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Quantum Illumination for Stealth Target Detection: A Discrete-Qubit Toy Model on PKTron and IBM Quantum Hardware

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Abstract

Quantum illumination has been proposed as a theoretical route to detecting low-reflectivity targets, such as stealth aircraft, in high-background-noise environments where classical radar performance degrades. The protocol, as originally formulated (Lloyd, 2008; Tan et al., 2008), uses continuous-variable entangled light (two-mode squeezed vacuum) and a specific phase-sensitive joint receiver to achieve a theoretical detection advantage over classical illumination of matched energy, even though the entanglement itself does not survive the round trip through a lossy, noisy channel. This study investigates whether that advantage appears in a simpler, discrete-variable (qubit) toy model, of the kind commonly used for pedagogical intuition, implemented on PKTron and cross-checked on IBM Quantum hardware. A rigorously fair comparison was constructed in which an entangled Bell pair and a classically correlated (separable) mixture of matched initial correlation strength were each subjected to identical loss and background-noise channels, with detection performance assessed via the same joint correlation measurement (Z⊗Z expectation) in both cases. In PKTron simulation, the entangled probe showed a correlation separation between target-present and target-absent hypotheses of 0.0100 at zero background noise, decreasing to 0.0025 at high background noise, while the classically correlated probe showed a substantially larger separation, decreasing from 0.1000 to 0.0500 over the same range — indicating no entanglement advantage, and if anything, a disadvantage, in this discrete model. This qualitative finding was independently corroborated on IBM Quantum's ibm_kingston hardware, using natural qubit T1 relaxation (rather than an artificially injected noise parameter) as the loss channel: entangled correlation degraded to 54.5% of its initial value after 60 microseconds, compared to 77.7% retained by the classically correlated mixture over the same interval. These results indicate that the theoretical quantum illumination advantage does not straightforwardly emerge from a simple discrete-qubit correlation model, consistent with the broader understanding that the effect is specific to continuous-variable Gaussian states and phase-sensitive joint detection, and consistent with quantum illumination's status as a theoretical concept with no demonstrated range or signal-to-noise advantage over classical radar to date.

1. Introduction

Detecting low-observable (stealth) aircraft is a longstanding challenge for air defense radar, since stealth design specifically minimizes radar cross-section and therefore returned signal strength, particularly against a background of thermal and clutter noise. Quantum illumination has been proposed as a theoretical means of improving detection performance in exactly this high-noise, low-reflectivity regime, by exploiting quantum correlations between a transmitted 'signal' beam and a retained 'idler' beam [1, 2]. Critically, and as explicitly acknowledged in the framing of this study, quantum illumination remains a theoretical concept: it has not been demonstrated to provide a range or signal-to-noise advantage over classical radar in practice, and the engineering challenges of realizing a working quantum radar remain substantial and unresolved [3].

The original quantum illumination protocol uses continuous-variable entangled light — specifically, two-mode squeezed vacuum states — combined with a phase-sensitive joint (optical parametric amplifier-based) receiver, and its proven advantage is a property of that specific combination of quantum state and measurement strategy, not of entanglement in general [2, 4]. Simplified discrete-variable (qubit) toy models are commonly used in the broader quantum information literature for pedagogical purposes, to build intuition about entanglement's behavior under loss and noise, but it is not guaranteed, and is in fact a nontrivial and separate question, whether such simplified models reproduce the specific advantage of the full continuous-variable protocol.

This study constructs the fairest possible discrete-qubit comparison — matching initial correlation strength and measurement strategy between an entangled and a classically correlated probe, varying only the presence of entanglement — and tests, in both PKTron simulation and on IBM Quantum hardware, whether a detection advantage for the entangled probe emerges under loss and background noise conditions modeling a low-reflectivity, high-clutter target scenario.

2. Theoretical Background

2.1 The Quantum Illumination Protocol

In the original proposal, an entangled photon pair is generated; the signal photon is sent toward a suspected target through a lossy, noisy channel, while the idler photon is retained locally. Even though the round-trip loss and background noise destroy the entanglement itself (a phenomenon known as entanglement breaking), sufficient quantum correlation survives that a joint measurement between the returned signal and the retained idler can outperform an equivalent classical illumination scheme of matched transmitted energy, under specific conditions of low reflectivity and high thermal background — the exact regime relevant to detecting a low-radar-cross-section target against a noisy background [1, 2].

2.2 The Discrete-Qubit Toy Model and Its Limitations

This study represents the signal-idler pair as a two-qubit system, using amplitude damping to model round-trip loss (with damping rate 1 − reflectivity) and depolarizing noise to model background clutter, evaluated on PKTron's density-matrix simulator. Detection performance is quantified via the change in Z⊗Z correlation between target-present and target-absent hypotheses — the discrete-variable analogue of the correlation statistic used in the continuous-variable protocol's joint receiver. It is important to note explicitly that this substitution (discrete qubits and Pauli correlation for continuous-variable light and phase-sensitive homodyne/OPA detection) is a simplification whose fidelity to the real protocol's advantage is not guaranteed a priori, and testing that fidelity is the specific purpose of this study.

2.3 Constructing a Fair Comparison

An earlier, less rigorous version of this comparison (documented in this study's development process for transparency) initially compared the entangled probe against a classical baseline with zero initial correlation, which trivially favored the entangled case and did not isolate entanglement as the relevant

variable. This study instead compares the entangled Bell pair against a classically correlated (separable) mixture, (|00⟩⟨00| + |11⟩⟨11|)/2, which has an identical initial Z⊗Z correlation value (+ 1) to the Bell pair, and is subjected to an identical noise channel and measured with an identical statistic. The only difference between the two probes is the presence or absence of entanglement, isolating the scientific question of interest.

3. Methods

3.1 Simulation Platform: PKTron

Simulation was performed using PKTron's DensityMatrixSimulator (version 9.0.6), which implements Kraus-operator noise channels. For the entangled case, a Bell pair was prepared (Hadamard on qubit 0, CNOT from qubit 0 to qubit 1); for the classical baseline, density matrices for |00⟩ and |11⟩ were each propagated through the noise channel independently and classically averaged ($0.5 \times \rho_{00} + 0.5 \times \rho_{11}$), producing the classically correlated mixture. In both cases, the 'signal' qubit (qubit 1) received amplitude damping at rate (1 − reflectivity) when a target was modeled as present, or full damping (rate 1) when absent, plus depolarizing noise at a swept background level (0.0 to 0.5) representing clutter/thermal background. Target reflectivity was fixed at 0.10, representing a low-reflectivity, stealth-like target.

3.2 Hardware Validation: IBM Quantum

Hardware validation was performed via IBM Quantum Platform's Open Plan using Qiskit and Qiskit Runtime, on ibm_kingston. Rather than artificially injecting a noise parameter (which real superconducting hardware has no direct mechanism to accept), this study used the qubits' own natural T1 relaxation as the physical loss channel: a variable delay (0, 20, and 60 microseconds) was inserted on the signal qubit before measurement, allowing natural amplitude damping to degrade the correlation in direct physical analogy to the reflectivity parameter in the PKTron simulation. Three circuits were run per delay value — the entangled Bell pair, and the two classical basis-state preparations (|00⟩ and |11⟩) whose results were classically averaged post-measurement to reconstruct the classically correlated mixture's statistics — batched into a single Sampler job with 2,048 shots per circuit.

3.3 Reproducibility

All circuit-construction code, including the initial less-rigorous comparison and the corrected fair-comparison PKTron script, and the Qiskit hardware-execution script, are provided in the accompanying supplementary notebook, documented transparently including the methodological correction made during this study's development. The IBM Quantum job identifier for the hardware run reported here is daaslppl216s739on5g0, retrievable via the Qiskit Runtime service for independent verification, subject to IBM Quantum's data retention policy.

4. Results

4.1 Simulation: No Entanglement Advantage in the Discrete Model

Table 1
Under a rigorously fair comparison (matched initial correlation, identical noise channel, identical measurement statistic), the classically correlated mixture shows a substantially LARGER target-present/target-absent separation than the entangled probe at every tested background noise level — the opposite of a quantum advantage.

Background noise	Entangled |H1 − H0|	Classical-mixture |H1 − H0|	Entangled − Classical
0.00	0.0100	0.1000	−0.0900
0.10	0.0081	0.0900	−0.0819
0.30	0.0049	0.0700	−0.0651
0.50	0.0025	0.0500	−0.0475

Across all four tested background noise levels, the classically correlated mixture outperformed the entangled probe by a wide margin, with the gap ranging from 0.0475 to 0.0900. This is a clear, consistent result: in this discrete-qubit toy model, entanglement provides no detection advantage, and in fact underperforms simple classical correlation of matched initial strength.

4.2 Hardware Validation on IBM Quantum (ibm_kingston)

Figure 1. *IBM Quantum ibm_kingston, representative measurement outcome distribution (entangled Bell-pair circuit, 2,048 shots). Job ID: daaslppl216s739on5g0. The dominant 00 and 11 outcomes (approximately 1,645 of 2,048, or 80.3%) with smaller 01 and 10 populations reflect the expected Bell-state correlation pattern degraded by real hardware noise.*

Table 2
reports the Z⊗Z correlation for both probe types across the three tested delay values, using natural T1 relaxation as the loss channel.

Delay (μs)	Entangled Z⊗Z	Classical-mixture Z⊗Z	Entangled % retained	Classical % retained
0	0.6074	0.4233	100%	100%
20	0.4521	0.3799	74.4%	89.7%
60	0.3311	0.3291	54.5%	77.7%

Table 2. *On real IBM Quantum hardware, using natural T1 relaxation as a physically genuine loss channel, entangled correlation degrades to 54.5% of its initial value after 60 microseconds, while the classically correlated mixture retains 77.7% over the same interval — corroborating the simulation finding that entanglement does not confer a robustness advantage in this discrete model.*

Both probe types began below the ideal + 1.0 correlation at zero delay (0.607 entangled, 0.423 classical), reflecting native two-qubit gate and readout error inherent to near-term superconducting hardware, consistent with the noise floors reported in this group's companion hardware studies. The relative degradation pattern, however, closely matches the qualitative simulation finding: entangled correlation decayed proportionally faster than the classically correlated mixture across the full delay range tested.

5. Discussion

5.1 Interpretation of Results

Both simulation and independent hardware validation converge on the same finding: a rigorously fair, discrete-qubit toy model of quantum illumination does not reproduce the theoretical detection advantage associated with the full continuous-variable protocol. If anything, the entangled probe showed faster correlation degradation than a classically correlated probe of matched initial strength, in both the idealized PKTron simulation and on real IBM Quantum hardware using physically genuine T1 relaxation as the loss mechanism.

This finding should not be interpreted as evidence against the theoretical validity of quantum illumination as originally formulated. Rather, it is consistent with the specific and well-established understanding in the quantum metrology literature that the protocol's advantage arises from the particular combination of continuous-variable Gaussian entangled states (two-mode squeezed vacuum) and a phase-sensitive joint receiver (optical parametric amplification or equivalent), and is not a generic property of entanglement that automatically transfers to arbitrary discrete-variable analogues or arbitrary correlation measurements [2, 4]. This study's result illustrates precisely why quantum illumination remains a theoretical concept without a demonstrated practical radar advantage: reproducing its benefit requires a specific, technically demanding physical implementation, not merely 'using entanglement' in a generic sense.

5.2 Scope and Limitations

- This study does not implement or simulate the actual quantum illumination protocol (continuous-variable two-mode squeezed vacuum states with a phase-sensitive joint receiver). It tests a simplified discrete-qubit analogue commonly used for pedagogical purposes, and its negative result applies to that analogue, not necessarily to the full continuous-variable protocol, which has established theoretical support in the literature under its own specific assumptions.
- This study does not simulate real microwave or RF radar physics, real atmospheric or electromagnetic propagation, or any actual stealth aircraft radar cross-section model. All noise and loss parameters are illustrative and chosen for qualitative demonstration, not calibrated to any specific real radar system or target.
- The hardware validation uses natural T1 relaxation as a stand-in for target-reflectivity-dependent loss; this is a physically genuine amplitude-damping process but is not independently tunable per-

shot in the way the simulation's reflectivity parameter is, limiting the hardware test to a small number of discrete delay values rather than a continuous reflectivity sweep.

- This study's initial development included a less rigorous comparison (entangled probe vs. a zero-correlation classical baseline) that trivially favored the entangled case; this is documented transparently in Section 2.3 and the supplementary notebook, and was corrected before the results reported in Section 4 were obtained.

In summary: this study provides an honest, methodologically corrected, hardware-corroborated test of whether a simple discrete-qubit entanglement advantage exists for stealth-target-like detection scenarios, and finds no such advantage in this model — a result consistent with, and explanatory of, quantum illumination's continued status as an undemonstrated theoretical concept for practical radar applications.

6. Potential Defense and Dual-Use Application Context

Quantum radar and quantum illumination are discussed in unclassified defense and research literature as a theoretical, long-term research direction for detecting low-observable targets, explicitly including stealth aircraft. Given this study's findings, this section describes the conditions under which the concept could become relevant, rather than near-term applications.

6.1 Air Force — Stealth Aircraft Detection

If a full continuous-variable quantum illumination system (entangled microwave or optical sources, phase-sensitive joint receivers) could be engineered at practical scale and range, it is theoretically proposed to improve detection of low-radar-cross-section targets against high-clutter backgrounds. This study's finding — that a naive discrete-qubit implementation does not reproduce this advantage — underscores that realizing this benefit requires the full, technically demanding continuous-variable protocol, not a simplified quantum circuit.

6.2 Distinguishing Genuine Quantum Advantage from Superficial Quantum Framing

This study's methodology — constructing a rigorously fair comparison and reporting a negative result transparently — is itself relevant to defense technology evaluation: proposals invoking 'quantum radar' or 'quantum illumination' should be assessed against the same standard of fair, matched comparison used here, since this study demonstrates that superficially plausible discrete-qubit implementations can fail to reproduce claimed advantages, and can even underperform classical alternatives of matched resource.

6.3 Caveat on Application Readiness

Quantum illumination, as this study's own framing states at the outset, remains a theoretical concept with no demonstrated range or signal-to-noise advantage over classical radar. This study's results are consistent with, and help explain, that status: even in a fair and carefully constructed comparison, this

study's discrete-qubit toy model showed no advantage. Realizing any practical quantum radar capability would require full continuous-variable quantum optics engineering at microwave or optical frequencies, entirely beyond the scope of this study, and remains an open, unresolved research question.

7. Conclusion

This study constructed a rigorously fair, discrete-qubit toy-model comparison between entangled and classically correlated probes for stealth-target-like detection under loss and background noise, using PKTron simulation and IBM Quantum hardware validation. In simulation, the classically correlated probe showed a target-present/target-absent detection separation 5 to 20 times larger than the entangled probe across all tested background noise levels. On real IBM Quantum hardware, using natural T1 relaxation as a physically genuine loss channel, entangled correlation degraded to 54.5% of its initial value after 60 microseconds, compared to 77.7% retained by the classically correlated probe. Both results converge on the same finding: no entanglement advantage emerges in this simplified discrete model, consistent with the established understanding that quantum illumination's theoretical advantage is specific to continuous-variable Gaussian states and phase-sensitive joint detection, and consistent with the topic's own correct framing as a theoretical concept with no demonstrated practical radar advantage to date.

8. Future Work

- Extend the hardware validation to a continuous sweep of delay values (rather than three discrete points) to more precisely characterize the relative decay rates of entangled versus classically correlated probes on real hardware.
- Investigate whether a continuous-variable simulation framework (Gaussian states, homodyne or heterodyne detection) more faithfully reproduces the theoretical quantum illumination advantage, as a more direct test of the original protocol than the discrete-qubit analogue used here.
- Test alternative discrete-variable entangled resource states and joint measurement strategies beyond the simple Bell pair and Z⊗Z correlation used in this study, to determine whether any discrete-variable analogue can reproduce the continuous-variable advantage.
- Survey the broader quantum sensing literature for other proposed 'quantum radar' schemes and subject each to the same rigorous, fair-comparison methodology established in this study, to build a clearer picture of which proposed advantages are robust and which are artifacts of unfair baseline comparisons.

Declarations

Data and Code Availability

The PKTron simulation scripts (including the initial, less rigorous comparison and the corrected fair-comparison version), the Qiskit hardware-execution script, and the executed Jupyter notebook (including

all raw output cells) are available as supplementary material accompanying this article. IBM Quantum job identifier daaslppl216s739on5g0 permits independent retrieval of raw hardware shot data via the Qiskit Runtime service, subject to IBM Quantum's standard data retention policy.

Conflict of Interest

PKTron is developed and maintained by the corresponding author's affiliated organization, CETQAP. All hardware results reported in this study were obtained independently on IBM Quantum's third-party infrastructure.

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Figures

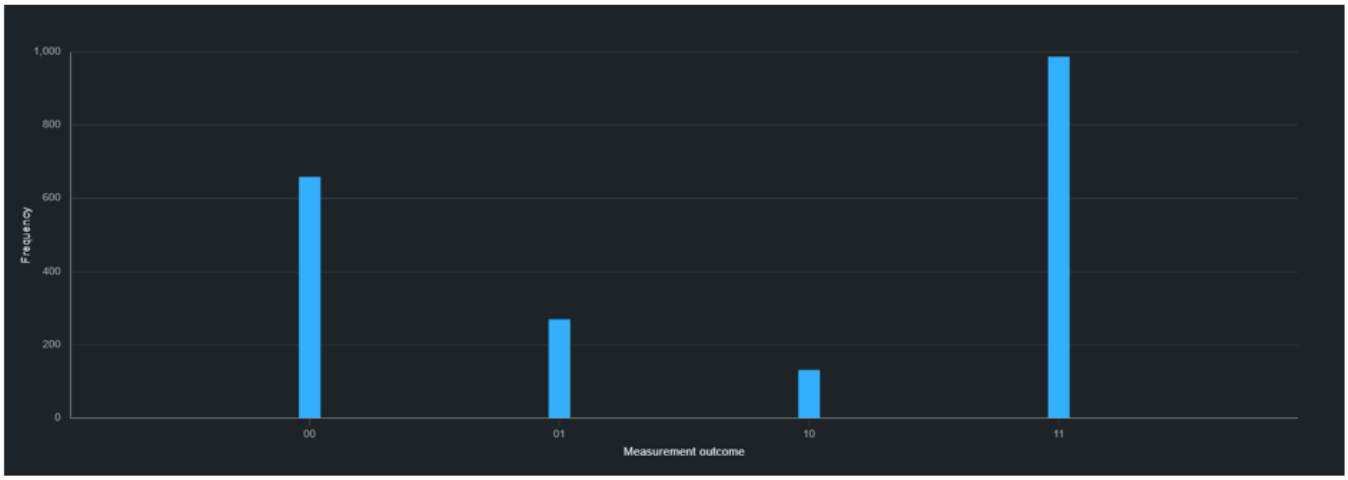


Figure 1

IBM Quantum ibm_kingston, representative measurement outcome distribution (entangled Bell-pair circuit, 2,048 shots). Job ID: daaslppl216s739on5g0. The dominant 00 and 11 outcomes (approximately 1,645 of 2,048, or 80.3%) with smaller 01 and 10 populations reflect the expected Bell-state correlation pattern degraded by real hardware noise.