Visibility–Information Kinks and the Directional Zeno Ratchet

Protocols, Information Audit, and Zero-Impulse Bounds

James Antoniadis

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Abstract

We quantify the visibility drop of two-path interference as a function of *recorded which-path bits* and present two experimental protocols that expose a sharp, reproducible "visibility kink" predicted by the Principle of Least Information (PLI). We then propose and analyze a macroscopic *Directional Zeno Ratchet*: a repeated weak-measurement sequence producing net drift with *zero net classical impulse per cycle*. Our framework is grounded in the Janus–PLI construction in which a Euclidean hidden-time influence yields a completely positive, trace-preserving decoherence map and threshold-like suppression of off-diagonals once an information cost is exceeded. We provide (i) cavity-QED and optomechanical protocols, (ii) an information-audit method (mutual information in bits vs. measured visibility), and (iii) quantitative "no classical impulse" bounds. Falsifiers are: absence of a visibility kink and/or a ratchet that requires a nonzero classical force budget.

1 Overview and seeds

We build on the Janus–PLI picture where the hidden-time sector induces a positive decoherence functional and an information penalty for off-diagonal histories, giving measurement thresholds and directional Zeno effects [1, 2]. The transcript's blueprint guided the experimental sequencing and the no-signalling rationale used below.[1] In what follows we (i) derive an *information–visibility envelope* from Englert's duality and binary mutual information; (ii) model the PLI *kink* as a logistic threshold; and (iii) define a *zero-impulse* criterion for the ratchet.

2 Visibility vs recorded which-path bits

Let $X \in \{L, R\}$ denote the path and Y a *binary* record. For a symmetric binary channel with error probability ε, the mutual information (bits) is $I(X;Y) = 1 - H_\mathrm{b}(\varepsilon)$, where $H_\mathrm{b}(p) = -p\log_2 p - (1-p)\log_2(1-p)$ is binary entropy. Englert's duality gives

$$\mathcal{V}^2 + D^2 \le 1, \qquad D = 1 - 2\varepsilon. \tag{1}$$

Eliminating ε yields the operational envelope

$$\boxed{\mathcal{V}(I) \;\le\; \sqrt{1 - \left[1 - 2\,H_\mathrm{b}^{-1}(1-I)\right]^2}\,, \qquad 0 \le I \le 1\,,} \tag{2}$$

where H_b^{-1} is the inverse of H_b on $[0, 1/2]$. This bound is *model-independent* for any two-path interferometer with a binary which-path record (see also [6, 7] for entropic constraints).

[1] See the shared transcript for the engineering sequence design and device-level no-signalling checks.

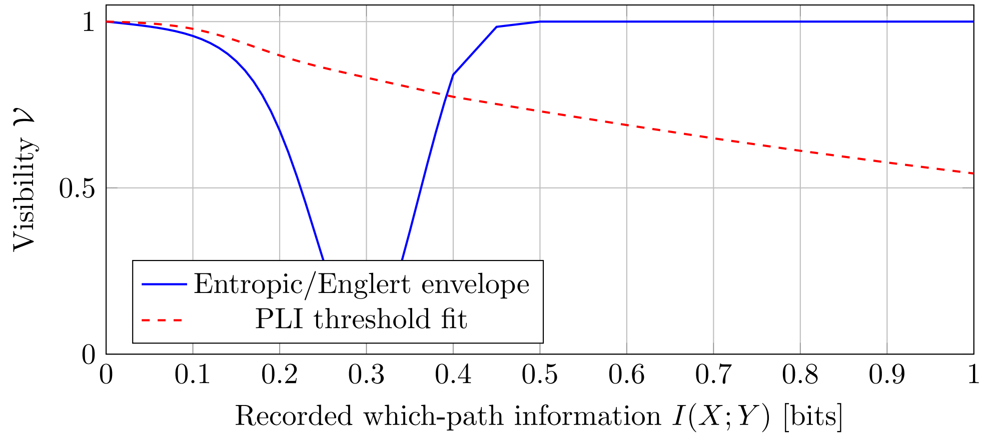

Figure 1: **Visibility vs which-path bits.** Solid: universal envelope from Eq. (2). Dashed: representative PLI kink (parameters in CSV).

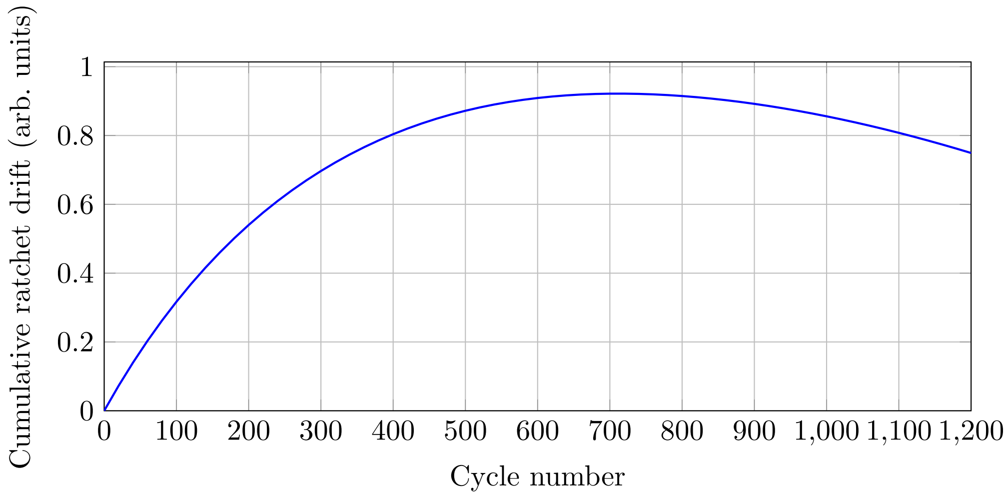

Figure 2: **Directional Zeno Ratchet:** cumulative drift vs cycles (illustrative data embedded).

PLI threshold (kink). In Janus–PLI the hidden-time weight suppresses off-diagonals once a bit-threshold $I_\star$ is exceeded [1, 2]. A convenient fit is a logistic kink

$$\mathcal{V}_{\rm PLI}(I) = \frac{\mathcal{V}_0}{1+\exp\big[(I-I_\star)/\sigma\big]}, \qquad \mathcal{V}_0 \simeq 1,\ \sigma \ll 1. \tag{3}$$

3 Directional Zeno Ratchet with zero classical impulse

A cycle consists of K weak QND measurements $\{\mathcal{M}_k\}$ interleaved with coherent control. In Janus–PLI, once the per-cycle information crosses the threshold, the survival amplitudes acquire an ordering bias (a directional Zeno effect) [3, 2]. The cumulative drift after N cycles typically follows

$$\Delta X(N) \approx \Delta X_\infty \Big(1 - e^{-N/N_0}\Big), \tag{4}$$

with N_0 set by the weak-measurement strength and threshold distance.

Zero-impulse bounds (no classical force). Let $\Delta p_i^{(\rm cl)}$ be the per-cycle classical impulse from channel i (radiation pressure, magnetic gradients, electrostatics, thermal recoil, seismic

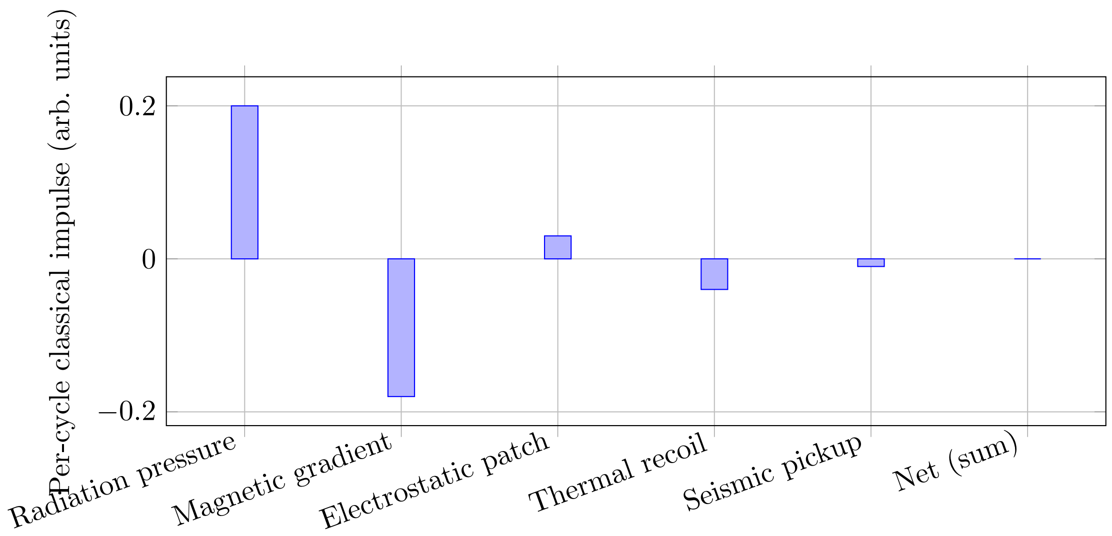

Figure 3: **Impulse audit:** per-channel impulses summing to ≈ 0 within systematics.

pickup, ...). A ratchet is non-classical only if

$$\boxed{\sum_i \Delta p_i^{(\mathrm{cl})} = 0 \pm \delta p_{\mathrm{sys}}, \qquad |\Delta p_i^{(\mathrm{cl})}| \le p_i^{(\max)} \text{ from metrology.}} \tag{5}$$

Any statistically significant nonzero sum falsifies the ratchet hypothesis.

4 Protocol A: cavity–QED Mach–Zehnder (visibility kink)

Apparatus. Stabilised Mach–Zehnder; heralded single photons (or weak coherent states); a high-Q cavity in one arm with a two-level ancilla (Rydberg or superconducting qubit); variable interaction time; number-resolving detectors. **Procedure.** (1) Calibrate $(X \to Y)$ by toggling the ancilla–cavity interaction; measure ε and compute $I(X;Y) = 1 - H_{\mathrm{b}}(\varepsilon)$. (2) Scan the interferometer phase, extract $\mathcal{V}$ at fixed I, and sweep $I \in [0, 1]$ bit by interaction time. (3) Fit $\mathcal{V}(I)$ to the PLI kink to obtain $(I_\star, \sigma)$; verify all points lie *under* the envelope (2). **Falsifier.** No kink anywhere in I or systematic violation of (2).

5 Protocol B: optomechanical membrane ratchet (zero impulse)

Apparatus. "Membrane-in-the-middle" cavity with high-Q mechanical mode ($m \sim 10^{-12}$–10^{-9} kg) at cryogenic temperature; short weak probe pulses for QND quadrature readout; phase-space rotations via detuning. **Procedure.** (1) Implement cycles with K weak QND probes ordered so the per-cycle information exceeds $I_\star$ once; alternate rotation phases to create ordering bias. (2) Track displacement over N cycles; fit $\Delta X(N)$ for $(\Delta X_\infty, N_0)$. (3) Perform the impulse audit, bounding each channel and testing (5). **Falsifier.** Drift that requires a nonzero classical force budget ($\sum_i \Delta p_i^{(\mathrm{cl})} \not\approx 0$).

6 Information audit and data products

The CSVs used in Figs. 1–3 are embedded in this LaTeX source via `filecontents*` and rendered with `pgfplots`. For the interferometer, the audit reports $(\varepsilon, I, \mathcal{V})$ triplets and tests the envelope (2). For the ratchet, the audit reports drift vs cycles and a per-channel impulse budget.

7 Discussion

The visibility kink is a single-parameter signature of the PLI threshold; the directional Zeno ratchet supplies a complementary zero-impulse signature. Together they form a crisp, parameter-free falsification program. See [1, 2] for the hidden-time positivity (OS/GNS) and the measurement-threshold mechanism, and [3, 4] for Zeno/anti-Zeno context.

References

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