peak limiters with −16 LUFS album-mode normalization so $CF_{dB} \geq 14$ dB is preserved; and (iii) embedding standardized .scl tuning descriptors and organological subtype tags (Sasando Haik vs. Sasando Biola; *Talempong Pacik* vs. *Talempong Kreasi*) in public release metadata.[42,48]

4.4 Methodological Strengths, Limitations, and Epistemic Humility

Several methodological strengths and boundary conditions need explicit consideration. The study triangulates 103 physical Scala measurements, 100 analytical paired-dyad simulations, and 195 real waveforms processed under an identical 22,050 Hz STFT and narrowband Hilbert pipeline. It therefore avoids reliance on subjective listening impressions or Western A440-anchored pitch trackers. Four limitations remain, however. First, Stream 3 analyzes polyphonic ensemble mixes (30-second standardized excerpts decoded from public archival and streaming distributions). It does not use isolated multi-microphone stem recordings of single bronze keys. Narrowband 4th-order Butterworth filtering (140–2,240 Hz) and 3–10 Hz Hilbert PSD integration effectively suppress low-frequency drum pulses (< 2.5 Hz). Even so, rapid interlocking *kotekan* and talempong figurations (5–8 notes/s) still contribute rhythmic envelope energy alongside pure acoustic beating. This explains why LMM 2 sub-tradition clustering (ICC = 0.357) is indispensable for isolating within-tradition differences. Second, lossy streaming codecs (AAC/MP3) can introduce subtle psychoacoustic masking relative to uncompressed studio masters. Still, 256 kbps AAC preserves fundamental pitch centers to < 0.1 cent and sub-10 Hz amplitude envelopes accurately. Third, archival field recordings (R1) and contemporary streaming releases (R2, R3) reflect historical differences in microphone dynamic range, analog tape saturation, and curated repertoire rather than randomized controlled trials. The observed regime coefficients therefore represent historical-platform associations rather than single-factor causal effects. Fourth, Stream 1's Sumatran physical Scala coverage (n = 2) points to an urgent metrological gap outside Java and Bali, which Pillar I directly addresses.

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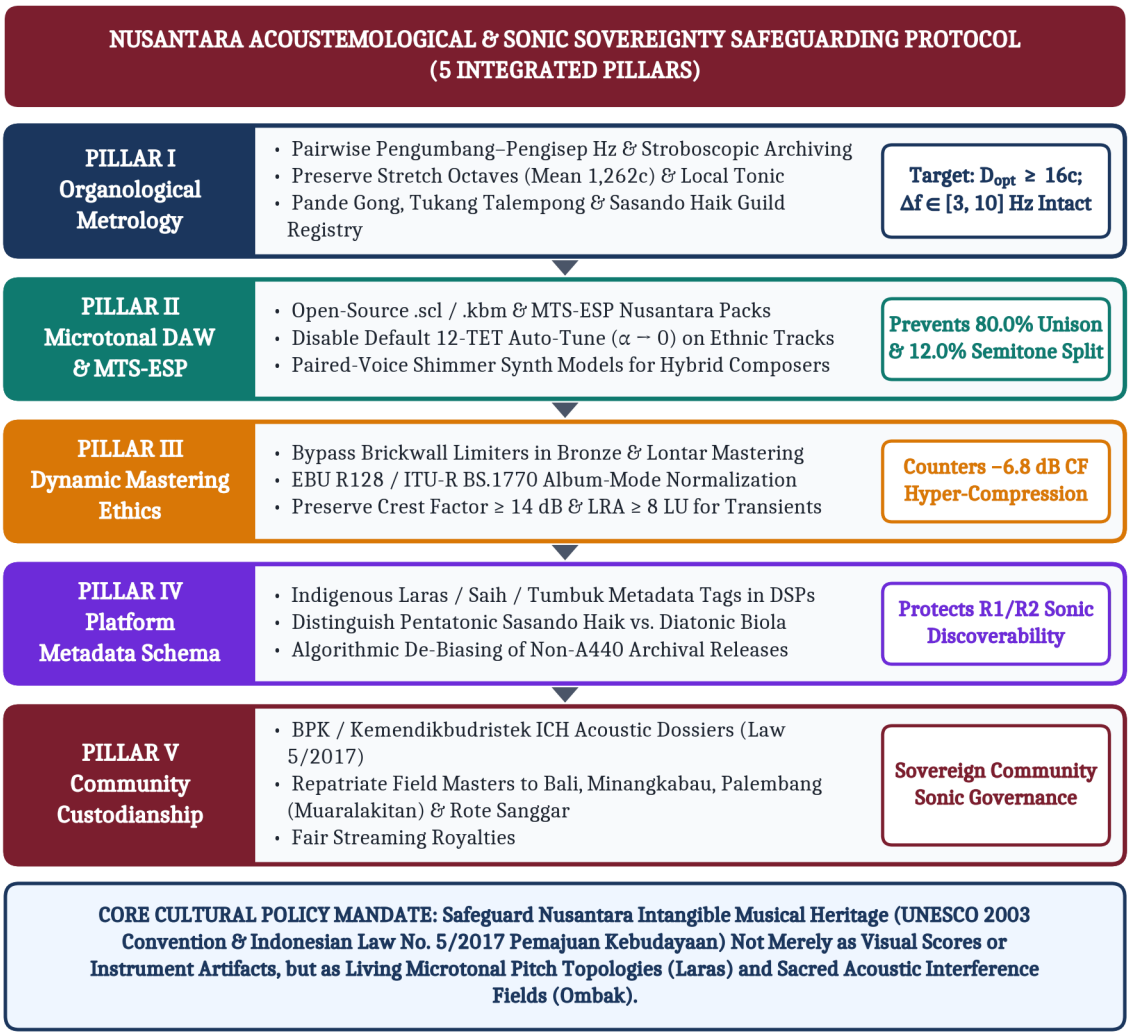

Figure 6. Proposed Five-Pillar Nusantara Acoustemological and Sonic Sovereignty Safeguarding Protocol operationalizing Indonesian Law No. 5/2017 (Pemajuan Kebudayaan) and the UNESCO 2003 Intangible Cultural Heritage Convention across pairwise stroboscopic metrology (Pillar I), open-source .scl/MTS-ESP microtonal DAW tooling (Pillar II), album-mode dynamic mastering ethics (Pillar III), indigenous acoustic platform metadata (Pillar IV), and community *sanggar* archival repatriation (Pillar V).

Further limits on interpretation follow from the design. Stream 2 is a simulation in which the beating rate is fixed by archetype and is constant across registers, so its hyperbolic cent separations and its collapse percentages describe the model, not measured ensembles. The 195 recordings are a stratified sample, so statements on catalog composition refer to the sample. Absolute pitch deviation from A440 in archival recordings can also reflect tape speed and playback. The 3–10 Hz envelope share is not specific to *ombak*, since a flat envelope spectrum would give 36.8%. Finally, crest factor and loudness range are consequences of the production regime, so adjusted regime coefficients differ in meaning from the unadjusted contrasts.

Table 7. Proposed Five-Pillar Nusantara Acoustemological and Sonic Sovereignty Safeguarding Protocol Operationalizing Indonesian Law No. 5/2017 (Pemajuan Kebudayaan) and the UNESCO 2003 ICH Convention.

Safeguarding Pillar & Empirical Rationale	Target Traditions, Actors & Platforms	Technical, Metrological & Policy Intervention	Community Custodianship & Sanggar Role	Verifiable 2026–2030 Acoustic Benchmark
Pillar I — Pairwise Organological & Stroboscopic Metrology (Addresses 48.84% microtonal degrees > 15c & stretched octaves)	Balinese *pande gong* smiths, Javanese/Sundanese *pusaka* gamelans, Minangkabau *tukang talempong*, Muaralakitan/Sumatran gong-rows, Rote sasando *haik* makers	Mandate dual-channel Hz stroboscopic archiving of every individual key/kettle (capturing exact *pengumbang–pengisep* Δf and octave stretch) in national *Warisan Budaya Takbenda* (WBTb) dossiers	Co-register tuning blueprints as communal *sui generis* intellectual property held by *sanggar* and smith guilds rather than generic public-domain MIDI presets	100% of newly inscribed WBTb musical ensembles documented with sub-0.1 Hz pairwise fundamental and partial spectra + open .scl/.kbm archival files

Safeguarding Pillar & Empirical Rationale	Target Traditions, Actors & Platforms	Technical, Metrological & Policy Intervention	Community Custodianship & Sanggar Role	Verifiable 2026–2030 Acoustic Benchmark
Pillar II — Microtonal DAW, MTS-ESP & Anti-Quantization Tooling (Prevents 80.0% dead-unison & 12.0% semitone collapse)	Indonesian conservatory composers, Nusantara fusion producers, virtual-instrument developers, and mobile/desktop DAW vendors	Distribute free, community-authorized Scala (.scl/.kbm) and ODDSound MTS-ESP microtonal tuning packs with paired-oscillator *ombak* synthesis; disable default 12-TET pitch-snap ($\alpha = 0$) on traditional stems	Partner ISI Denpasar, ISI Padangpanjang, ISI Yogyakarta/Surakarta, and Kupang/Rote cultural centers in certifying microtonal sample libraries	Preserve $\Delta f \in [3.0, 10.0]$ Hz beating and floating-tonic deviation $C_{float} \geq 15$ cents in ≥85% of conservatory-affiliated digital hybrid releases
Pillar III — Dynamic Mastering Ethics & Album-Mode Loudness Governance (Counters −6.83 dB Crest Factor collapse, $p = 1.81 \times 10^{-22}$)	Mastering engineers, digital aggregators, national archival labels (Lokananta, BPK media units), and global streaming DSPs	Replace aggressive brickwall peak limiting on bronze/*lontar* recordings with ITU-R BS.1770 / EBU R128 album-mode normalization (−16 to −18 LUFS target) preserving natural strike transients	Provide subsidized high-headroom location recording kits (24-bit/96 kHz stereo/ambisonic) for regional *sanggar* self-documentation	Maintain waveform Crest Factor $CF_{dB} \geq 14.0$ dB and short-term Loudness Range LRA ≥ 8.0 LU across archival and traditional acoustic releases
Pillar IV — Indigenous Acoustic Metadata & Algorithmic De-Biasing (Counters Sasando Haik erasure, R2 TAI = 0.828)	Global streaming platforms (Spotify, Apple Music, YouTube Music), digital distributors, and *Satu Data Kebudayaan Indonesia*	Introduce structured ethnomusicological metadata fields distinguishing *laras*/saih/*embat*, tonic Hz, and ancestral Sasando Haik / *Talempong Pacik* from chromatic Sasando Biola / *Talempong Kreasi*	Curate editorial 'Living Microtonal Nusantara' discovery pathways audited by regional ethnomusicologists and indigenous musicians	≥3-fold increase in catalog visibility and verified metadata tagging for non-12-TET pentatonic/heptatonic recordings across major DSPs
Pillar V — Archival Repatriation & Equitable Streaming Stewardship (Operationalizes Law No. 5/2017 Pemajuan Kebudayaan)	*Balai Pelestarian Kebudayaan* (BPK) Wilayah I–XXIII, international sound archives, and village *nagari* / *banjar* / *nusak* custodians	Digitally repatriate historical cylinder, reel-to-reel, and CD field masters (including South Sumatran, Minangkabau, Balinese, and Rote recordings) to originating communities with collective micro-royalty splits	Embed repatriated archival tunings into youth apprenticeship workshops for *pande gong*, *talempong pacik*, and 9–11-string sasando *haik*	Bilateral digital repatriation agreements covering ≥90% of pre-2000 international ethnographic Nusantara audio collections by 2030

Notes: Policy architecture aligns empirical psychoacoustic thresholds from Streams 1–4 with Indonesian Law No. 5/2017 on the Advancement of Culture (*Undang-Undang Pemajuan Kebudayaan*) and the UNESCO 2003 Convention for the Safeguarding of the Intangible Cultural Heritage.[48]

5. Conclusion

This study combined organological scale metrology (N = 103 Nusantara scales), multi-octave paired *ombak* physics (N = 100 dyads), and multi-platform audio signal econometrics (N = 195 waveforms across 64 sub-traditions). The scales examined deviate from the 12-TET grid (mean D_{opt} = 17.15 cents; 48.84% of degrees > 15 cents). In the paired-dyad simulation, 3–10 Hz interference beating with hyperbolically shrinking cent separation is largely lost under 12-TET quantization (80.0% dead-unison collapse). On global streaming catalogs, temperament assimilation and dynamic hyper-compression (−6.83 dB crest-factor loss) appear along different organological routes. Chromatic Sasando Biola predominates in acoustic streaming. Hybrid Gamelan shows 12-TET assimilation (OR = 1.90). The adjusted mixed-model regime effects on pitch deviation are not significant. Talempong suffers extreme limiter compression. Within traditions, the adjusted 3–10 Hz envelope share is lower (−6.32 percentage points in R2; −4.89 in R3). The proposed five-pillar protocol offers a practical way to protect Indonesia's living microtonal and *ombak* ecologies for future generations.

Declarations

Ethical Approval. Not applicable. This computational-ethnomusicological and psychoacoustic study analyzed only an open-access archive of scale measurements (the Huygens-Fokker Foundation Scala Archive) and publicly distributed archival and commercial recordings. No human participants, clinical interventions, private records, or unconsented ethnographic interviews were involved.

Consent to Participate. Not applicable. No human participants were recruited, surveyed, or experimentally tested in this secondary archival and signal-modeling study.

Consent for Publication. Not applicable. This manuscript contains no identifiable private personal data, restricted imagery, or redistributed audio waveforms.

Use of Artificial Intelligence. None declared.

Author Contributions. M.H.: Conceptualization, Methodology, Software, Formal analysis, Data curation, Visualization, Writing – original draft. N.S.: Validation, Investigation, Writing – review & editing. N.M.N.I.: Resources, Investigation, Writing – review & editing. M.M.: Formal analysis, Validation, Supervision, Writing – review & editing.

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Competing Interests. The authors declare no competing financial or non-financial interests.

Data Availability. All physical scale measurements analyzed in Stream 1 are publicly available from the Huygens-Fokker Foundation Scala Archive (https://www.huygens-fokker.org/docs/scales.zip). The track-level metadata, catalog identifiers, derived feature matrices, and reproduction scripts are available from the corresponding author on reasonable request.

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