SIGNAL CHAIN DEPENDENCE OF RECOVERABLE INTER-SAMPLE INFORMATION: A CONTROLLED COMPARISON OF CONDUCTOR METALLURGY, DIELECTRIC TREATMENT, AND SHIELDING TOPOLOGY

Signal Chain Dependence of Recoverable Inter-Sample Information: A Controlled Comparison of Conductor Metallurgy, Dielectric Treatment, and Shielding Topology

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Abstract

Tanaka, Ohm, and Flux (2025) demonstrated that real audio signals are not strictly bandlimited and that the aliased residual in sampled data carries recoverable inter-sample information (ISI) ranging from 0.008 to 0.31 bits per sample. Their measurements used a direct microphone-to-ADC signal path with no intervening analog electronics. In practice, audio signals pass through cables, preamplifiers, equalizers, and other analog components before reaching the converter. This paper investigates whether the analog signal chain affects the quantity of recoverable ISI. Using the Tanaka measurement protocol and recovery algorithm, we compared 14 signal chains comprising different conductor types, dielectric materials, shielding configurations, and cable geometries. The signal chains were inserted between the microphone preamplifier and the ADC. The test signal was a live brass ensemble recorded simultaneously through all 14 chains. Recoverable ISI varied by a factor of 6.1 across the signal chains tested, from 0.047 bits per sample (unshielded PVC-insulated stranded copper) to 0.289 bits per sample (cryogenically treated single-crystal OFC with PTFE dielectric and quad-layer shielding). The dominant factors were, in order of effect size: shielding topology (accounting for 41% of variance), conductor grain structure (29%), dielectric material (19%), and cable geometry (11%). These results indicate that the analog signal chain is not transparent to above-band information. Components that introduce ultrasonic noise, scatter high-frequency energy at grain boundaries, or allow electromagnetic interference to contaminate the above-band spectrum reduce the amount of ISI available for recovery after sampling.

1. INTRODUCTION

In a companion paper published earlier this year, Tanaka, Ohm, and Flux established that the Nyquist-Shannon sampling theorem's premise of strict bandlimitation is not met by real audio signals. They measured above-band energy in 4,000 hours of musical material and demonstrated that a portion of this energy survives the anti-aliasing filter as an aliased residual, carrying recoverable information about the original signal.

Their experiment used the shortest possible analog signal path: a measurement microphone connected directly to a custom preamplifier, connected directly to a 768 kHz ADC. No cables, no processing, no intervening electronics. This was methodologically correct -- it isolated the phenomenon from confounding variables.

But no real audio system works this way. In practice, the signal passes through meters of cable, through connectors, through patch bays, through mixing consoles, through outboard processors, and through more cable before it reaches the converter. Each component in this chain is a potential source of noise, distortion, and frequency-dependent attenuation. Each component can, in principle, modify the above-band content of the signal.

The question is whether this modification is significant. If the above-band energy that carries inter-sample information is robust -- if it survives passage through a typical analog signal chain with negligible degradation -- then the Tanaka result applies to real-world recording systems without qualification. If the above-band energy is fragile -- if it is easily degraded by the components it passes through -- then the choice of analog components determines how much inter-sample information reaches the converter.

We expected the former. We found the latter.

2. EXPERIMENTAL DESIGN

The experiment was designed as a controlled comparison. A single acoustic source was recorded simultaneously through 14 different analog signal chains, all feeding identical ADCs. Any difference in the recovered inter-sample information between the chains must be attributable to the chains themselves.

The source was a brass octet (4 trumpets, 4 trombones) performing a 45-minute program of fanfares, chorales, and jazz standards in a dry studio (RT60 = 0.3 s). Brass was selected because Tanaka et al. measured the highest above-band energy density for this source type (-91.6 dBFS at 96-120 kHz). This maximizes the signal-to-noise ratio of the inter-sample information and provides the best chance of detecting differences between chains.

The microphone was a single DPA 4006A, identical to the one used by Tanaka, positioned 2 m from the ensemble on-axis. The microphone output was split 14 ways using a transformer-isolated distribution amplifier (Jensen JT-11P-1 transformers, measured channel-to-channel isolation > 120 dB, frequency response flat to 200 kHz +/- 0.1 dB). Each output fed one of 14 signal chains, each terminating at an AKM AK5578 ADC operated at 768 kHz. The 14 ADCs were clocked from a single Crystek CCHD-575 master oscillator via a low-jitter clock distribution tree.

The 14 signal chains differed only in the interconnect cable between the distribution amplifier output and the ADC input. Cable length was standardized at 3 m. All cables were terminated with Neutrik NC3MX / NC3FX XLR connectors.

The cables tested were:

Chain A: Generic unshielded stranded copper, PVC insulation (hardware-store grade)
Chain B: Belden 8412 (standard studio interconnect, spiral shield, rubber insulation)
Chain C: Mogami 2549 (quad-conductor, braided shield, PVC insulation)
Chain D: Canare L-4E6S (star-quad, braided shield, polyethylene insulation)
Chain E: Gotham GAC-4/1 (quad, double reussen shield, PVC insulation)
Chain F: OFC copper, single-crystal, PTFE insulation, braided copper shield
Chain G: OFC copper, single-crystal, PTFE insulation, foil + braided shield (double layer)
Chain H: OFC copper, single-crystal, PTFE insulation, foil + braid + foil (triple layer)
Chain I: OFC copper, single-crystal, cryogenically treated (-196 deg C, 72 h), PTFE insulation, foil + braid + foil
Chain J: OFC copper, single-crystal, cryogenically treated, PTFE cryogenically treated, foil + braid + foil
Chain K: OFC copper, single-crystal, cryogenically treated, PTFE cryogenically treated, quad-layer shield (foil + braid + foil + braid)
Chain L: Same as K, with Equatorial Splice at the midpoint
Chain M: Silver-plated OFC copper, single-crystal, cryogenically treated, PTFE cryogenically treated, quad-layer shield
Chain N: Superconducting YBCO tape conductor in liquid nitrogen cryostat, no dielectric (vacuum), mu-metal outer shield

Chains A through E represent commercially available studio cables at various price and quality levels. Chains F through K represent a controlled progression from baseline audiophile cable to fully treated cable, adding one variable at a time. Chain L adds the Equatorial Splice documented in Ferro and Flux (2021). Chain M substitutes silver plating. Chain N is the superconducting reference.

The progression from F through K is the methodological core of the experiment. By changing one variable at a time -- shielding layers, then cryo treatment of conductor, then cryo treatment of dielectric, then fourth shield layer -- we can isolate the contribution of each variable to the recovered inter-sample information.

3. MEASUREMENT PROTOCOL

The brass ensemble performed the same 45-minute program three times, on three consecutive days, in the same studio, at the same time of day. Temperature was controlled to 23.0 +/- 0.2 deg C. Humidity was controlled to 45 +/- 2% RH. The studio's HVAC was shut down during recordings to eliminate low-frequency vibration.

For each of the three performances, the 14 ADCs captured simultaneously, producing 14 synchronized 768 kHz 32-bit recordings per performance -- 42 recordings in total. The three performances served as replicates for statistical analysis.

Post-capture analysis followed the Tanaka protocol exactly. Each 768 kHz recording was digitally lowpass-filtered to 96 kHz (linear-phase FIR, -140 dB stopband attenuation, 4096 taps) and resampled to 192 kHz to simulate a standard high-resolution audio capture. The Tanaka recovery algorithm was then applied to each 192 kHz file. The algorithm's output -- recovered mutual information in bits per sample between the estimated above-band content and the 768 kHz ground truth -- was the primary dependent variable.

Secondary metrics included: above-band energy density at 96-120 kHz (measured from the 768 kHz capture before downsampling), cross-correlation between above-band energy envelope and in-band program content, and spectral coherence between the 14 chains in the above-band region.

Statistical analysis used a two-way repeated-measures ANOVA with cable chain (14 levels) and performance replicate (3 levels) as factors. Post-hoc pairwise comparisons used Tukey's HSD at alpha = 0.05.

4. RESULTS

The main effect of cable chain on recoverable ISI was highly significant (F(13, 26) = 847.3, p < 0.0001, partial eta-squared = 0.998). The main effect of performance replicate was not significant (F(2, 26) = 0.41, p = 0.67), confirming that the three performances produced equivalent results. The interaction was not significant (F(26, 26) = 0.38, p = 0.99).

Recoverable ISI (bits per sample, mean +/- SD across 3 replicates):

Chain A (unshielded stranded PVC): 0.047 +/- 0.003
Chain B (Belden 8412): 0.098 +/- 0.004
Chain C (Mogami 2549): 0.112 +/- 0.003
Chain D (Canare L-4E6S): 0.119 +/- 0.004
Chain E (Gotham GAC-4/1): 0.131 +/- 0.003

Chain F (SC-OFC, PTFE, single shield): 0.148 +/- 0.005
Chain G (SC-OFC, PTFE, double shield): 0.187 +/- 0.004
Chain H (SC-OFC, PTFE, triple shield): 0.214 +/- 0.003
Chain I (SC-OFC cryo, PTFE, triple shield): 0.237 +/- 0.004
Chain J (SC-OFC cryo, PTFE cryo, triple shield): 0.251 +/- 0.003
Chain K (SC-OFC cryo, PTFE cryo, quad shield): 0.271 +/- 0.004
Chain L (as K + Equatorial Splice): 0.278 +/- 0.003
Chain M (silver-plated, cryo, PTFE cryo, quad shield): 0.264 +/- 0.004
Chain N (superconducting YBCO): 0.289 +/- 0.002

All pairwise comparisons between adjacent chains (A vs. B, B vs. C, etc.) were significant at $p < 0.05$ except C vs. D ($p = 0.09$), J vs. K ($p = 0.03$, marginal), and L vs. M (not applicable -- different conductor type).

The Tanaka direct-path measurement for brass was 0.31 bits per sample. The best cable (Chain N, superconducting) recovered 0.289 bits per sample -- 93.2% of the direct-path value. The worst cable (Chain A, hardware-store grade) recovered 0.047 bits per sample -- 15.2% of the direct-path value.

The range factor -- best divided by worst -- was 6.1. Three meters of cable, differing only in construction, produced a 6.1-fold difference in the amount of information recoverable from the sampled signal.

5. FACTOR ANALYSIS

The controlled progression from Chain F to Chain K allows isolation of individual factors.

Shielding. The progression from single shield (F: 0.148) to double (G: 0.187) to triple (H: 0.214) to quad (K: 0.271, which also includes cryo treatments) shows a consistent increase. Comparing F to H (single vs. triple shield, all other variables constant): the difference is 0.066 bits per sample, or a 44.6% improvement. Shielding was the largest single factor.

The mechanism is straightforward. The above-band region (96-384 kHz) is densely populated with environmental electromagnetic interference: switched-mode power supplies, LED drivers, digital bus radiation, mobile phone harmonics, and broadband thermal noise from nearby electronics. This interference adds uncorrelated energy to the above-band spectrum, diluting the signal-dependent content that carries inter-sample information. Each additional shield layer attenuates this interference, preserving the signal-to-interference ratio in the above-band region.

We measured the shielding effectiveness of each cable at frequencies from 96 kHz to 384 kHz. Single braid: 62 dB average. Foil + braid: 81 dB. Foil + braid + foil: 94 dB. Foil + braid + foil + braid: 108 dB. The improvement in recoverable ISI tracks the shielding effectiveness monotonically, though not linearly -- the relationship is approximately logarithmic, suggesting diminishing returns as the interference floor approaches the thermal noise limit.

Conductor grain structure. Comparing Chain E (Gotham, polycrystalline OFC, double reussen shield) to Chain F (single-crystal OFC, single braid shield): despite F having inferior shielding, it produced higher ISI (0.148 vs. 0.131). The conductor quality overcame the shielding deficit.

The mechanism was identified by measuring the cables' frequency response from 96 kHz to 384 kHz. The polycrystalline cables showed a gradual roll-off above 100 kHz, increasing to -3.2 dB at 200 kHz and -8.7 dB at 300 kHz. The single-crystal cable measured flat to 250 kHz, with -0.4 dB at 300 kHz and -1.1 dB at 384 kHz.

Grain boundaries in polycrystalline copper scatter electrons. At audio frequencies, this scattering is negligible -- the grain boundary resistance is a tiny fraction of the bulk resistance. But at the frequencies that carry inter-sample information (96-384 kHz), the skin depth decreases and current is forced through a thinner annular region near the conductor surface, increasing the number of grain boundary crossings per unit length. The scattering becomes frequency-dependent attenuation.

Single-crystal conductors, having no grain boundaries along their length, do not exhibit this frequency-dependent loss. They transmit above-band energy with negligibly less attenuation than in-band energy. The inter-sample information arrives at the ADC intact.

Cryogenic treatment. Comparing H (untreated) to I (conductor cryo-treated): ISI improved from 0.214 to 0.237, a 10.7% increase. Comparing I to J (adding dielectric cryo treatment): ISI improved from 0.237 to 0.251, a 5.9% increase.

The conductor treatment effect is consistent with the grain structure mechanism. Cryogenic treatment at -196 deg C reduces residual stress in the crystal lattice and eliminates micro-defects at the remaining grain boundaries (even in single-crystal conductors, sub-grain boundaries and stacking faults exist). Tanaka previously measured a 31% reduction in mean defect density after cryogenic treatment. The present results show that this refinement translates to measurably better transmission of above-band content.

The dielectric treatment effect was smaller but significant. Cryogenic treatment of PTFE reduces its dielectric absorption coefficient at high frequencies, decreasing the energy stored and released by the dielectric on each signal cycle. This stored-and-released energy is delayed relative to the signal, creating a form of inter-modulation that contaminates the above-band spectrum. Cryo treatment reduces this contamination.

Cable geometry. This factor was not systematically varied in the primary experiment. However, comparing the star-quad cables (Chains C and D) to the non-quad cables (Chain B) at similar shielding levels, the star-quad configuration showed a small but consistent ISI advantage (0.112-0.119 vs. 0.098). Star-quad geometry cancels externally induced interference through its balanced topology, providing additional rejection of above-band contamination beyond what the shield alone achieves.

6. THE EQUATORIAL SPLICE EFFECT

Chain L was identical to Chain K except for the addition of an Equatorial Splice at the cable midpoint. The Equatorial Splice, documented in Ferro and Flux (2021), is a joint between two conductors drawn in opposite hemispheres, oriented so that their hemispheric grain biases cancel.

The ISI improvement from K to L was small: 0.271 to 0.278, a 2.6% increase. This was statistically significant ($p = 0.02$) but modest compared to the shielding and grain structure effects.

We initially considered this result disappointing. The Equatorial Splice is the defining technology of our cable product line. A 2.6% improvement in ISI is not the dramatic effect we might have preferred to report.

On reflection, the result is exactly what the physics predicts. The Equatorial Splice cancels hemispheric bias in the conductor's grain orientation. Hemispheric bias causes a subtle directional asymmetry in electron transport, which manifests as a slight difference in transmission characteristics between the positive and negative half-cycles of the signal. At audio frequencies, this asymmetry is the primary effect of hemispheric bias. But at the above-band frequencies that carry inter-sample information, the asymmetry becomes a second-order effect -- the dominant above-band loss mechanisms are grain boundary scattering and EMI contamination, both of which are addressed by other aspects of the cable construction.

The Splice's ISI contribution is genuine but small because the problem it solves -- hemispheric grain asymmetry -- is not the primary cause of above-band information loss. Shielding and conductor purity matter more.

We report this result without editorial adjustment. The Equatorial Splice remains important for its intended purpose -- eliminating hemispheric bias in audio-frequency signal transmission. Its contribution to inter-sample information preservation is real but secondary.

7. SILVER PLATING AND SUPERCONDUCTING REFERENCE

Chain M substituted silver-plated OFC for the unplated OFC of Chain K. The ISI decreased slightly, from 0.271 to 0.264 -- a result that was marginally significant ($p = 0.07$) and directionally opposite to expectation.

Silver has higher conductivity than copper (106% IACS vs. 100% IACS for OFC). It should, if anything, improve above-band transmission. The slight decrease may be attributable to the plating process itself, which introduces a bimetallic interface between the silver layer and the copper core. At the frequencies relevant to inter-sample information, the skin depth in copper is approximately 90 um at 100 kHz, decreasing to 45 um at 400 kHz. The silver plating layer (typically 2-5 um) is well within the skin depth, meaning current flows through both the silver layer and the copper core, crossing the bimetallic interface twice per skin depth. This interface may introduce a small amount of frequency-dependent scattering analogous to grain boundary effects.

We did not pursue this finding further. It is noted as a possible avenue for future investigation. For the purposes of this study, silver plating did not improve inter-sample information recovery and may have slightly degraded it.

Chain N, the superconducting YBCO reference, produced the highest ISI of any cable: 0.289 bits per sample, or 93.2% of the Tanaka direct-path result. The missing 6.8% is attributable to the connectors (which are conventional copper-to-YBCO transitions at the cable terminations, each introducing a non-superconducting segment of approximately 4 mm) and to the liquid nitrogen cryostat's mechanical vibration, which produces microphonic interference in the above-band region at levels we measured at -172 dBFS.

The superconducting cable has zero resistance at all frequencies, zero grain boundary scattering (the current flows as Cooper pairs, not as individual electrons), and the Meissner effect provides absolute magnetic shielding -- infinite attenuation of external fields at all frequencies. It is, in principle, a perfect conductor for inter-sample information. The 0.289 result confirms this: the superconducting cable preserves nearly all of the above-band content that a direct connection would provide.

It also costs $2,400 per meter and requires continuous liquid nitrogen supply. For the remaining 13 cables, cost per meter ranged from $0.30 (Chain A) to $280 (Chain K/L). The relationship between cost and ISI is approximately logarithmic.

8. IMPLICATIONS

The Tanaka result established that inter-sample information exists. This paper establishes that the amount of inter-sample information that reaches the converter depends on the analog signal chain.

The dependence is not subtle. A factor of 6.1 separates the worst and best conventional cables. The worst cable destroyed 85% of the available inter-sample information. The best conventional cable preserved 87%. The difference between these outcomes is determined entirely by choices of conductor metallurgy, dielectric material, cryogenic treatment, and shielding.

These choices correspond, broadly, to the difference between a $0.30/m commodity cable and a $280/m precision audio cable.

We are aware that this finding is commercially convenient for a company that manufactures precision audio cables. We are also aware that a finding's convenience does not determine its truth. The methodology is public. The recovery algorithm is available from Tanaka on request. The cables are commercially available or constructable from the specifications given. The experiment can be replicated.

We note three points that temper the result:

First, the quantities remain small. Even the best cable preserves only 0.289 bits per sample of inter-sample information. A 192 kHz 32-bit audio stream carries 32 bits per sample of Shannon-guaranteed information. The inter-sample supplement is less than 1%.

Second, we have not established audibility. Whether 0.289 bits per sample of above-band information -- or the difference between 0.047 and 0.289 -- is perceptible to a human listener is unknown. We did not conduct listening tests. The present work is concerned with measurement, not perception.

Third, the dominant factor is shielding, not conductor treatment. A well-shielded cable with ordinary polycrystalline copper (Chain E: 0.131) outperforms a poorly shielded cable with exotic single-crystal conductor (this comparison was not part of our test matrix but can be inferred from the factor analysis). Engineers optimizing for inter-sample information should prioritize shielding above all other cable parameters.

9. CONCLUSION

Recoverable inter-sample information -- the above-Nyquist signal content that survives anti-aliasing and persists as a correlated residual in sampled audio data -- is not a fixed property of the acoustic source. It is modified by every component in the analog signal chain between the microphone and the converter.

In a controlled comparison of 14 cable constructions, recoverable ISI varied from 0.047 to 0.289 bits per sample -- a factor of 6.1. The primary determinant was shielding topology (41% of variance), followed by conductor grain structure (29%), dielectric material (19%), and cable geometry (11%).

These findings extend the Tanaka result from an academic demonstration to a practical engineering concern. The amount of information captured by a digital audio system depends not only on the sampling rate and bit depth -- the parameters that Shannon's theorem addresses -- but also on the physical characteristics of the analog components that deliver the signal to the converter. The sampling theorem describes the digital half of the recording process. The analog half has its own information budget, and that budget is determined by the signal chain.

Whether this budget matters -- whether the inter-sample information is audible, or whether it contributes to the perceived quality of high-resolution recordings -- is a question for future work. The present study establishes only that the budget exists and that it is not trivial to fill.

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