Algorithmic correction of time-correlated noise in QETU

Shivane Dadi[1] Dhruv Patel[1] Grecia Castelazo[1] Murphy Niu[1]
[1]University of California, Santa Barbara

Abstract

QETU (Quantum Eigenvalue Transformation of Unitaries) prepares a ground state with a classically-precomputed filter set by QSP (Quantum Signal Processing) phase factors; hardware drift slowly slips those phases. **The circuit's own ancilla-success probability is a first-order sensor for the drift – while the energy density is variationally blind to it.** Read the rate off that sensor and feed a single-scalar correction forward to recover the ground state fidelity .

QETU is an algorithm that filters the ground state

A polynomial filter $F(\sigma)$ in $\sigma = \cos(\lambda/2)$, built from phase factors $\Phi = (\phi_0, \ldots, \phi_d)$, keeps the ground state and suppresses the rest:

$$F(H)|\psi_{\text{init}}\rangle = c_0 F(E_0)|\psi_0\rangle + \sum_{k\geq 1} c_k F(E_k)|\psi_k\rangle$$

Post-selecting the ancilla on $|0\rangle$ leaves $\approx |\psi_0\rangle$; it sits on the **steep band edge**.

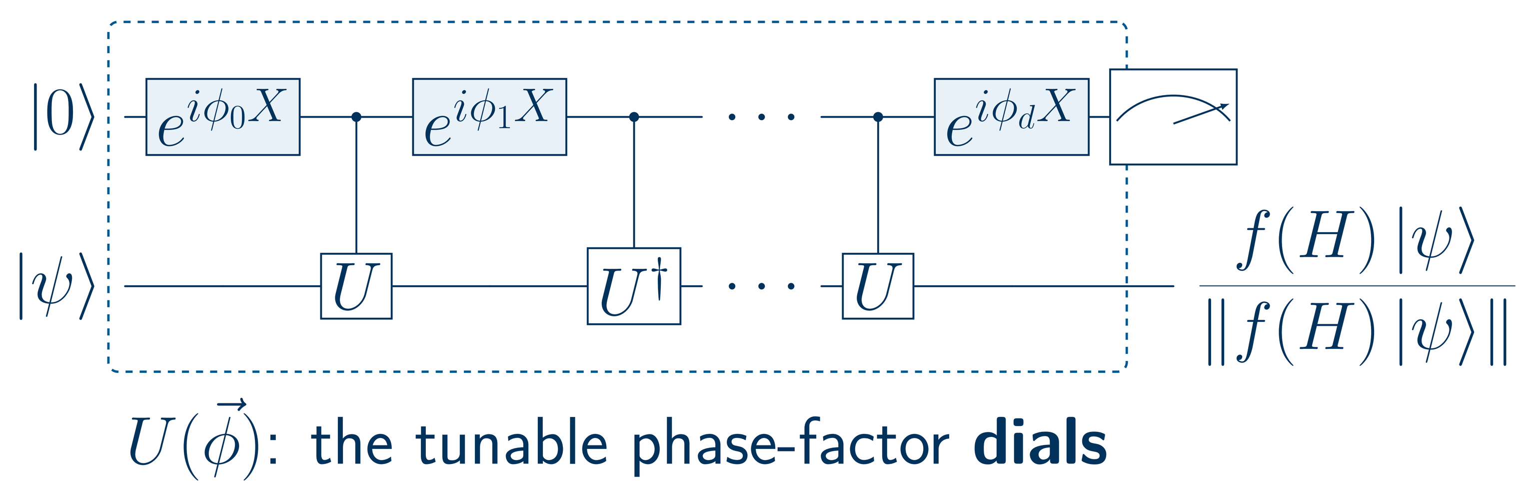
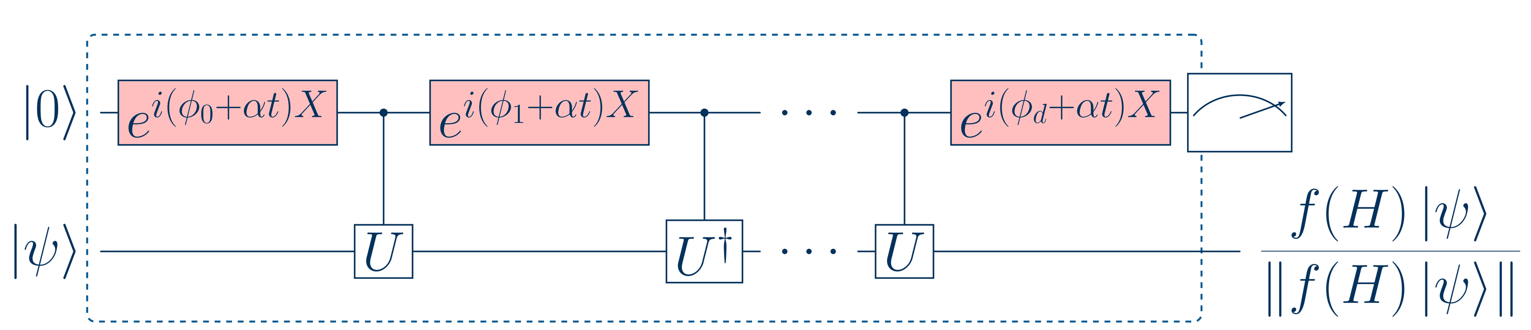


Figure 1. Ancilla X-rotations $e^{i\phi_j X}$ interleave controlled $U = e^{-iH}/U^\dagger$. The phase factors $\vec{\phi}$ are the dials that set $F(\sigma)$; ancilla $|0\rangle$ post-selection gives $f(H)|\psi\rangle/\|\cdot\|$, $p = \|f(H)|\psi\rangle\|^2$.

Drift slips the dials

Low-frequency coherent drift adds a common, slowly growing offset to every phase, deforming the filter

$$\phi_j(t) = \phi_j + \alpha\, t,$$



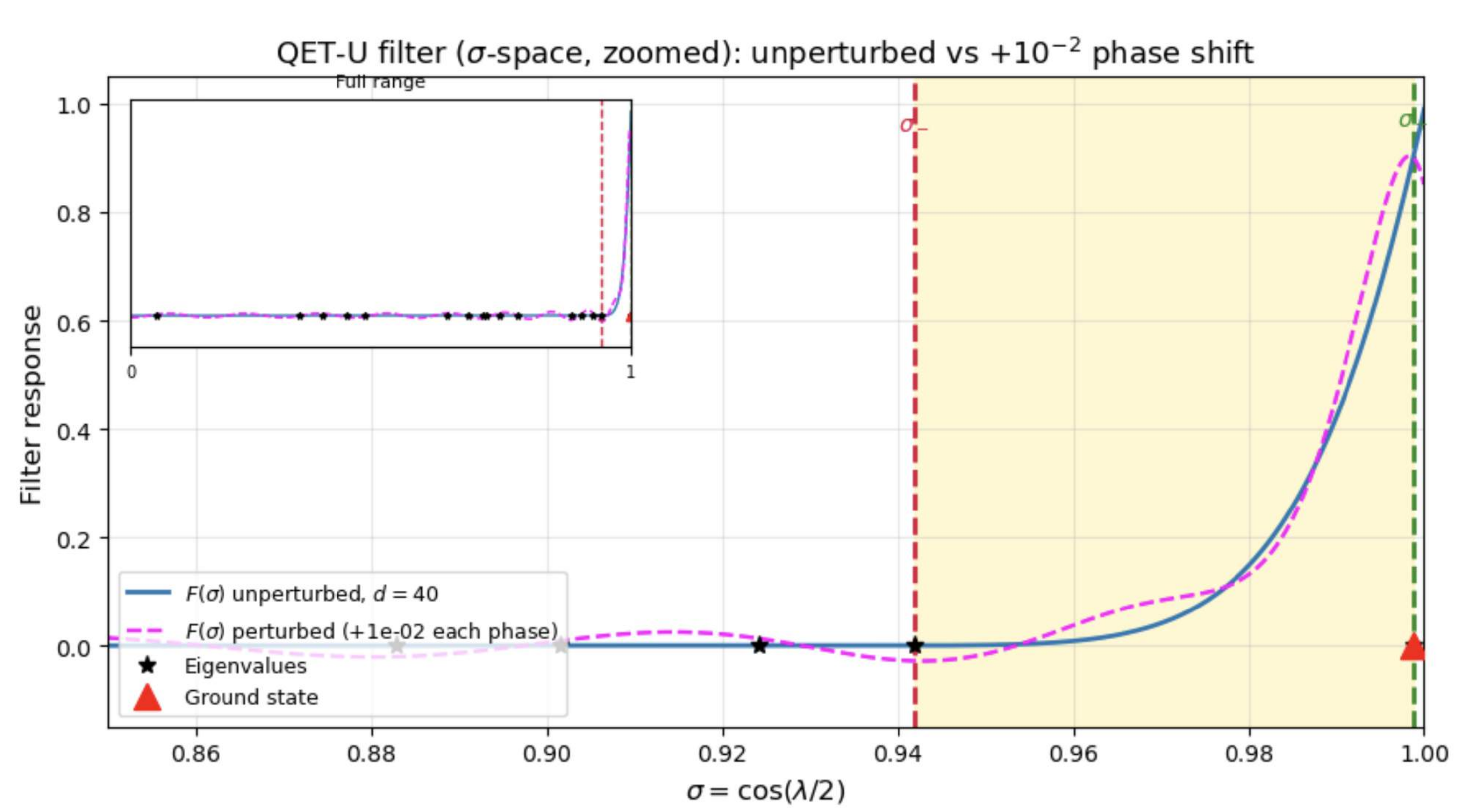


Figure 2. Unperturbed vs. drifted filter near the band edge ($\alpha t = 10^{-2}$): the edge slides across the ground state, so fidelity and energy density decay.

Prepare, measure, repeat – for hours

QETU is a *prepare-and-measure* primitive: each run prepares the ground state and measures an observable $\langle O\rangle$ on it. The cycle repeats over a long experiment, and coherent control drift slips the phases *between* runs.

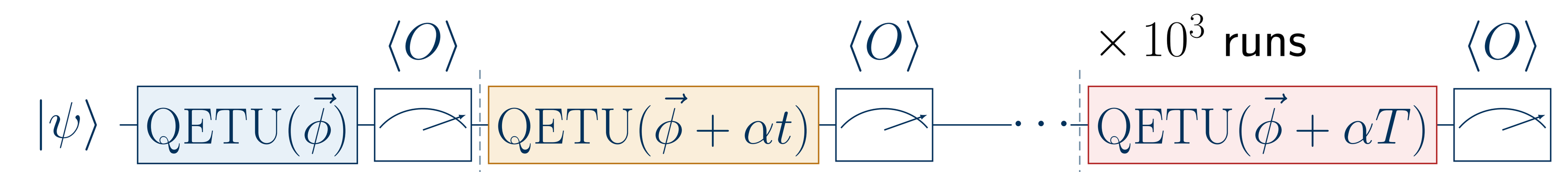


Figure 3. Each run prepares the ground state and measures an observable $\langle O\rangle$ on it. The cycle repeats $\sim 10^3$ times over minutes–hours; coherent control drift shifts the phases $\vec{\phi} \to \vec{\phi} + \alpha t$ between runs (blue $\to$ red), so later runs return a biased $\langle O\rangle$. (The ancilla success rate p, recorded each run, becomes the drift sensor – next.)

The solution: Exploiting the time-correlation in the noise

The linear ramp is the leading term of any slow drift, so the **rate α is the only unknown**. By the internal model principle the correction collapses to estimating a single scalar $\delta = \alpha t$.

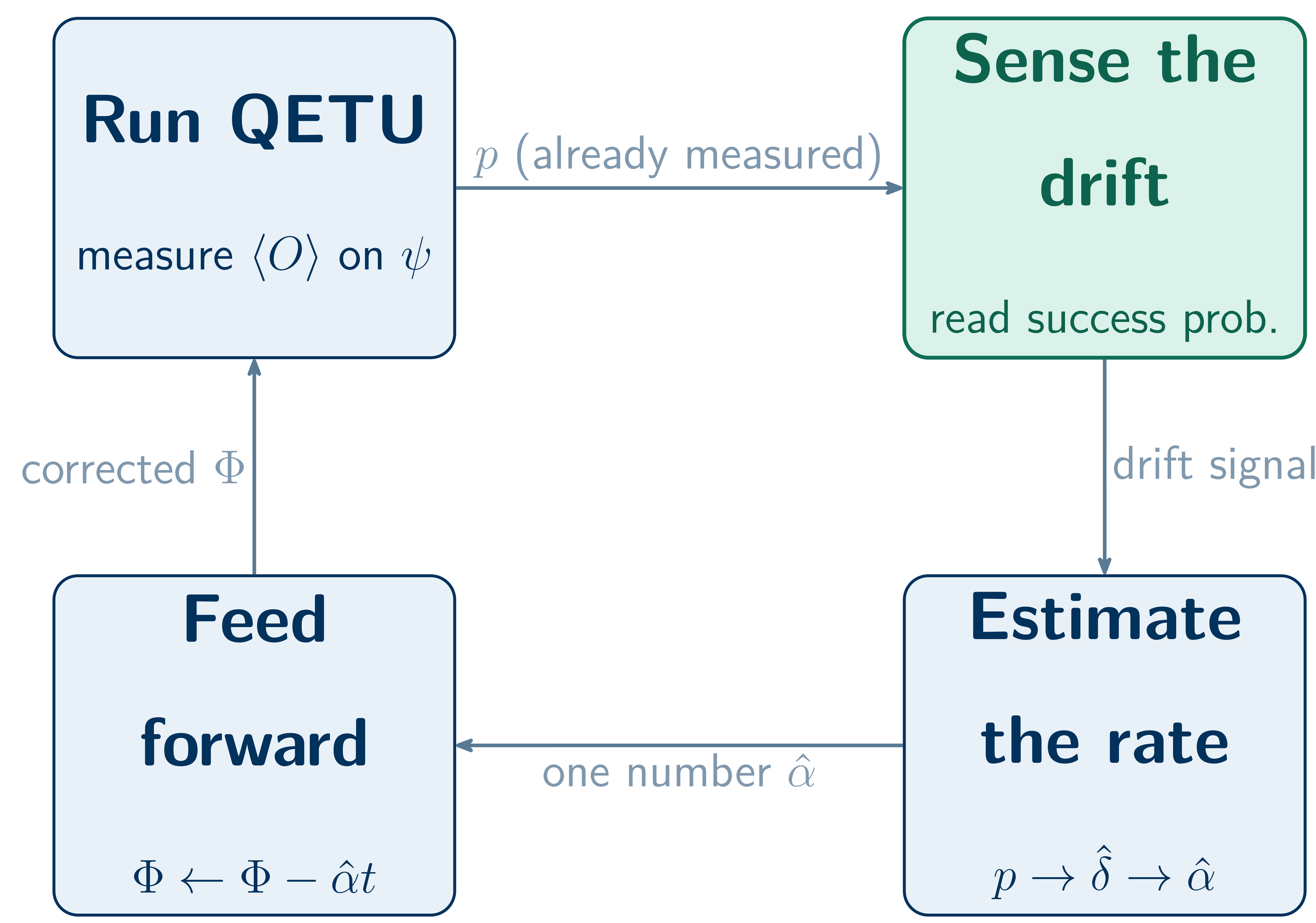


Figure 4. Closed-loop drift correction. Drift enters the QETU run; the ancilla p already recorded senses it; a single rate $\hat{\alpha}$ is estimated and fed forward at zero re-optimization cost.

How the ancilla reads the drift

The success probability $p(\delta)$ has a **monotone window** around $\delta = 0$: measure p, invert the window, read the offset $\hat{\delta}$ directly. (Energy density cannot do this – it sits at a variational minimum and is first-order blind: $R = |d\varepsilon/d\delta| \,/\, |dp/d\delta| \approx 8\times 10^{-4}$.)

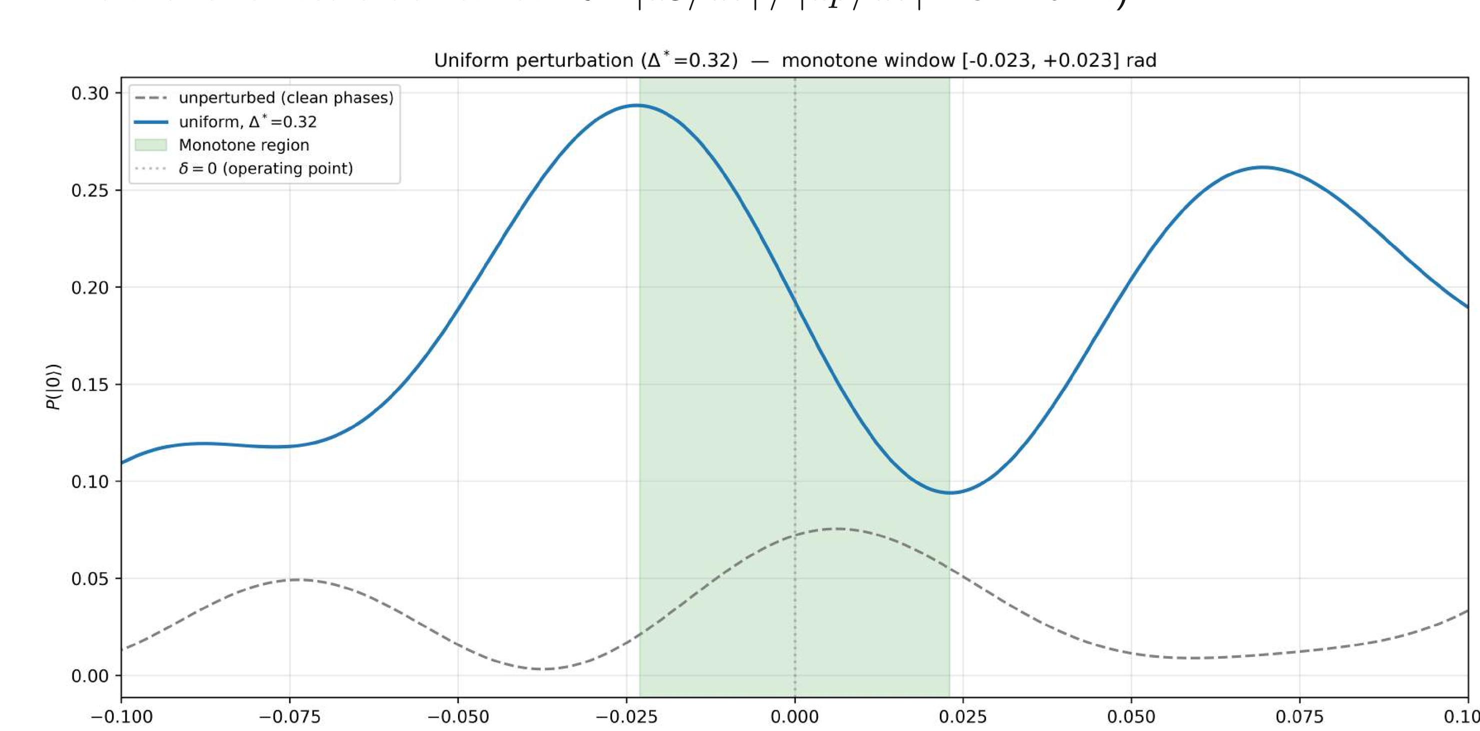


Figure 5. $p(\delta)$ near $\delta = 0$ (bare sensor, $|c_0|^2 \approx 0.9$) with the monotone region shaded. Measure p, look up $\hat{\delta}$ on the curve.

From measurement to correction

At each diagnostic, invert the monotone window, and fit the drift rate:

$$\hat{\delta}_k = \frac{p_k - p_0}{g_0}, \qquad \hat{\alpha} = \frac{\sum_k \hat{\delta}_k \cdot k}{\sum_k k^2}$$

Correct all phases – at **zero** re-optimization:

$$\boxed{\phi_j \leftarrow \phi_j - \hat{\alpha}\, t}$$

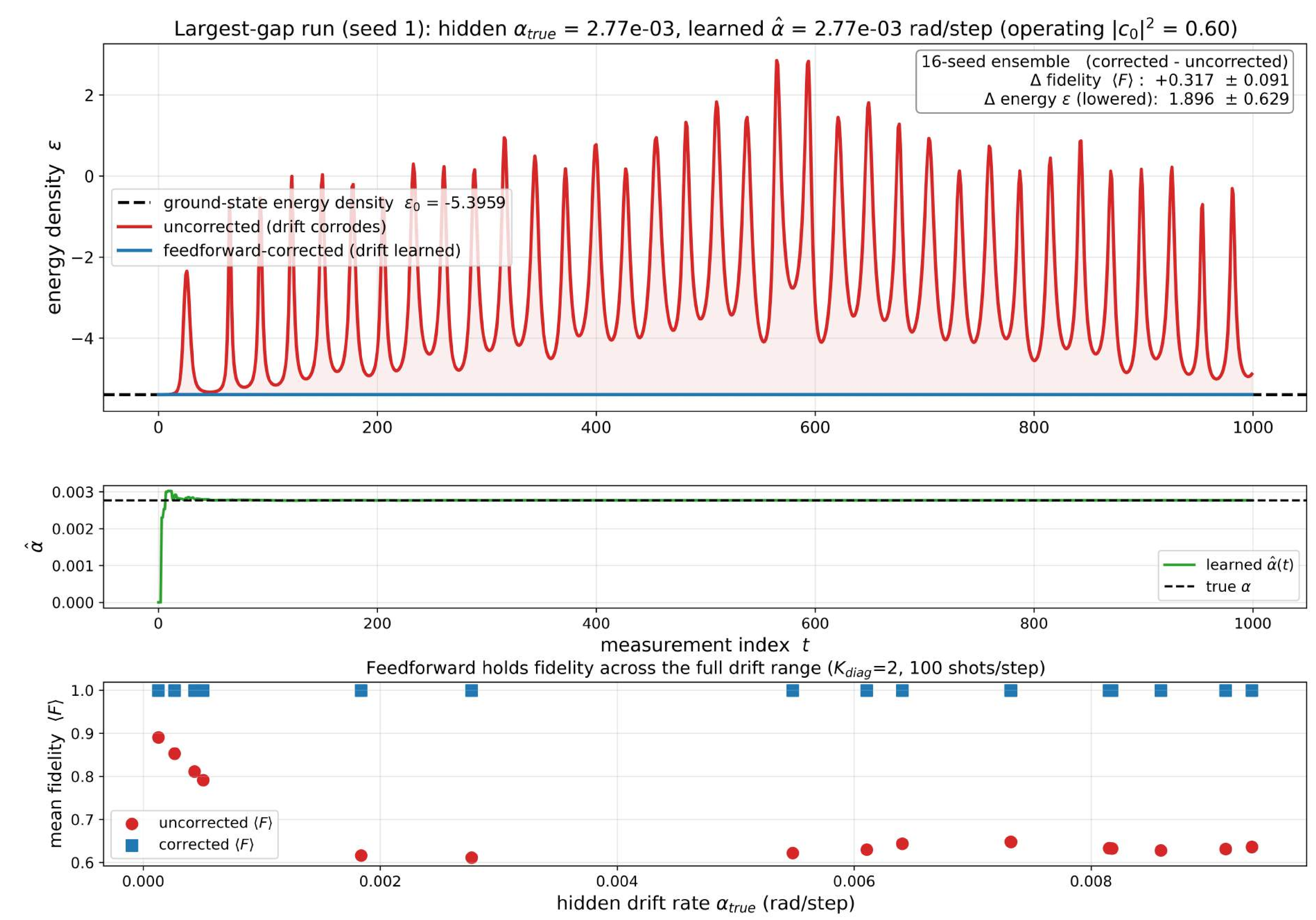


Figure 6. Tracking, 16 seeds at $|c_0|^2 = 0.6$: corrected fidelity holds (band = IQR) vs. uncorrected decay; rate locks in ~16 diagnostics.

0.682 → 0.995

uncorrected vs. corrected fidelity

Cost

98,000 Shots

reasonable for quantum experiments

Key results

- **Single-rate feedforward**: $\langle F\rangle_{\text{cor}} = 0.9995$ (16-seed ensemble at $|c_0|^2 = 0.6$, from uncorrected 0.683 ± 0.091); ~98,000 diagnostic shots total.
- **Agnostic**: transfers to multiplicative drift; rank-1 correction holds $\langle F\rangle \approx 0.93$ on rank-3 drift.
- **A different layer**: prior work fixes drift in *hardware* or only *detects/tolerates* it; here the algorithm's own output is the sensor and the fix lives in software phases.

Future directions

Curved drift → Kalman/Bayesian estimator (sensor unchanged); higher-rank drift → multi-probe readout; other Hamiltonians & platforms (mechanism is algorithm-agnostic).

References

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